IGLC 30

INTERNATIONAL GROUP FOR LEAN CONSTRUCTION

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Proceedings of the 30th Annual Conference of the International Group for Lean Construction

Towards the **integration** of:
Inspired people
Intelligent processes
Innovative technologies

Proceedings of the 30th Annual Conference of the International Group for Lean Construction (IGLC 30)

Farook Hamzeh and Thais Alves (editors)

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Message from the Multi-conference Chairs

We are pleased to have had the opportunity to host the 2022 construction multi-conference held at the University of Alberta, one of Canada's leading public universities, known for world-class research and innovative discoveries.

The 2022 multi-conference event comprises the 30th annual conference of the International Group for Lean Construction (IGLC), the Modular and Offsite Construction (MOC) Summit, and the Construction Innovation Centre (CIC) Forum.

When compared to current conventional construction methods, lean construction and industrialized construction offer a number of advantages, including increased productivity, reduced costs and construction time, higher quality products, healthier environments for workers and occupants, and decreased environmental footprint (CO_2 emissions).

As construction methods and technologies evolve, stakeholders need to be informed and engaged at every phase of the construction project in order to effect a fundamental change in construction culture. To address this need, the 2022 IGLC30 / MOC Summit / CIC Forum multi-conference provided a venue for academics, practitioners, and industry stakeholders to share their knowledge and expertise regarding the opportunities and challenges associated with implementing innovative construction methods and technologies. Through participation in interactive sessions and workshops, delegates challenged current policies and practices, and discussed how to improve efficiency and productivity.

IGLC30 INTERNATIONAL GROUP FOR LEAN CONSTRUCTION | CIC FORUM CONSTRUCTION INNOVATION CENTRE | MOC MODULAR AND OFFSITE CONSTRUCTION SUMMIT

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Department of Civil & Environmental Engineering, University of Alberta

Foreword

The 30th annual conference of the International Group for Lean Construction brought together academic and industry professionals to discuss pressing topics in lean construction research and practice. It was a milestone event not only because it was the first in-person event after two consecutive online conferences due to the COVID-19 pandemic, but also because it brought elevated the level of collaboration by bringing together three conferences under one roof to produce a dynamic multi-conference event. IGLC30 was held in conjunction with two other conferences: the 2022 MOC Summit, a globally recognized conference creating an active platform for idea exchange between leaders, scholars, and practitioners in modular and offsite construction; and the 2022 CIC Forum, an annual event launched in 1997 to establish a venue for circulating ideas, practices, and solutions among researchers, students, industry partners and members of the Alberta construction industry.

Moreover, this was the first time that IGLC adopted the hybrid conference format so that participants could attend in-person or remotely due to the ever-evolving nature of the COVID-19 pandemic. A total of 116 full papers were received, and following a double-blind review, 104 papers were accepted for publication and 12 were rejected. The accepted papers represent 17 countries including (in alphabetical order): Australia, Brazil, Canada, Chile, Colombia, Denmark, Finland, France, Germany, India, Iran, Ireland, Israel, Italy, Lebanon, Mexico, Norway, Peru, Qatar, Sweden, UK, and USA. Table 1 shows the number of published papers from each country.

Table 1: Papers accepted to IGLC30 by country of first author's institution

Countries	Papers published	Countries	Papers published
USA	21	Australia	3
Canada	13	Lebanon	2
Brazil	12	Colombia	1
Finland	12	France	1
India	8	Iran	1
Norway	8	Ireland	1
Chile	6	Israel	1
Germany	6	Italy	1
UK	6	Mexico	1
Denmark	4	Qatar	1
Peru	4	Sweden	1

The high quality of the submissions led us to choose nine plenary papers worthy of presentation to the entire IGLC audience. The plenary papers are listed in Table 2. Additionally, the eleven themes were chosen to reflect the most pressing issues of interest to researchers in the field, and two full pages were permitted for reference lists in order to allow for a systematic literature review. The breakdown of papers received for each theme is shown in Table 3.

Table 4 includes the names of all the volunteers and staff at the University of Alberta who worked tirelessly to organize and produce the multi-conference event.

The technical co-chairs would like to acknowledge the efforts of all those who committed their time to review the papers. The reviewers, listed in Table 5, were diligent in their efforts to ensure that the papers accepted for this conference were of a high standard. We would also like to thank the authors for addressing the reviewers' comments and improving the quality of their submissions.

Table 2: Selected plenary papers of IGLC30

Plenary paper title	Authors
Gregory Howell Plenary Session: Uncovering and visualizing work process interruptions through quantitative workflow analysis	*Christopher Görsch, Alaa Al Barazi, Hisham Abou Ibrahim, Olli Seppänen*
Rethinking project delivery to focus on value and innovation in the public sector	*Patricia Tillmann, Stuart Eckblad, Fred Whitney, Niall Koefoed*
Sensemaking of guiding principles in construction projects	*John Skaar*
The need for a human-centric approach in C4.0 technologies	*Karim Noueihed, Farook Hamzeh*
The development of simulations and pull planning for lean construction learning and implementation	*Cynthia C.Y. Tsao, Gregory A. Howell*
Is construction industry still performing worse than other industries?	*Jan Alarik Elfving, Olli Seppänen*
Location-based work sampling	*Cristina Toca Pérez, Stephanie Salling, Søren Wandahl*
Developing a multi-project collaboration based IPD framework for small and medium enterprises in the construction industry	*Raviteja Vaitla, Vrinda Arjun Gaikwad, Abhinav Reddy Singireddy, Jong Han Yoon*
Putting the collaborative style of a successful football team in a lean construction context	*Tobias Onshuus Malvik*

Table 3: Papers submitted by theme

Theme	Number of papers	Theme	Number of papers
Production Planning and Control	24	Lean Theory	8
People, Culture, and Change	12	Learning and Teaching Lean	8
Product Development and Design Management	11	Safety, Quality, and Green-Lean	7
Enabling Lean with Information Technology	9	Supply Chain Management and Off-Site Construction	7
		Production System Design	5
Lean and BIM	9	Contract and Cost Management	4

Table 4: Volunteers and staff

Abbey Dale Abellanosa	Diana Salhab	Kristin Berg	Ramin Aliasgari
Ali Golabchi	Elyar Pourrahimian	Lynn Shehab	Rana Ead
Amanda Peters	Enric Barkokebas	Malak El Hattab	Regina Dias Ferreira Barkokebas
Anas Badreddine	Fatima Alsakka	Mohamad Darwish	Rose Parvaneh
Anas Itani	Ghulam Muhammad Ali	Nazanin Najafizadeh	Salam Khalife
Asif Mansoor	Hisham Soliman Mahmoud	Negar Mansouri Asl	Samaneh Momenifar
Beda Barkokebas	Jonathan Tomalty	Omar Abdel-Jaber	Serhii Naumets
Brenda Penner	Karim Noueihed	Omar Azakir	Sida Wang
Danial Gholinezhad Dazmiri	Karl Keyrouz	Pablo Martinez Rodriguez	Vahid Abbasianfar

Table 5: Reviewers

Name	Affiliation	Name	Affiliation
Mohammed Adel	The University of Auckland	Ricardo Codinhoto	The University of Bath
Muhamad Abduh	Institut Teknologi Bandung	Manoela Conte	UFRGS
Mohamed Abou El Fish	KEO International	Dayana Bastos Costa	Federal University of Bahia
Hisham Abou Ibrahim	Aalto University	Ype Cuperus	Delft University of Technology
Julia Sofia Acosta Rojas	Pontificia Universidad Católica de Chile	Patrick Dallasega	Free University of Bozen-Bolzano
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Toni Henrik Ahonen	YIT Suomi Oy	Ganesh Devkar	CEPT University
Opeoluwa Akinradewo	University of Johannesburg	Regina Dias Barkokebas	University of Alberta
Wassim Al Balkhy	Centrale Lille	Janosch Manuel Dlouhy	BMW Group
Alaa Al Barazi	Aalto	Doanh Do	UC Berkeley
Luis Fernando Alarcon	Pontificia Universidad Católica de Chile	David R. Drake	Washington State University
Ghulam Muhammad Ali	University of Alberta	Frode Drevland	NTNU
Ghulam Ali	University of Alberta	Jan Alarik Elfving	Skanska
Alexandre Almeida Del Savio	Universidad de Lima	Mahmoud Elsayed	University of Alberta
Fatima Alsakka	University of Alberta	Fidelis Abumere Emuze	Central University of Technology, Free State
Thais Alves	San Diego State University	Andrews Alexander Erazo-Rondinel	Universidad Continental
Tatiana Gondim Amaral	Universidade Federal de Goiás	Bernardo Martim Beck Da Silva Etges	Climb Consulting Group
Patricia Andre Tillmann	Superior air handling	Chao Fan	University of Alberta
Caroline Silva Araújo	Federal University of Bahia	Laura Florez Perez	University College London
Yasaman Arefazar	Texas A&M University	Salazar Santos Fonseca	Coanfi, S.L.
Paz Arroyo	DPR Construction	Daniel Forgues	ETS Montreal
Elnaz Asadian	Pennsylvania State University (PSU)	Carlos T. Formoso	UFRGS - Federal University of Rio Grande do Sul
Omar Azakir	University of Alberta	Alejandro Javier Garcia De Taboada	Pontifical Catholic University of Peru
Anas Badreddine	University of Alberta	Nelly Paola Garcia-Lopez	Grupo Galopa
Glenn Ballard	University of California Berkeley	Christy P. Gomez	Universiti Tun Hussein Onn Malaysia
Fernanda Saidelles Bataglin	Federal University of Rio Grande do Sul	Elizabeth Ann Gordon	DPR
Fabrice Berroir	Luxembourg Institute of Science & Technology	Christopher Görsch	Aalto University
Marco Binninger	weisenburger bau GmbH	David Grau	Arizona State University
Clarissa Biotto	UFC	Cecilia Gravina Da Rocha	UTS
Trond Bølviken	University of Agder	Shervin Haghsheno	Karlsruhe Institut of Technology
Seth Yeboah Botchway	The University of Hong Kong	Heikki Pentti Halttula	Civil Soft Ltd.
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Krishna Chauhan	Aalto University	Anas Itani	University of Alberta
Xue Chen	University of Alberta	Tony Jacob	KEO International Consultants
Randi Muff Christensen	COWI	Hrishikesh Sanatkumar Joshi	Indian Institute of Technology, Madras
David K H Chua	National University of Singapore	Prasad K V	VIT University, Chennai
Diego Cisterna	Karlsruhe Institute of	Bo Terje Kalsaas	University of Agder

Table 5: Reviewers

Name	Affiliation	Name	Affiliation
Dorra Karmaoui	Centrale Lille	Guillermo Prado Lujan	University of California Berkeley
Salam Khalife	University of Alberta	Shobha Ramalingam	NICMAR, Pune
Sergei Kortenko	University of Huddersfield	Seyedreza Razavialavi	Northumbria University
Ivana Kuzmanovska	Monash University	Mohd Akif Razi	The University of British Columbia (Okanagan)
Ola Lædre	Norwegian University of Science and Technology	Slim Rebai	Centrale Lille Institut
Camilo Ignacio Lagos Crua	Pontificia Universidad Católica de Chile	Dean Steven Reed	Capability-Building
Eelon Mikael Lappalainen	Aalto University	Ana Virginia Reinbold	Aalto Univertity
Joonas Lehtovaara	Aalto University, Finland	Zofia Kristina Rybkowski	Texas A&M University
Jon Lerche	Aarhus University	Rafael Sacks	Technion
Shuai Liu	University of Alberta	Luis Arturo Salazar	Universidad Técnica Federico Santa María
Tobias Onshuus Malvik	Norwegian University of Science and Technology	Diana Salhab	University of Alberta
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Negar Mansouri Asl	University of Alberta	Olli Seppänen	Aalto University
Musab Jamal Maraqa	Technion-Israel Institute of Technology	Sheyla Mara Serra	Uni. Federal de São Carlos
Renato Mariz	University of Campinas and Lean Institute Brasil	Lynn Shehab	University of Alberta
Amirhossein Mehdipoor	ETS University	Vishesh Vikram Singh	University of California Berkeley
Reymard Savio Melo	Federal University of Bahia	John Skaar	University of Agder
Ricardo Mendes Jr	Federal University of Paraná	James Packer Smith	Brigham Young University
Osama Mohsen	University of Alberta	Joao Soliman-Junior	University of Huddersfield
Alan Mossman	The Change Business	Sahar Soltani	Monash University
Claudio Mourgues	Pontificia Universidad Catolica de Chile	Matt Stevens	Western Sydney University
Sean M. Mulholland	United States Air Force Academy	Marcus Costa Tenório Fireman	Federal University of Rio Grande do Sul
Danny Murguia	Pontifical Catholic University of Peru	Algan Tezel	Aston University
Kristoffer Brattegard Narum	Norwegian University of Science and Technology	Shamnath Thajudeen	Jönköping university
Ming Shan Ng	ETH Zurich	Iris D. Tommelein	University of California, Berkeley
Karim Noueihed	University of Alberta	Olav Torp	Norwegian University of Science and Technology
Rafael Novais Passarelli	UHasselt	Cynthia Tsao	Navilean LLC
Rajeswari Obulam	Texas A&M University	David Umstot	Umstot Project and Facilities Solutions, LLC
Nicole Tamara Odo	University of New Brunswick	Kalyan Vaidyanathan	Nadhi Information Technologies
Joseph K Ofori-Kuragu	Anglia Ruskin University	Valeria Veronica Vecchio	University of Alberta
Svenja Oprach	Karlsruher Institute of Technology (KIT)	Daniela Dietz Viana	UFRGS
Pablo Orihuela	Pontificia Universidad Católica del Perú	Kenneth D Walsh	George Mason University
Jesus Andres Ortega Fernandez	Pontificia Universidad Católica de Chile	Soren Wandahl	Aarhus University
Alejandro Palpan	TSC Innovation	Yiheng Wang	University of Alberta
Barbara Pedo	University of Huddersfield	Yu Wei	University of Alberta
Antti Peltokorpi	Aalto University	Jan Wolber	Karlsruher Institut of Technology
Cristina Toca Pérez	Aarhus University	Qiuling Yang	University of Alberta
Flavio Augusto Picchi	Unicamp/ LIB	Jong Han Yoon	Georgia Institute of Technology
Ergo Pikas	Aalto University	Hayyan Nasser Zaheraldeen	American University of Beirut
William Power	DPS Group	Yuxuan Zhang	University of Alberta

IGLC 30 included the following four value-added and popular events:

(1) insightful keynote speeches, the first by Dr. Glenn Ballard (UC Berkeley) titled "The Last Planner System and the Waste of Making-Do: A Research Proposal", and the second by Dr. Patricia Tzortzopoulos (University of Huddersfield) titled "Reflections on Industry 5.0 to foster Lean Design and Digitalisation";

(2) five sessions of Lean simulation games led by Dr. Iris Tommelein (UC Berkeley), Dr. Zofia Rybkowksi (Texas A&M University), Dr. Cynthia Tsao (Navilean), Dr. Thais Alves (San Diego State University), and Alan Mossman;

(3) the Greg Howell best paper session, which was awarded to "Uncovering and visualizing work process interruptions through quantitative workflow analysis" by Christopher Görsch, Alaa Al Barazi, Hisham Abou Ibrahim, and Olli Seppänen (all affiliated with Aalto University) ; and

(4) the panel on "Perspectives on Generative Design for Construction" hosted by the Construction Innovation Center (University of Alberta).

Thank you to the multi-conference volunteers, organizing committee, reviewers, authors, track chairs, and conference participants for contributing to this dynamic event.

May these proceedings be of value to practitioners and researchers for years to come.

Sincerely,

Farook Hamzeh and Thais Alves

Your 2022 IGLC proceedings editors and technical co-chairs

Dr. Farook Hamzeh

IGLC30 Technical Co-chair

Associate Professor, Department of Civil & Environmental Engineering, University of Alberta

Dr. Hamzeh is a Lean Construction expert. His theoretical and applied research in the US, Canada, and the MENA region aim at improving the design and construction of projects. Dr. Farook Hamzeh is an Associate Professor in Civil and Environmental Engineering at the University of Alberta. He was full time faculty at Colorado State University and at the American University of Beirut. Dr. Hamzeh is an active member of the International Group of Lean Construction (IGLC) and has published heavily on Lean Construction and related topics. Dr. Hamzeh has worked for more than seven years in the construction industry on several mega projects: the $1.7 Billion Cathedral Hill Hospital in San Francisco, the 333 m high Rose Rotana Hotel in Dubai, Losail motor-bike racetrack in Qatar, Olympic Tower in Qatar, Al-Amal Oncology Hospital in Qatar, Serail 1374 Building in downtown Beirut, and Sibline Cement factory 2nd production line in Lebanon.

Dr. Thais Alves

IGLC30 Technical Co-chair

Associate Professor, Department of Civil, Construction and Environmental Engineering, San Diego State University

Dr. Thais Alves is currently the AGC - Paul S. Roel Chair in Construction Engineering and Management at the J.R. Filanc Construction Engineering and Management Program at San Diego State University (SDSU). Prior to SDSU, Dr. Alves was a faculty member at the Federal University of Ceará, Brazil. She specializes in construction management and project-based production systems, including the use of lean production/construction concepts, principles, and tools to improve the performance of production systems and how people organize, collaborate, and learn from planning activities. Dr. Alves has published extensively in the International Group for Lean Construction (IGLC) since 2000, and has been part of the core group of the Lean Construction Institute San Diego Community of Practice since 2010.

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LEAN THINKING TO IMPROVE CURRICULUM DELIVERY IN CIVIL ENGINEERING USING MONTE CARLO SIMULATION

Osama Mohsen[1], Serhii Naumets[2], and Farook Hamzeh[3]

ABSTRACT

Lean education can refer to teaching Lean principles or applying Lean thinking to improve educational content delivery. Applying Lean in education can enhance supportive services such as admissions and program selections. In this paper, we developed a simulation study to examine course offerings in the third and fourth years of civil engineering at the University of Alberta, given an anticipated number of students registered in different subdisciplines. This study uses Monte Carlo simulation to model student enrolment in the curriculum aiming to reduce curriculum planning time and incorporate the end users' (i.e., the students) preferences into the course offerings by evaluating various what-if scenarios. The study investigates the effect of course selection flexibility on curriculum delivery and estimates the seating capacity to accommodate all enrolled students. In one scenario, all variables were simulated using random numbers and predefined statistical distributions. In a second scenario, we introduced restrictions where one subdiscipline offers limited courses, and graduate course offerings are restricted. In a third scenario, an additional restriction was added by raising the GPA eligibility threshold for graduate courses. The results show that simulation is an effective tool to test and incorporate Lean ideas into curriculum planning and management.

KEYWORDS

Continuous Improvement, Curriculum Development, Engineering Education, Learning, Simulation.

INTRODUCTION

The core of today's Lean thinking and methodology is based on the success of the Toyota Production System (TPS) (Ohno 1988), which founded the worldwide spread of Lean principles, not only in the manufacturing sector but also in other industries and service environments. Many researchers have investigated the Lean applications in the construction industry (Lauri Koskela 1992; Ballard and Howell 2003; Alarcón et al. 2008; Jørgensen and Emmitt 2009). Also, Lean tools and techniques were utilized in various

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service fields such as healthcare (Ker et al. 2014), hospitality (Abdelhadi 2016), and finance (Wang and Chen 2010).

The application of Lean principles in higher education institutions (HEIs) provides numerous benefits at operational, administrative, and strategic levels. The inclusion of Lean thinking and principles in education is two folds: 1) as curriculum contents and 2) as a method of improving educational delivery (Alves et al. 2017). Specifically, the quality of engineering education affects, to a large extent, the quality of future engineers; hence, HEIs are required to identify and search for the skills and competencies that a modern engineer must retain. Lean higher education (LHE) refers to the adoption of Lean philosophy and thinking in higher education, both at academic activity levels (e.g., course design, improving degree programs, managing assignments) and administrative activity levels (e.g., admission process, hiring, purchasing) (Vukadinovic et al. 2016).

The fundamental nature of Lean philosophy is to eliminate all types of waste, shortfalls, and non-value-adding activities. Lean practices and principles have the potential to significantly improve the curriculum planning process. To the best of our knowledge, there are rarely any studies that attempt to incorporate Lean thinking into the curriculum planning processes via the use of Monte Carlo simulation. This paper intends to use simulation modeling to examine the effect of applying different sets of rules that restrict undergraduate student enrollment in the civil engineering program courses at the University of Alberta. We propose that a curriculum simulation modeling can be used and lead to a lean planning process by reducing the time required to forecast seat requirements for each subdiscipline. Also, it allows curriculum planners to better prepare for unforeseen changes in course offerings and curriculum guidelines. This approach will also improve the student experience by allowing planners to match the course offerings with the students' preferences and forecasted enrollment. The implemented method in this study supports the Lean principles of 1) "Create a continuous process flow to bring problems to the surface," and 2) "Make decisions slowly by consensus, thoroughly considering all options," as described by Liker (Liker 2021). Without using the proposed model, curriculum and program planners have to spend a significant amount of time trying to satisfy many contradicting constraints regarding student enrolment and course offerings. In addition, using our proposed model, the decisions made by the planners are based on objective measures and forecasts and are less prone to subjectivity.

The paper starts with a brief literature review about Lean application in higher education. Then, the study methodology is presented, followed by results and a discussion section. Concluding remarks are then presented, including suggestions for future work.

LITERATURE REVIEW

The literature on Lean application in higher education institutions is still evolving compared to the wealth of information on lean in the manufacturing industry (Thomas et al. 2015). In this section, we provide a brief overview of the literature on Lean application in higher education as well as curriculum development.

LEAN FOR EDUCATION

Lean is gaining attention in the educational sector as valuable organizational philosophy and administrative toolkit. Lean initiatives have been developed and implemented to promote sustainable universities by identifying the best Lean practice at the institutional level (Comm and Mathaisel 2003). Also, Emiliani (2004) described the application of Lean principles and practices to improve the consistency of business courses taken by part-time students who are working professionals. In a subsequent paper, the author used the Kaizen process for ten courses in a part-time executive management degree and concluded that Kaizen could be an effective way to improve business courses and values for students (Emiliani 2005). In applying Lean principles and techniques at HEIs, Balzer et al. (2015) discussed the respective successes, challenges, and potentials for improving institutional readiness, enhancing leadership awareness and support, and facilitating an institution-wide transition to LHE.

Other authors tried to combine different techniques with Lean to achieve a more efficient curriculum delivery. For example, Thomas et al. (2017) proposed a framework that attempts to create a more balanced and integrated approach between Lean and Six Sigma that can accomplish enhanced efficacy of curriculum and program development in a higher education environment. On the other hand, Tsao et al. (2013) discussed distinct perspectives on teaching Lean Construction (LC) in a university setting. They illustrated how LC could be taught effectively by combining a broad range of tasks that integrate theory with action. These tasks may include readings, lectures, discussions, exercises, field trips, and guest speakers. Also, Pusca and Northwood (2016) demonstrated how Lean principles can be applied to improve the quality of an engineering design course in terms of course content, delivery, and assessment. They considered engineering design education a process, and the instructors can apply value stream mapping, root cause analysis, and Kaizen to improve the quality of teaching and learning.

More recently, and intending to eliminate waste in the business school curriculum, Kazancoglu and Ozkan-Ozen (2019) defined eight wastes of lean philosophy in higher education institutions. They investigated the causal relationship to create an importance-order using a multicriteria decision-making method. Lean thinking and practices can also be applied for other educational purposes. In one study, the authors proposed a “hands-on team simulation exercises” method to teach LC. The technique is used to accommodate different learning styles and engage students throughout the learning process by replicating various real-life processes, projects, and systems to enhance teaching, analyzing, and understanding (Hamzeh et al. 2017). In another study, the authors examined the use of "Lean Simulation" as an effective way to learn lean principles and understand the impact on process optimization. The authors developed a simulation model on a digital platform that supports user interactions to educate participants about lean principles, including the Last Planner ® system (Cisterna et al. 2021). Also, Hao and Florez-Perez (2021) conducted empirical research to identify the effect of the physical classroom environment on the motivational attributes of students in HEI. Based on the Lean thinking methodology, the authors provided design recommendations that support absenteeism reduction, enthusiasm boost, and improving the "person-environment relationship" to fulfill the students' needs.

CURRICULUM DEVELOPMENT

With the increasing competition for student recruitment and retention, credit transfer flexibility, and quality assurance strategies at HEI, continuous curriculum development has become a necessity in today's global higher education. A curriculum has been defined by Hubball and Gold (2007) as "a coherent program of study (such as a four-year B.Sc.) that is responsive to the needs and circumstances of the pedagogical context and is carefully designed to develop students' knowledge, abilities, and skills through multiple integrated and progressively challenging course learning experiences." Due to many social, economic, organizational, and individual factors, as well as the various phases of development and the number of people involved at several institutional levels, undergraduate curriculum development is a multifaceted and complex process (Wiles and Bondi 2015).

Wolf (2007) presented a model used to systematically assess the department's undergraduate curriculum at the University of Guelph. The model is based on a data-driven approach that engages faculty members and teaching supportive services using curriculum assessment to foster a continuous improvement process in curriculum development. The process consists of three phases: 1) curriculum visioning, 2) curriculum development, and 3) alignment, coordination, and development. Hines and Lethbridge (2008) argued that the academic environment is more challenging to change than many other conventional environments and have presented the steps necessary for developing an effective Lean enterprise in such an environment. The authors proposed the Lean iceberg model in which the technology, tools, and techniques that affect the processes are just a visible part of the iceberg. Litzinger et al. (2011) proposed that curriculum-level instructional processes should be used to design and implement changes to improve the alignment of developing expertise and engineering education. They asserted that the engineering education curriculum should embrace a set of learning skills that grant students deep conceptual knowledge, technical and professional fluency, and engagement in real-world engineering projects where the students adapt to address novel and complex problems.

One of the recent studies used Monte Carlo simulation to assess curriculum efficiency and propose improvements to increase graduation rates by identifying bottlenecks in a degree plan (e.g., course prerequisites). The study is designed to predict the time it takes each student to complete a degree by enrolling a large number of virtual students and simulating their progress in a degree plan (Torres et al. 2021).

It is observed that curriculum development is an essential process in the success of engineering programs, and it has been an active area of research in the past few years. More recently, Lean thinking and philosophy have seen increasing interest as it applies to higher education. However, using Monte Carlo simulation to examine the different processes that can improve the engineering program curriculum and produce a "leaner" degree plan is a promising approach that has not been investigated well in the literature. This study is conducted to fill this gap and to promote using simulation with Lean Thinking to support curriculum development in HEI.

RESEARCH METHOD

This study examines different cases of student progression through the civil engineering degree plan by enforcing various restrictions on what courses the student is allowed to take during the sixth, seventh and eighth semesters. Different scenarios are examined using a Monte Carlo simulation developed in MS Excel. Program administrators can utilize this tool to select the most feasible set of rules in terms of optimizing the overall seat utilization for all course sections while at the same time providing flexibility for students to select the courses and specializations that are of interest to them. The methodology that guided the activities in this study is outlined in Figure 1.

Every year, the number of students enrolling in and graduating from each term of civil engineering faculty can not be predicted with certainty. The authors acknowledge that enrolment unpredictability can be said about any faculty in a given university. However, this paper focuses only on the civil engineering faculty at the University of Alberta. The factors that contribute to the unpredictability of students' flow through curriculum include, but are not limited to, failure to score passing marks, cooperative students who alternate semesters between working and studying, students taking breaks or switching to part-time programs, and of course, the choices students make between different classes and specialties.

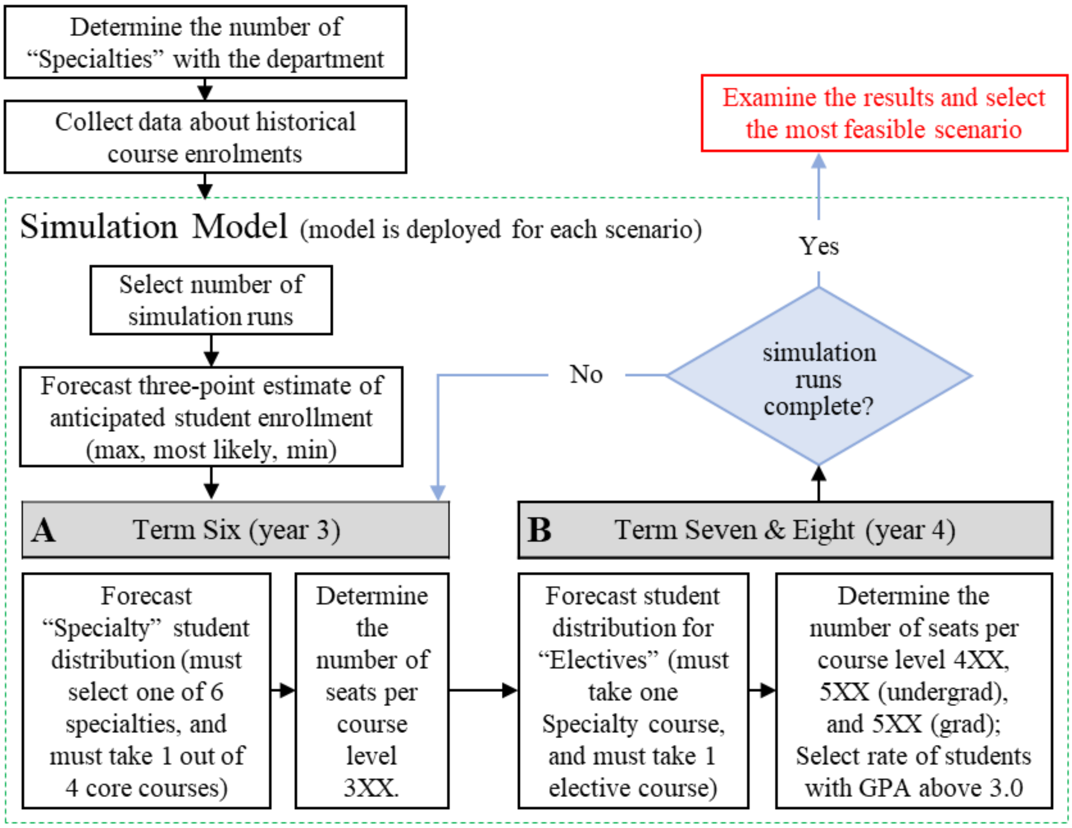

Figure 1: Research methodology

The traditional way of dealing with these uncertainties is to rely on historical data and base the estimate on the average attendance. However, this is a new curriculum, and historical data do not hold much weight in this case. There is no doubt that the conventional method works to some extent; nevertheless, after applying Lean Thinking to the problem, the authors quickly realized that a more sophisticated approach is required to deal with enrolment uncertainties. To quote a great statistician, "Plans based on average assumptions will be wrong on average" (Savage 2009).

MONTE CARLO SIMULATION MODEL

Monte Carlo simulation is a great tool that can be used to optimize deterministic problems based on "known unknowns." From the students' standpoint, their choices are determined based on circumstances, causes, and their will. On the other hand, all these deterministic factors are unknown from the curriculum planner's standpoint. Hence, students' choices can be considered stochastic (random) in nature. In the Monte Carlo method (Metropolis and Ulam 1949), random numbers are used to simulate "known unknowns." These numbers are generated in the range between zero and one and then transformed into variables based on predefined distributions or custom-made distributions supported by empirical data. In statistical layman terms, the random number represents cumulative density function (CDF) which is then inversely transformed into probability density function (PDF, area under the curve). Every iteration of random numbers constitutes a possible scenario in which all other dependable elements of the model are calculated (e.g., number of students per semester, number of courses per semester).

In our study, we used the Monte Carlo method to simulate the flow of students through the curriculum of the civil engineering department for terms six, seven, and eight. These terms were not chosen arbitrarily by the researchers but were aligned with the ongoing engineering department reorganization, which had an emphasis on the third and fours academic years. This is because the courses offered in the first two years are common for all students. The students have no flexibility to select elective courses until they reach the third year. Nevertheless, the developed Monte Carlo model can be customized to accommodate any number of semesters or for all semesters together, simulating the whole degree length.

RESULTS AND DISCUSSION

In the developed model, hypothetical students choose their specialty in the second semester of the third year (i.e., term six). They can select one of the following civil engineering subdisciplines: Structural, Environmental, Geotechnical, Water Resources, Construction, or Transportation. In addition, they need to choose three more courses in term six as electives from which one course can be from their specialty (two specialty courses maximum in one term; a maximum of four specialty courses in three terms combined). In the following terms (i.e., terms seven and eight), students are required to select two core courses each term (specialty or elective) with the constraint of having two identical electives maximum over the three terms.

Table 1: Model inputs, their respective values, and distributions

Inputs	Min	Most likely	Max	Probability density function
Anticipated number of students	125	150	160	Beta-Pert
GPA above 3.0/4.0	-	30%	-	Constant
Students' distribution across specialties:				
Structural	24%	26%	28%	Normal
Geotechnical	17%	19%	21%	Normal
Water	17%	19%	21%	Normal
Environmental	17%	19%	21%	Normal
Construction	8%	10%	12%	Normal
Transportation	5%	7%	9%	Normal

In Figure 1, the process is illustrated by the two boxes A and B, which depict the sequence of inputs that need to be forecasted or extracted from historical databases to run the model. Refer to Figure 2 for a visualization of two examples of a student progressing through the civil engineering curriculum. All the inputs presented in this paper are aligned with the ongoing restructuring of the undergraduate curriculum and course offerings. The inputs are shown in Table 1. The probability density functions for each input are selected based on the granularity of available data. The anticipated number of students' input required more flexibility in minimum and maximum extremities adjustment (possibility of asymmetry). GPA input was modeled as constant since it is a hard threshold required by the department. The PDF for students' distribution inputs (for each specialty) is selected as normal due to the absence of precise historical data. Experienced curriculum planners predict these inputs as "most likely plus-minus percentage" (symmetrical).

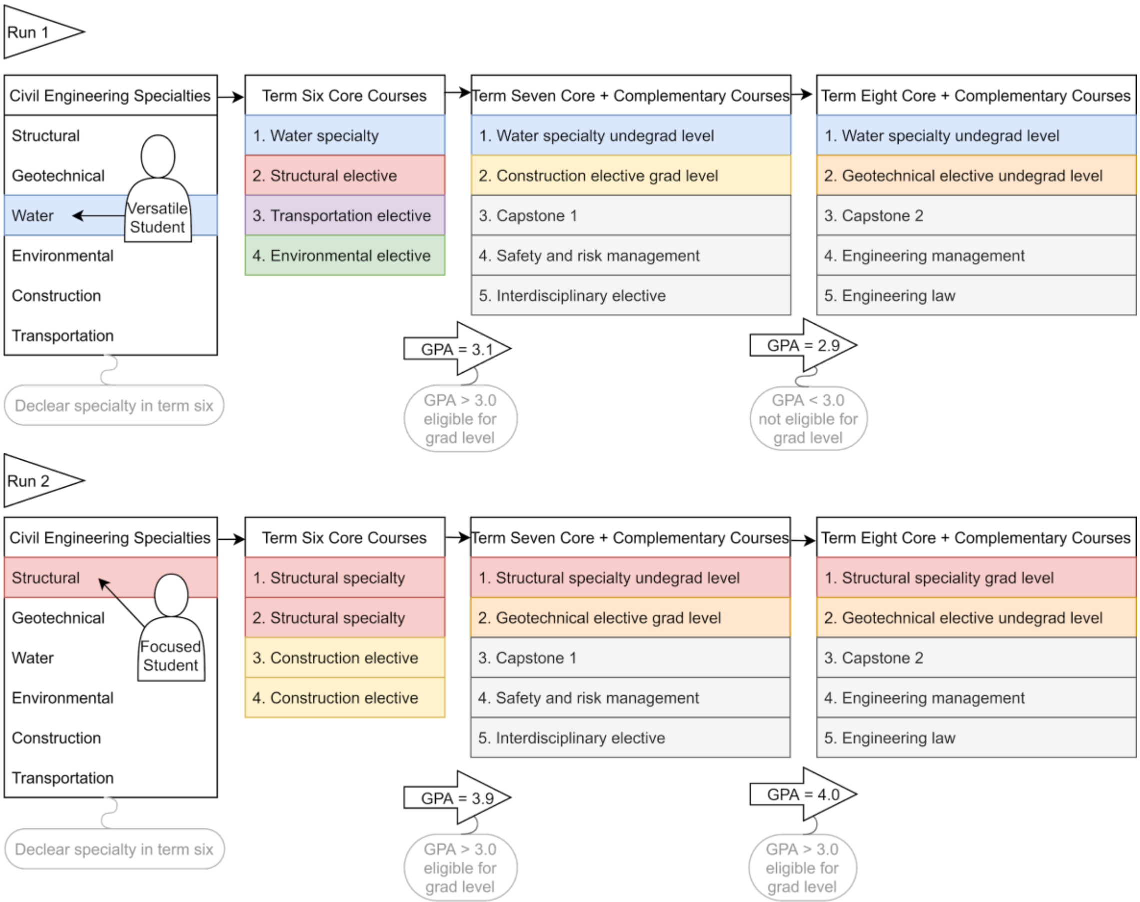

Figure 2: Example of students' flow through Monte Carlo simulation in two iterations

In Figure 2, we describe a flow of two hypothetical students through the simulated curriculum in two iterations (runs)—for example, student 34 in iteration one and student 151 in iteration two. Every student in the model undergoes a similar flow. As it can be observed, in the first run, a student chooses the "Water" specialty in term six and selects three more courses from structural, transportation, and environmental engineering specializations. After finishing term six, their GPA is generated as 3.1; hence they are eligible for graduate-level core courses (maximum of one graduate-level core course per semester). In term seven, the same student picks one specialty course from the undergraduate level and one elective graduate-level course from the construction specialization. The other three complementary courses (in grey) are the same for all the students in the civil engineering program. After finishing term seven, the student's GPA is generated as 2.9, which is lower than 3.0—a threshold for graduate-level courses. In this case, both their core courses must be undergraduate level in term eight. In the second run, we show another student whose flow through the curriculum is somewhat similar except for being less versatile in selecting courses from different specializations.

To demonstrate the capabilities of the Monte Carlo simulation model, we consider three different what-if scenarios. In the first scenario, the curriculum is simulated using the distributions shown in Table 1, with the output being the number of course seats needed for each program specialty. Further, we assume a seat cap for each specialty with the constraint of a maximum of 100 seats. The seat cap constraint of 100 seats is assumed based on the largest auditorium capacity and desirable student-teacher ratio. Lastly, we find several courses (or sections) needed for each specialty and a planned seat utilization ratio for the whole term. The simulation results constitute the 80th percentile of 1000 Monte Carlo simulation runs, which can be found in Table 2. The 80th percentile is chosen to accommodate most of the possible student choices.

In the second scenario, we assume, "what if the Environmental department is too busy and refuses to offer any courses for the civil engineering department?" In addition, we put a hard constraint on graduate course availability. In the second scenario, they are only offered in the winter (seventh) term.

In the third scenario, in addition to the constraints used in the two previous scenarios, we assume that the Transportation department decides to offer courses only in winter terms. Furthermore, the percentage of students eligible for graduate courses is increased to 40%. It is worth mentioning that graduate courses are out of the scope of this paper and are not showcased in Table 2. According to the newly developed curriculum, the students who qualify for the grad level are simply added to the existing graduate courses.

The three scenarios are chosen not hypothetically but as real-world circumstances of curriculum planning that took place during the Civil Engineering program reorganization at the University of Alberta.

In Table 2, "Seats" refers to the required number of course seats to accommodate all the student choices simulated by the model (model's output). "Cap" refers to the established course seat limit, which is set based on maximizing seat utilization ratio and the maximum seat limit of 100. "Ut. r." stands for utilization ratio and indicates the percentage of filled seats based on simulation results. "Courses" refers to the number of courses that each specialty must offer to accommodate all the student choices.

From observing the results in Table 2, we can see that in Scenario 1, the simulated number of seats is somewhat proportional to the initial student distribution in Table 1. This is the case due to students virtually having no restrictions on their choices. After introducing a what-if case and a hard constraint in Scenario 2, we observe that the seat allocation has considerably altered. Because graduate courses are not offered in term eight anymore, the seat requirement for undergraduate courses is increased. In addition, due to the absence of Environmental offerings, the number of seats for each specialty is also increased in each term. At last, in the third scenario, the seat requirements are further altered due to additional what-if cases and a modified GPA threshold.

Table 2: Simulated results (in bold), calculated number of courses, and seat utilization ratios for the three scenarios

Scenario 1: All specialties offer courses according to the distribution from Table 1									
	Term six (fall)			Term seven (winter)			Term eight (fall)		
	Seats	Cap	Courses	**Seats**	Cap	Courses	**Seats**	Cap	Courses
Structural	**147**	75	2	**76**	80	1	**76**	75	1
Geotechnical	**118**	60	2	**56**	60	1	**56**	60	1
Water	**118**	60	2	**55**	60	1	**56**	60	1
Environmental	**118**	60	2	**56**	60	1	**56**	60	1
Construction	**68**	70	1	**30**	35	1	**29**	30	1
Transportation	**49**	50	1	**21**	25	1	**21**	25	1
	Ut. r.	98%	Σ 10	Ut. r.	91%	Σ 6	Ut. r.	94%	Σ 6
Scenario 2: Scenario 1 + Environmental does not offer courses + Graduate courses are only offered in the winter term									
	Term six (fall)			Term seven (winter)			Term eight (fall)		
	Seats	Cap	Courses	**Seats**	Cap	Courses	**Seats**	Cap	Courses
Structural	**175**	90	2	**93**	100	1	**108**	60	2
Geotechnical	**146**	75	2	**68**	70	1	**80**	85	1
Water	**146**	75	2	**68**	70	1	**80**	85	1
Environmental	**-**	-	-	**-**	-	-	**-**	-	-
Construction	**87**	90	1	**36**	40	1	**43**	45	1
Transportation	**63**	65	1	**26**	30	1	**31**	35	1
	Ut. r.	97%	Σ 8	Ut. r.	93%	Σ 5	Ut. r.	92%	Σ 6
Scenario 3: Scenario 2 + Transportation offers courses only in winter terms as electives + Percentage of students with GPA above 3.0 increases to 40%									
	Term six (fall)			Term seven (winter)			Term eight (fall)		
	Seats	Cap	Courses	**Seats**	Cap	Courses	**Seats**	Cap	Courses
Structural	**191**	95	2	**92**	95	1	**118**	60	2
Geotechnical	**163**	85	2	**70**	75	1	**88**	95	1
Water	**163**	85	2	**68**	75	1	**88**	95	1
Environmental	**-**	-	-	**-**	-	-	**-**	-	-
Construction	**98**	100	1	**37**	40	1	**47**	50	1
Transportation	**-**	-	-	**13**	15	1	**-**	-	-
	Ut. r.	98%	Σ 7	Ut. r.	92%	Σ 5	Ut. r.	93%	Σ 5

The results described in this paper were presented to various stakeholders (i.e., those at the highest level of the faculty at the University of Alberta). The findings were highly appreciated, and a note was made that such simulations should be used across all engineering programs. The added value that our modeling approach brings to the table is to serve two customers, namely the curriculum planners and the students. The curriculum planner team emphasized that using this model will considerably reduce curriculum preparation time for future semesters and significantly improve the existing planning methodology. Moreover, students gain the freedom of choosing their specialty and elective courses with minimal limitations. Students are often promised by their departments a variety of course choices that quickly become invalid due to numerous course overlapping.

CONCLUSIONS

In this paper, we presented a Monte Carlo simulation model in an attempt to introduce Lean thinking to the higher educational institution. To our knowledge, there have not been any undertakings in merging the Monte Carlo simulation, curriculum planning, and Lean principles. We suppose that the current approach to the curriculum planning practices can be significantly improved using Lean philosophy by developing a tool to examine continuous improvement efforts in less time as well as incorporating the end users' (i.e., students) preferences into the planning process.

The authors want to emphasize that the main contribution to the body of Lean knowledge is not in the results of the model but in the approach to curriculum planning. The findings of this study suggest that a minimal amount of data or even knowledge of experienced curriculum planners in combination with the showcased Monte Carlo model can reduce the time in organizing course offerings and increase the quality and accuracy of a curriculum plan. The introduction of what-if scenarios further demonstrated the flexibility of the model and its capabilities to provide meaningful results outside of its original settings. Curriculum administration practitioners can use this modeling approach for a variety of department specializations.

From our perspective, educational institutions are yet at the entry point to Lean thinking and Lean practices. The current or similar Lean modeling approaches to curriculum planning can be used by any educational institution regardless of geographical location, department structure, or accreditation level.

It is important to note that while the Monte Carlo curriculum simulation model is very powerful, it may render itself useless without accurate inputs. In the current study, the authors used data created by experienced curriculum planners, and it is theoretical in nature. At this stage, the curriculum of the University of Alberta is being reorganized, and real-world data does not exist yet. In the future, more work is required to test real datasets and improve the model's assumptions, distributions, and constraints. For future work, the authors consider (1) adding Lean, collaborative courses with much smaller seat caps that will add another layer of complexity to the existing model; (2) limiting the number of project-intensive courses that prevent the curriculum from being lean by adding extra inter-course constraints.

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TAKT PLANNING EFFECTIVENESS INTO ONE BILLION DOLLARS PROJECTS

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ABSTRACT

Takt Planning (TP) is a prominent Lean tool that is gaining wide applicability on construction projects; it helps assess project progress status from the beginning of a project until the end. TP techniques pinpoint the weaknesses in a project's scope of work and assist in identifying appropriate ways to integrate resources into any given project. The approach has been thoroughly studied in building projects but not on infrastructure ones, and little empirical results have been reported. Hence, this paper presents results from a case study of applying TP in mega infrastructure projects in Qatar. The paper showcases issues faced by teams during the execution of work, their TP approach to remedy the situation, their approach for integrating TP into the existing system, and the corresponding outcomes. Results show that adoption of TP helped the construction team to properly control, organize, and place resources into projects to achieve desired goals. This study is an accurate example of how TP technique can resolve project problems and provide a clear 'X-ray' to scan large projects.

KEYWORDS

Takt Planning, Infrastructure Projects, Lean tools.

INTRODUCTION

TP aims at creating flow; flow is a basic Lean management principle that allows efficient execution of construction processes (Binninger et al., 2019). Takt is a German word that means beat; Takt time is the time unit required to produce a product in a way to match demand rate of the product (Frandson et al., 2014). The concept originated in Lean manufacturing to achieve the goal of meeting customer demand (Seppänen, 2013). Put simply, in construction Takt means creating a balance between work activities' rates to ensure they advance at similar beats around similar time units to prevent waste. Implementing TP into processes results in prevention of overproduction, reduction in lead times, stability of work processes, reduction in inventory and waiting times, continuity of flow, and increase in production capacity (Haghsheno et al., 2016). Consequently, Takt time planning offers the opportunity of exposing problems, helping thereby teams to

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identify breakdowns in other processes such as identifying and removing constraints (Linnik et al., 2013).

In theory, implementing TP steps sounds manageable, but the real challenge is how to apply them successfully to a specific project which has unique characteristics. It has been observed that previous TP studies focused on building projects, and empirical results of implementing TP have been little reported (Heinonen & Seppänen, 2016). However, applying TP to infrastructure projects is more challenging because such projects are different in terms of risk and crew distribution. Unlike building projects that have mainly static work locations, infrastructure projects' work locations are dynamic, and these projects face continuous and unforeseen risks. Implementing TP into these projects requires a smooth approach to avoid disrupting the existing system. Therefore, this study presents empirical results from case studies of implementing TP in infrastructure projects. It also presents a systematic approach to integrate TP into a company's system in a way to create a harmonized holistic system of different Lean tools. The novel contribution of this study lies in applying TP to infrastructure projects, considering TP as a problem-solving tool, and presenting an approach for integrating TP with other Lean tools such as the Last Planner System (LPS). The case studies illustrate the problems faced by teams on infrastructure projects, their TP approach to remedy the situation, their approach to integrate TP into the existing company system, and corresponding results. The next sections describe previous state-of-art, present the case studies, carry on discussion, and present conclusions and future recommendations.

LITERATURE REVIEW

TP gained wide applicability in construction over the past years. For instance, Yassine et al. (2014) presented a method to align production rates and accordingly calculate Takt time. Their results proved that Takt time enhances construction workflow. Heinonen and Seppänen (2016) presented empirical results from applying TP on a cruise ship cabin refurbishment case study. A 380% increase in productivity, 99% decrease in Work In Progress (WIP), 99% decrease in quality defect, and 73% decrease in project lead time were reported as a result of implementing Takt time method. Binninger et al. (2017) described the development of a simulation game to support teaching participants about abstract Lean concepts and TP. The game proved efficiency when teaching employees in companies about Takt. Another study is the one done by Lehtovaara et al. (2019) who conducted 14 interviews and collected site data in order to assess suitability of applying TP for residential projects. Their results revealed that TP indeed shortened project duration however they listed some barriers and enablers in planning and control phases that might be embraced as basis for continuous improvement. Haugen et al. (2020) contributed to identifying general challenges anticipated during execution of TP, and highlighting Takt performance indicators which expose these challenges. Results from a preliminary study conducted showed that 16 general challenges for execution stages were linked to 4 Takt components and 5 adjustment mechanisms. The performance indicators that were used are manhours and staffing, overtime, additional choices, returns, perfect handovers, and PPC. Singh et al. (2020) developed an interactive tool for visual management that is based on work density to support TP. The tool showcases potential value of having readily available work density data to support what-if type of analysis in assessing if desired Takt time can be met given certain production rates, zoning, and other considerations. Another study done by Slosharek et al. (2021) went further into integrating TP with sustainability of construction processes. They established a conceptual framework that helps assessing the environmental aspect of construction processes through an interdisciplinary approach using Life Cycle Assessment (LCA) and TP. It is stated that this method forms a starting point into a holistic approach for assessing sustainability of construction processes.

RESEARCH METHOD

Dlouhy et al. (2018) described construction work content through distinguishing three detail levels namely macro, norm, and micro-level. As the name signifies, macro-level entails minimized detail depth, and it is used for decision and communication basis. The norm-level entails coordinating construction processes with an average detail degree. As for micro-level, it is the lowest, most detailed level that represents actual progress of construction processes, and where work packages are itemized (Dlouhy et al., 2018). Since the knowledge acquired at micro-level transfers automatically to norm-level, impacting future planning, and norm-level responds to findings at micro-level through harmonizing workloads (Dlouhy et al., 2018), this paper poses the question of whether TP should be implemented simultaneously on both micro and macro-levels. And if so, what would be the correct steps for proper TP implementation and integration with existing systems. The study adopts a case study research method that is analogues to the one by Hartmann et al. (2008) to aggregate results from a case study in answering the posed question. The unit of analysis is the detail level of construction work content. The adopted method differs from traditional multiple case design method proposed by Yin (2003) in that it advocates summarizing findings from different cases, offering a broad overview of actual state of TP implementation, instead of replicating multiple cases' findings. A TP approach that is based on previous studies is amended and adopted throughout the study. Research is carried out with applying TP at micro-level (stage one), applying TP at macro-level (stage two), aggregating results, deducing conclusions, and presenting a proper way of integrating TP with existing systems.

CASE STUDY

BACKGROUND

This study intends to show how TP method is tested by application, and its positive impact on the delivery of multiple large-scale infrastructure projects. The company handles multiple large infrastructure projects simultaneously. Generally, when work commences on multiple projects, the project team only applies common Lean tools and concepts such as LPS system, four weeks look ahead, and PPC. However, couple of months into execution, some projects faced a slow flow of activities, and the construction teams couldn't successfully implement appropriate rhythms for major project activities. The teams found that some activities were absorbing their full efforts and substantial project resources, constituting a noticeable bottleneck.

In the projects undertaken to test this study's hypotheses, the team started executing infrastructure projects by applying traditional planning tools such as master scheduling, then adding Lean tools and technique like LPS, collaborative meetings, 5S techniques, and measuring PPC. The results were not satisfactory, and the Lean team, as well as the construction team, found that a significant part of the process was missing because they didn't get the desired flow of activities. Moreover, LPS couldn't help to control and accomplish contractor's and consultant's goals because after applying the above techniques for months, many problems surfaced such as absence of resources, and inability of teams to meet their goals. Applying Lean tools to the project was perceived as more of an information-gathering exercise than a contributing factor to the project outcome.

Addressing the situation required a solution from Lean perspective, that would align the activities' rhythm or 'beat' by implementing TP time and techniques. At that time, the project team was looking for a serious solution or additional tools to help in finding a proper solution. Project team could not simply eliminate Master Planning, LPS, and PPC and just implement TP as an absolute solution in order to resolve the problems due to many contractual factors.

TP APPROACH

The TP method employed in this study is based on the one by Frandson et al. (2013). The method consists of five applicable phases or steps for TP, whose implementation on a project requires iteration. The steps are 1) collecting information, 2) defining work zones/areas and time requirements, 3) identifying and understanding trade sequence and trade durations, 4) balancing plan and workflow, and 5) establishing and finalizing the production plan and schedule. On the other hand, later studies by Dlouhy et al. (2018) considered TP a separate entity and tool that is applicable to projects. They adopted a three-level tiered flexible system and noted that the knowledge gained at the micro-level will automatically transfer to the norm-level and will influence planning in the future.

To expand this research and knowledge, it is argued that TP must be considered and applied as part of the whole system, from the beginning of projects and maintained until completion. Having mentioned in the previous sub-section all such issues facing the projects, and failure of segregated techniques, the best solution for the company was to integrate TP as an advanced technique into the current planning systems and control process, instead of dealing with it as a separate entity. This was done in two stages, leading to progressive resolution of all major problems. Many issues were captured at stage one which required the team to mobilize resources and adopt techniques in order to prevent the rock encountered from affecting the flow. To do so, a continuous flow was sought, allowing further issues to be captured and resolved in advance. Practically, prior to starting implementation of TP properly, the project team has to fully understand the specific nature of the project, including all major project activities. The second step in the process focuses on creating an appropriate and measurable rhythm for activities, through identifying Takt time. TP was integrated into the system in two stages. Table 1 presents sequential steps which the teams took in order to implement and integrate TP into the existing process.

Table 1: Sequence of Steps to implement TP

Step	Phase	Stage
1	Master Plan	Case Study for Stage One
2	LPS System for a three months period	
3	TP analysis for activities (defining wagon)	
4	PPC	
5	TP for entire project	Case Study for Stage Two
6	Update LPS System for the three months period	
7	Update TP for entire project	

Implementing the above method requires that TP including LPS, must be implemented in a continuous cycle as depicted in Figure 1 in order to ensure smooth flow and sequencing of activities, proper rhythm, and proper project control. TP appears to be a systemic set of steps in theory; however, during implementation, teams find that continuous TP needs to be maintained for success, which is not always an easy task. The use of TP is like getting an X-ray of the project's entire zones; it identifies the problems on the whole project. Therefore, it must be applied continuously to prevent errors during project execution. The following sub-sections detail stage one case study followed by stage two case study.

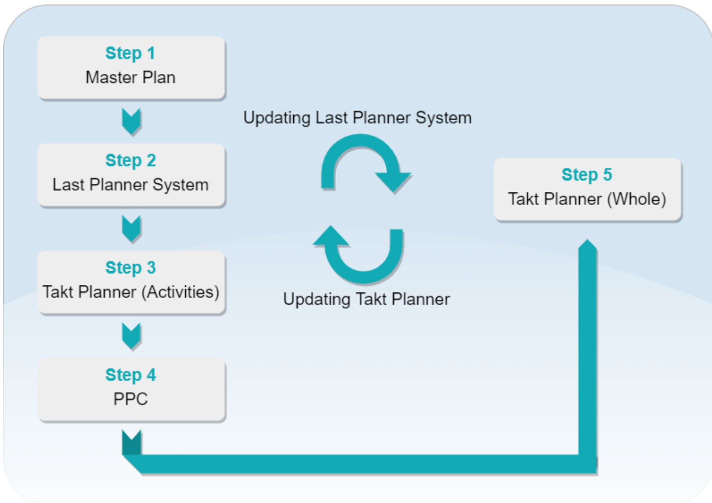


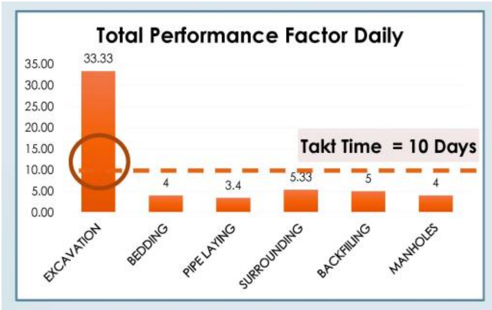
Figure 1: Integration of TP into the Existing Process

CASE STUDY RESULTS

STAGE ONE - APPLYING TP AT MICRO-LEVEL

Stage one was undertaken as a pilot project to investigate possible efficiency gains at the micro-level, from site excavation works. This micro assessment was undertaken to ensure efficiency improvements were possible and then obtain buy-in to implement TP project-wide, on a macro-scale. According to Binninger et al. (2016), levelling of activities in construction processes is done by defining Takt units and then matching the required workload to the available workforce. If some activities take longer than others, their durations can be optimized according to the selected Takt time. The Lean team started applying this method to a local road project in Qatar with a total cost of 800 million dollar. Figures 2(a) and 2(b) show that there is a bottleneck and unbalance in activities' rates.

The first step carried out by the Lean team includes analysing and balancing activities; by doing so, they were able to determine takt time, identify bottlenecks that occurred within the existing process, and then resolve them. Takt rhythm includes deployment of resources in a proper way to avoid waiting and to eliminate waste. As Figure 3 shows, excavation activity length now matches takt time. The activity time has been manipulated, so the work performed aligns with the work gang size.



(a)

Trade Sequence	Total Performance Factor Daily	Gang
EXCAVATION	10.00	10
BEDDING	4	4
PIPE LAYING	3.4	5
SURROUNDING	2.67	6
Backfilling	5	5
MANHOLES	4	4

(b)

Figure 2: Current Project Status (a) Total Performance Factor Chart, (b) Trade Sequence

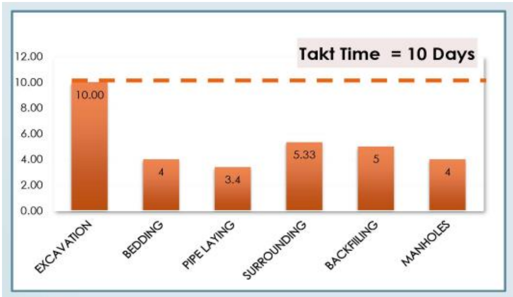
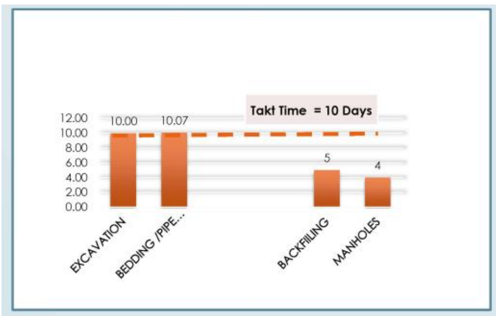


Figure 3: Harmonizing the Work - Improving

Moreover, activities are merged and optimized as shown in Figure 4(a). Levelling is performed where activities durations are optimized as work gangs are deployed to a resource plan aligned with the activity’s Takt time as displayed in Figure 4(b). Also, different work packages were combined to create efficiencies as to how time was allocated to work gangs. Planning Results were adopted and implemented gradually; the construction team started rectifying their way of managing the project, considering fast activities.

Hence, it is shown that applying TP techniques helped to improve outputs, create harmony between activities, and balance them together. Table 2 summarizes the three different states of the project.



(a)

Trade Sequance	Total Performance Factor Daily
EXCAVATION	10.00
BEDDING /PIPE laying / SOUROUNDING	10.07
BACKFIILING	5
MANHOLES	4

(b)

Figure 4: Harmonizing the work (a) Combining Activities, (b) Levelling Activities

Table 2: Summary Comparison of Different Project States

Current Status	Improving Status	Combining and Leveling Status
Unbalanced activities No proper sequence of activities No proper deployment of resources	Matching excavation activity length to Takt time Altering working group sizes to match Takt time	Merging activities Combining different work packages to make up a single time slot, such as the surrounding gang

As can be seen from the site pictures in Figure 5, the construction team used TP to resolve bottleneck issues, as well as to balance overall activities in a different way.

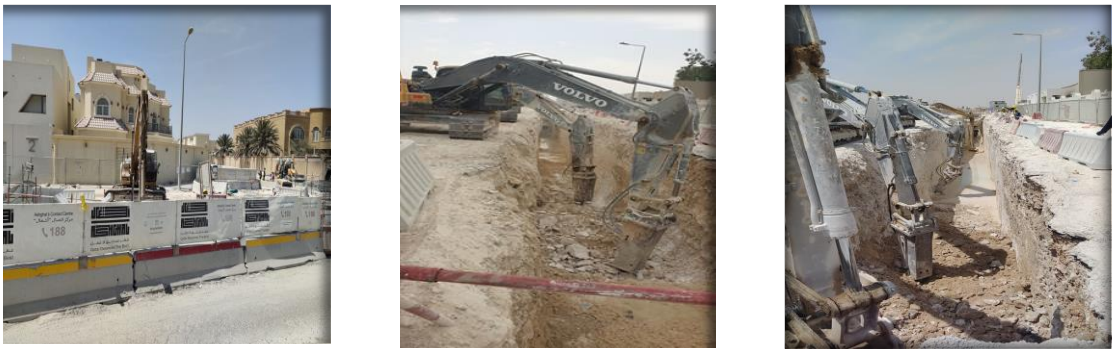


Figure 5: Case Study Stage One Site Impact

STAGE TWO - APPLYING TP AT MACRO-LEVEL

After successfully implementing the first stage analysis in the project, the Lean team wanted to utilize the preliminary TP results from case study stage one to the next level and apply them to the whole project's zones in a more accurate and practical manner. The Lean Team began by analysing the project status, identifying the bottlenecks and major challenges to progressing the works expeditiously and in a consistent manner. Five major challenges were identified and resolved as part of this stage. Figure 6 depicts how TP was applied fully in the entire project’s zones. This provided an X-ray view of the project which enabled the analysis of the project status, at the resource level, providing information relating to timing, activities gaps, and waste. Five major bottlenecks were identified as a result of applying stage two analysis. These are 1) gaps between activities, 2) critical activities to be considered for further analysis, 3) congestion of the schedule, 4) resources distribution, and 5) milestone alert. After running TP stage two for a couple of months, we observed that smoothness of activities appears visually in the plan and better resources deployment which became visually apparent in the plan at the macro-level as shown in Figures 7(a) and 7(b).

DISCUSSION

This study showcases how TP was implemented in two stages at two different levels. Stage one began with a method for calculating Takt time, which led to a preliminary theoretical Takt Plan depicted in Figure 8. By utilizing this method, the team avoided delays and mitigated project risks, leading to more accurate work execution, and avoiding delays. Additionally, it helped the project team understand the nature of the project and deploy appropriate resources. Generally, TP is seen in many projects as a complex and very rigid process where trades are optimized individually (Dlouhy et al., 2018). However, proper, and gradual TP implementation can be less rigid, and this is reflected in the study' results such as achieving milestones more smoothly, having more accurate deliverables, and attaining easier project control. Moreover, applying Takt Planning to mega infrastructure works at a macro-level is risky, yet necessary to improve the efficiency rate of the project delivery (Binninger et al., 2016). Nonetheless, this case study demonstrates that TP helped teams to pinpoint micro-level issues that delayed an infrastructure project, and it explains how random distribution of resources led to an unsound investment for the company owner, as well as shortages of material and other resources. After analysing TP, managers understood exactly the problem and took appropriate steps to implement a proper solution; case study number one analysis was applicable at the micro-level.

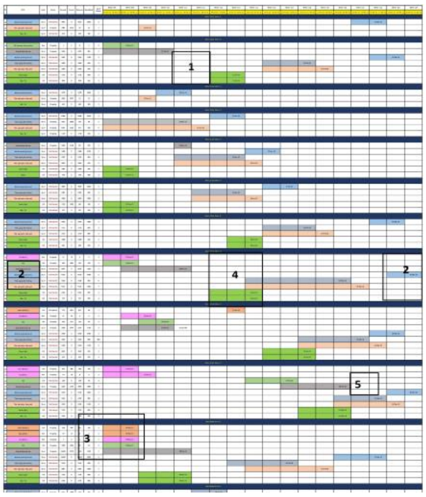
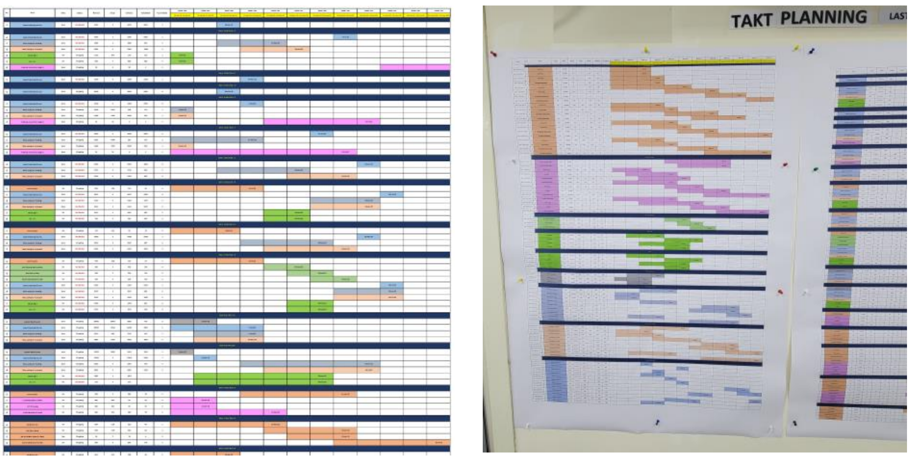


Figure 6: Stage Two TP for Full Zones

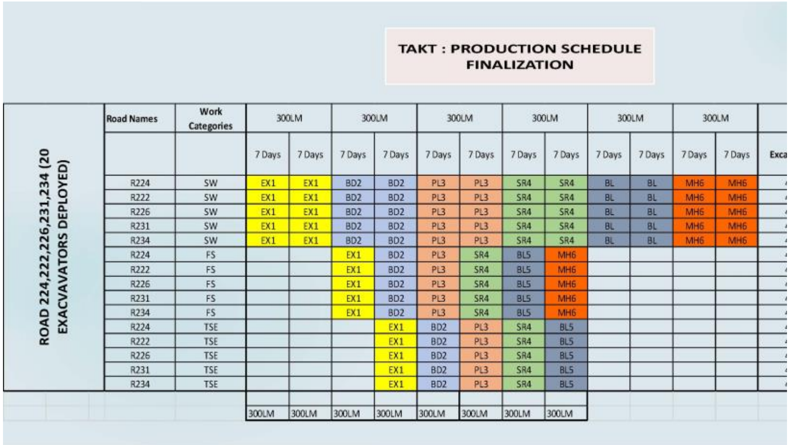


(a) (b)

Figure 7: TP Positive Impact at Macro-level

As a technique, TP analysis in stage one helped stakeholders capture major activities' bottlenecks. During the process, the size of main activities and the boundaries of Takt time wagons were measured. The outputs from TP's first step analysis led the construction team to change the project execution plan, following a TP rhythm; it was an important shift in the construction team's thinking. It also had a direct positive impact on project site activities. Lehtovaara et al. (2019) stated that planning TP wagons in more detail is regarded as an enabler for continuous improvement, along with a narrower collaboration among project participants. This confirms that micro-level TP implementation is essential for greater gains.

Upon receiving results of stage one study, the Lean team realized they needed to do more at a macro-level to control the entire project; consequently, they proceeded to put the outcome of stage one study into practice on a greater scale for the entire project to



TAKT : PRODUCTION SCHEDULE FINALIZATION

	Road Names	Work Categories	300LM		300LM		300LM		300LM		300LM		300LM		
			7 Days	7 Days	7 Days	7 Days	7 Days	7 Days	7 Days	7 Days	7 Days	7 Days	7 Days	7 Days	Exca
ROAD 224,222,226,231,234 (20 EXACVAVATORS DEPLOYED)	R224	SW	EX1	EX1	BD2	BD2	PL3	PL3	SR4	SR4	BL	BL	MH6	MH6	
	R222	SW	EX1	EX1	BD2	BD2	PL3	PL3	SR4	SR4	BL	BL	MH6	MH6	
	R226	SW	EX1	EX1	BD2	BD2	PL3	PL3	SR4	SR4	BL	BL	MH6	MH6	
	R231	SW	EX1	EX1	BD2	BD2	PL3	PL3	SR4	SR4	BL	BL	MH6	MH6	
	R234	SW	EX1	EX1	BD2	BD2	PL3	PL3	SR4	SR4	BL	BL	MH6	MH6	
	R224	FS			EX1	BD2	PL3	SR4	BL5	MH6					
	R222	FS			EX1	BD2	PL3	SR4	BL5	MH6					
	R226	FS			EX1	BD2	PL3	SR4	BL5	MH6					
	R231	FS			EX1	BD2	PL3	SR4	BL5	MH6					
	R234	FS			EX1	BD2	PL3	SR4	BL5	MH6					
	R224	TSE				EX1	BD2	PL3	SR4	BL5					
	R222	TSE				EX1	BD2	PL3	SR4	BL5					
	R226	TSE				EX1	BD2	PL3	SR4	BL5					
	R231	TSE				EX1	BD2	PL3	SR4	BL5					
	R234	TSE				EX1	BD2	PL3	SR4	BL5					
			300LM	300LM	300LM	300LM	300LM	300LM	300LM	300LM					

Figure 8: Preliminary Theoretical TP

make sure all zones are controlled effectively. Stage two required the project team to dwell deep into the project detail at the macro-level. All project zones had to be considered and re-planned. The outcome of stage two helped to identify the location of key problems, as well as provide a visual X-ray of the project. This process helped the team to improve the plan for the whole project in a reliable way, smoothing activities, and solving critical activities and problem areas. The X-ray visual aid enabled the team to plan and then deploy resources in an effective and economical way that reduced waste.

The outcome of stage two case study was considered an extension of stage one. Both had improved the focus of the project team, enabling problems to be identified, allocated, and treated, which then improved the project throughout and output by avoiding disruption to work processes at the macro-level. TP makes it easier to detect errors and steer continuous production proactively. Although spotting and correcting daily errors is stressful, it prevents cascading delays which improves overall flow (Vatne & Drevland, 2016). Thus, gradual implementation of TP from micro to macro levels can improve overall flow. The pictures depicted in Figures 9(a) through 9(c) display teams applying TP on three different infrastructure projects; whose total cost was more than one billion dollars. The collected feedback from the team was that TP techniques added edges to them and helped them to accomplish and to plan future activities collaboratively and adequately. After applying TP and testing its capability, the teams agreed that is beneficial if it is integrated as part of the full project management and control process, and not as a separate entity. Also, it was shown that TP can be used successfully as a problem-solving tool on micro and macro-levels during project implementation. Although the production flow measurement technique from LPS method seems to be the most favourable for TP projects (Haugen et al., 2020), Lean tools including LPS couldn't deliver a full solution for the team and the project; adding TP helped noticeably in resolving many problems. Thus, integrating TP with other Lean tools is a must for successful realization of projects. Although TP was used in projects as a result of an emergency need, without knowing what the outcome would be and after tracking the results for a couple of months, it was revealed that TP helped to understand project critical issues in a better way. The team applied TP taking into consideration all stakeholder values and needs.

(a) Project 1 (b) Project 2 (c) Project 3

Figure 9 Deploying TP (a) Project 1, (b) Project 2, Project (3)

CONCLUSIONS

This study has outlined how TP has been applied to improve project tempo, setting the rhythm for major activities, both at micro and macro-levels. It has also highlighted the importance of adopting TP as an essential Lean tool that can be used to regain control of projects in crisis, where work waits on workers, workers are forced to wait on work, and waste impedes progress. TP was implemented in two stages, first at the micro-level and then at the macro-level. Stage one work balanced the outflow, work-worker allocation and distribution, and harmonized the pace of work. At stage two, TP was applied at the macro-level, streamlining the project delivery process. Implementing TP delivered an important missing part of the process, by identifying problems at both micro and macro-levels; it also helped project team to zoom into activities by creating a smooth flow of activities from beginning until completion; making it a tool that ensures project success.

The study shows that integrating TP into projects helps to identify the appropriate Lean plan for new and ongoing projects; the team called it an X-ray of the entire project. Applying TP clarifies the project scope of work in a precise way. The study considered that adoption of TP in addition to existing Lean tools such as LPS is essential, which differs from other studies that consider TP as a separate entity. Therefore, TP must be flexible, and a proper relationship between LPS and TP must exist and be adequately maintained to ensure effectiveness and smooth project control. The study shows in practical examples how TP can be selected as an essential tool in analysing project difficulties, such as gaps between activities, critical scope of work, milestones, deployment of resources, and time management at both micro and macro-level.

The article shows that TP is an essential addition to the existing process and can’t be considered a sole solution. Applying TP helps teams to clearly identify difference between the outputs they get from Master Planning, LPS, and TP. Master Planning gives a broad picture of project, whereas LPS scales that image in more specific details, and TP proves its success in accomplishing both benefits in more detail. Future studies should address digitizing TP, making it more reliable and user-friendly. Also, future research can tackle Takt production’s long-term effects over several projects, in addition to a more detailed comparison of various methods and implementations of Takt.

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NINE INNOVATION BARRIERS IN AUSTRALIAN CONSTRUCTION CONTRACTING

Matt Stevens[1]

ABSTRACT

The Australian construction industry ranks below average in intellectual property and software creation value compared to other sectors. The innovation performance of the built environment contractors is well chronicled. Importantly, these organisations have the most time and cost risk of all stakeholders. Therefore, improvements should have significant benefits to them and their customers. However, their innovation efforts face significant economic, regulatory and market barriers that are stubborn. This paper asserts that these sector characteristics slow the creation of novel products, services, and information technology more than most major industries. Overcoming these invention barriers should enable faster innovation and more significant improvement.

This paper outlines the nine most significant innovation barriers researched by the author in Australian construction contracting and suggests potential solutions. Addressing the seminal reasons for the lack of invention should decrease the impact of these obstacles leading to a better system and culture of innovation, thereby producing better industry performance. The relationship between construction organisation characteristics and industry innovation is relatively unexplored.

KEYWORDS

Construction invention, constructor innovation, breakthroughs, system barriers, novel products

INTRODUCTION.

Construction contracting businesses deliver most of the value while accepting risks such as cost, schedule and safety responsibility for their projects. However, mitigating this with innovation is difficult since the industry suffers from significant underlying economic, regulatory and market barriers. One indication of construction's anaemic invention activity is the value of intellectual property products, including software. In 2020, it was assessed at AUD 1,028,000,000, which was ¼ of manufacturing's output and ranked 13th out of 18 major market sectors (ABS 2021). Although, invention adoption provides better value for money for improved services or products and can help construction firms gain a competitive advantage (Kamal et al. 2016). This paper suggests that these sector

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characteristics seem to slow the creation of new products, services, and technology more than many industries.

We theorise that the unique combination of factors present in the construction industry is a significant barrier to improving safety, quality, cost and schedule. Innovation can improve these four outcomes, creating a sustainable and resilient built environment for businesses. Kamal et al. (2016) found no evidence of more innovation in larger firms. The largest companies have the most resources and incentives to develop breakthroughs but have been unable to in the modern era. Due to these observations, significant and stubborn reasons seem to exist; the researcher searched for them from experience in the literature review. This research outlines the nine substantial barriers in the researcher's experience and asserts potential solutions to overcome them. Querying SCOPUS, the Australian Bureau of Statistics, and other databases with key search words reflecting the nine factors yielded research findings.

LITERATURE REVIEW

According to Lim et al. (2010), innovation assists construction firms in lowering their costs, meeting deadlines and deepening their positive brand. Hillebrandt (1984) noted that many individual factors present in construction are not unique; however, the combination of factors is not found in other sectors. Critically, the relationship between industry characteristics and company innovation orientation is relatively unexplored. (Kamal et al. 2016)

The Built Environment is a crucial component to improving the quality of life (QOL) (Gregory 2009). With improved QOL comes higher levels of prosperity and increased chances of sustainability adoption (UN Habitat 2012). Innovating more of the material, processes and equipment used in construction will improve outcomes

Pheng and Teo (2004) observed resistance to change by construction organisations. They cite three factors: 1) organisational instability, 2) product diversity, and 3) misperceptions about the cost. First, predictability of construction company revenue is difficult due to the industries' highly competitive nature and sensitivity to the Australian economy. Additionally, the range of projects that a firm may pursue and build is unpredictable and determined by invidual customer procurement processes.

Research literature supports the assertion that there are multiple barriers to innovation in the Australian construction industry. Contractors in the Australia Pacific region were surveyed in 2022, cited "cost, effort and changes needed" 51% and "no clear demand from clients of stakeholders" 43% (RICS) As a result of these perceptions and impediments, this sector ranks below many others in intellectual property and software creation. Recent research by Leviakangas et al. (2017) shows that the Australian Construction Industry's investment in ICT is the bottom third of the nine major industries studied but is ranked third in multifactor productivity.

This literature review attempts to specify nine substantial barriers.

AUSTRALIAN CONSTRUCTION INNOVATION BARRIERS

1. Low percentage of net profit before tax

The construction industry invests in research and development much less than other parts of the economy. This sector invests less than 0.5% of sales in research and development (R&D), while the Australian national average is approximately 4% (Hassell et al., 2009). Large construction firms' net profit before tax is less than 10%, , e.g. Simonds, Lendlease, and Global Construction, whereas technology companies range between 20-30%. Refer to Table 1.

Table 1. Australian Publicly Held Firms by Selected Industry & Net Profit Before Tax Percentage
Source: Australian Stock Exchange–2021

Construction	Technology	Medical
Global Construction 8.1%	OFX 21.0%	Ansell 35.1%
Lendlease 6.4%	Technology One 21.2%	Sonic Healthcare 11.2%
Simonds Group 0.5%	Telstra 13.7%	Zenitas 13.6%

However, our industry's financial ability to invest in R&D can be viewed in other ways. If turnover is analysed per employee basis, construction's ratio is less than manufacturing: AUD 190,814 versus 487,000. On a per firm view, AUD 533,008 as compared to 4,698,014 (ABS 2021)

2. Lumpy asset problem

The investment needed to enable research and development of a product or service is a "lumpy asset". This is a financial term defining a type of investment expenditure that must be paid with a liquid asset. A firm cannot lease or pay for using a lumpy asset incrementally (Alvarez & Lippi 2013). Therefore, an innovation's value or utility cannot be realised unless purchased entirely in application. A recent study indicated that a significant investment in time and resources was required to introduce innovative systems and products (London and Pablo 2017).

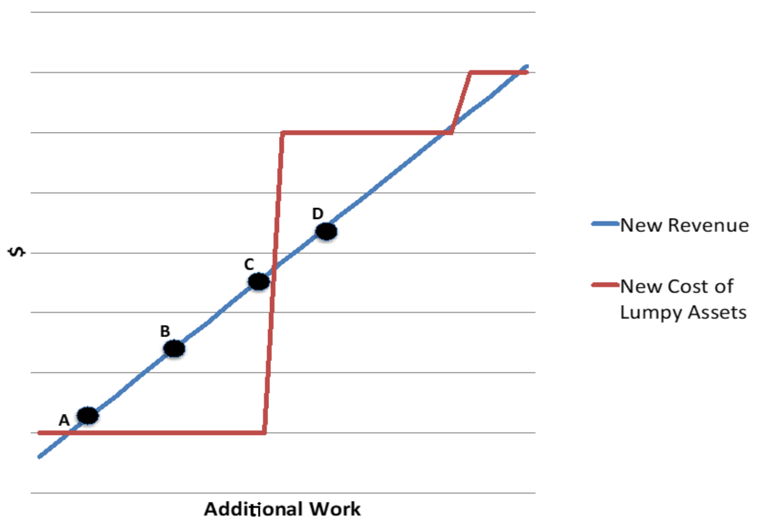

Figure 1. The stepped nature or "lumpy asset" dynamic of innovation

From Table 1, it is assumed that the net profit before tax is approximately 4%. This means that 25 times the cost in revenue recoups the additional expense of innovation. Therefore, as shown in Figure 1, an AUD 100,000 investment must be recouped by AUD in 2,500,000 turnover.

3. Low market share for industry leaders

The largest construction companies in Australia do not dominate the market. For example, CIMIC's market share of 2.0%, whereas BBPHA 1 Pty Ltd has approximately 1.0%, and Lendlease is less than 1.0% (IBISWorld 2022). Furthermore, market dominance has never occurred for any one firm. However, in other industries, for example, Google controls a majority of internet search activity, and Telstra has earned a plurality market share of cell phone services in Australia.

4. Extreme and nimble competition

Construction continues to be the industry with the largest number of businesses in Australia in FYE 2021 and accounts for approximately 16% or 410,839 of all businesses. Additionally, new entrants, which appear to be more aggressive in pricing and promises to customers, numbered most (6.1%) of the nine major industries (ABS 2021).

Construction is sometimes referred to as a "cottage" industry; 98.5% of construction firms employ less than 20 people, and only 0.1% of firms have workforces of 200 or more (ABS 2022). These small competitors are far more flexible in meeting customer needs and addressing their wants.

5. The "intersectionality" problem of construction

Classifying construction businesses as homogenous is problematic. Each business' operation is significantly affected by its characteristics. A simple categorising may include: a) trade focus, b) project type, c) region(s) operating in, d) client types, e) contract type(s) working under, f) publicly or privately owned, g) amount and type of technology used, h) number of employees, i) accounting basis and j) management culture. Since there are multiple choices for each of these nine areas, it is clear that over 3.6 million (10 factorial) combinations are possible. However, there are 410,839 built environment firms in Australia (ABS 2021); therefore, few organisations are similar (see Table 2).

Table 2. Sample differences of construction firms

Characteristic	Number	Factor
Trade	10	General, Civil, Marine, Façade, Electrical, Plumbing HVAC, Structural, Roofing, Flooring
Home Office Location	6	NSW, QLD, VIC, NT, WA, SA
Market Location Focus	3	Rural, Urban or Suburban
Client Types	3	International, National or Local
Contract Types	6	Lump-Sum, Alliance, PPP, D-C, Time & Materials or Cost Plus
Company Ownership	2	Private or Public

Technology Adoption	3	Robust, Average or Weak Adoption
Employee Number	3	Small (1-19), Medium (20-100) or large (100+)
Accounting Basis	2	Accrual or Cash
Management Culture	4	Owner-Operator, Family, Team, or Bureaucratic

Most innovations cannot be economically feasible for the inventor if they appeal to only a few customers i.e. if there are few buyers of a construction-specific innovation-its high cost and time investment cannot be formally justified. Projects are also dissimilar, making possible targets less in number (see Table 3)

Table 3. Sample differences in construction projects

Characteristic	Number	Number and Type General Factors
Use Type	7	Residential. Commercial, Industrial, Institutional, Civil, Marine, and Infrastructure.
Location	3	Urban, Suburban, and Rural
Funding	3	Public, Public or PPP
Client Type	3	Government (Federal, State. And Local), Corporate (Local or International), or Individual.
Construction Process	4	New Construction, Remodeling, Rehabilitation, or Replacement

6. The industry is precarious

The construction industry has a high failure rate when compared to other sectors. Recent data from the ABS (2021) reported 14.0% of the companies that started 2021 exited by the end of the year. The Australian Tax Office (ATO) latest filings report that 78% of Business Owning Households hold some form of debt. Additionally, 54% of Australian companies declared a loss and thus paid no taxes. This appears to point to a financially meagre environment with little means to pay for innovation. It seems to justify an aversion to speculative investment, which characterises research and development. Further demonstrating risk, a bankruptcy study sponsored by Australia's Construction Forestry Maritime Mining Energy Union (CFMEU 2014) concluded that the construction industry outscored all other industries for each deficiency category above $500,000.

IBISWorld (2022) identified Key Success Factors (KSF) for a construction business that indicates nimbleness is critical. The top 3 most significant include 1. Ability to expand and curtail operations rapidly in line with market demand. 2. Operators must be able to quickly alter labour force numbers to match short-term cycles in market demand. 3. The ability to hire experienced, productive workers, especially during periods of low labour availability, is crucial to success.

7. The construction industry has problematic employment dynamics

The Australian Bureau of Statistics (ABS 2021) documents that 37% of worker services are secured by contract, whereas the next highest – administrative and support services - is slightly over 20%. This seems to indicate that there is little incentive to make employees more productive since they are on contract for a fixed hourly rate, lumpsum outcome or a fee per piece, and thus, there is less need to create or adopt innovation to make them more productive. Similarly, independent contractors have little incentive to invest in large-scale and risky innovation since these arrangements represent employment, not a business opportunity.

The Australian government labour statistics show that between 1991 and 2019, involuntary employment separation (Lost Last Job) ranged from 76% to 274% of the total employment population (ABS 2022). This means that the knowledge of a specific innovation may travel with a departing employee, thus disincentivising the creation of a unique task methodology and training to facilitate mastery.

8. A service such as construction is difficult to patent

Nagy (2013) notes the difficulty of patenting services and protecting the inventor's intellectual property rights. It is partially due to its intangible nature. In Australia, patents are strong protection for unique tangible products for a legally prescribed 20-year period. However, this can be a protracted and challenging process that is a high risk to the creator of patents. Research by London and Siva (2013) indicates the challenges for those in the construction industry to create and protect their patents. The Australian system affords few rights to the creator of patents and little protection with the onus solely with the creator. Coupled with this, it is not easy to patent a process, construction or otherwise, and protect it from duplication by competitors. In preserving a method as intellectual property, it is difficult to prove where the employee's expertise and experience (current or former) stops and the organisational, institutional knowledge rights start.

9. The Government is not keeping pace nor encouraging construction innovation

Western nations have robust laws governing construction activity and limiting risk to the construction service buyer and end-user. This risk governance is core to the role of industry regulators and appears to lag the rapid pace of invention (Soeteman-Hernández et al. 2019). Few proactive processes conditionally approve early phase creation of innovative ideas or development. Rose and Manley (2014) noted that regulatory agencies in Australia lack clear procedures for assessing new products. Suprun and Stewart (2015) found repeated "Regulations, public policy, and supporting mechanisms" barriers in many countries.

DISCUSSION

Expecting organic innovation in the construction industry has been minimally effective over decades. The barriers listed appear to be too great for contractors to tackle alone. Eight of the nine barriers cited cannot be significantly changed. They are a product of the industry's dynamics. . However, government inspired innovation support can be grown. Seeking ways to overcome these barriers may include partnerships with universities, government, and associations, using activities such as hackathons and business incubators.

Longterm, creating an industry culture of innovation could be a strong leverage point for increasing value for all stakeholders. Isaacson (2014) suggests three main parties are crucial to involve: Peer Inventors, Market and Government. Unequal attention of one over the others is suboptimal. Critically, Australian Universities are an extension of the government and should be equally engaged as part of the solution.. In Australia, the government has created programs for businesses and inventors, regardless of industry, to assist in accelerating the development and market deal-making process. The construction sector has sponsored innovation incubators and hackathons

Generally speaking, there is a strong commonality between macro-level motives and benefits for industry and university actors (Ankrah 2013). Private companies appear to want to engage and collaborate with the best researchers (Abramo et al. 2009). Universities have created innovation hubs. These have grown the size of peer inventor groups. They should be included as part of a transformative plan. Suprun and Stewart (2015) found that most contract relationships between industry and universities were strong and enduring. Universities are well-positioned since they perform the "triangle of knowledge" for novel creation composed of research, education, and innovation (Abramo et al. 2009). Universities are performing these functions better than other stakeholders as a group.

Industries can benefit from partnering with allied ones. This is known as a sister industry strategy. Examples include motor vehicles, the petroleum industry, or computer software and hardware manufacturers. It should help the construction industry if it utilises the same approach. Manufacturing is a viable candidate due to modular construction and prefabrication's value. Construction's custom non-mass production nature could improve this partner sector's fortunes.

People innovate via multiple approaches such as "learning by doing". Charles and Ray Eames were furniture design legends in the 1940s that took the "learning-by-doing" mentality to new heights and mastered collaboration throughout their careers. Another approach is "combined thinking of the creative arts and hard sciences". George W. Carver at the turn of the 20th century balanced his interests and talents in science and art. Carver's observation, experimentation, replication, and communication skills enabled novel combinations resulting in his inventions.

Innovation is a team endeavour. The lone inventor who carries the product from idea to market has a poor probability of succeeding. Importantly, investors do not bet on this model. Instead, team members should have "learned on someone else's nickel". The raw graduate is worth more after they have industry experience, i.e., their idealism is tempered by failure and confidence boosted by success. They understand the complexities and uneven pace of the innovation cycle. Importantly, if the young inventor has learned the foundations first and then advanced their thinking, they can bring the transcendent ideas to the present, creating more value and thus quicker adoption by the market.

According to Isaacson (2014) Each inventor group should possess three skills to create their product or service vision and bring it to reality:

1) Excellent ideation energy
2) Robust product or service development skills
3) Strong business savvy, including deal-making

This list suggests that more than one person must be involved. Rare is the person who can master all three. Investors know that a product's chances of success are what they are wagering on and a team of people with profound skills in the needed areas improves probabilities. The quality of the team perfecting the invention helps determine the amount of funding and its disbursement schedule. Another investor decision-making criteria the innovation in fitting an uninhabited market. This means more value is perceived earlier in a product's lifecycle.

Some may assert that implementing information and communication technology (ICT) will significantly improve efficiency. However, recent research by Leviakangas et al. (2017) shows that the Australian Construction Industry's investment in ICT is in the bottom third of the nine major industries studied but is ranked third in value-added.

This inverse result of construction's significant value increase versus a low technology expense from a return on investment perspective seems to be supported by some of the other factors mentioned in this paper. Most construction contractors do not see evidence of a productivity increase from more ICT investment. So, productivity improvement seems to be a product of other focuses such as more intelligent project management, organisational leadership, process improvements and entrepreneurial thinking.

Contractors are not alone in investing modestly in ICT. The Toyota Production System's (TPS) thinking is the same. The company believes in purchasing, implementing and training proven software as stated in its principle 8, "Use only reliable, thoroughly tested technology that serves your people and processes". The reference to proven implies the previous version. They assert it is a hallmark of an efficient organisation. Lean does not teach leading-edge or next-generation software utilisation. Other experts, such as Collins and Hansen (2011), assert from their research that the highest performing publicly held corporations are careful about technology investment. They found that top-quartile firms in several industries utilise one or more software version(s) older than the current one. This appears to keep negative impacts manageable such as training expense, unknown software problems and small, unknowing user groups.

There are other disincentives for construction innovation. For the investor, the service nature and its openly viewable construction conditions challenge the protection of intellectual property. Contrastingly, manufacturers may close off factory sections for inspection or view. Additionally, today's innovation may be less valuable tomorrow. For instance, information technology has shown increasingly rapid change; Moore's law shows evidence of that. Therefore, another robust industry-centric software may be eclipsed quickly. These are not only applicable to programming but to the companies that create them. This is a risk. These organisations' status changes over time through decision-making, ownership transition or management succession. The construction organisation experiences a change in customer support, costs or software functionality which can ripple to projects and organisational performance.

Our observation is that construction companies seem to prefer late adoption for four reasons 1) employee mastery of software over time will improve its value, 2) it will become less expensive to purchase, and 3) a novel breakthrough may become available while the contractor is in the adoption or implementation stage. 4) Information technology company product or support negatively changes long-term. Contracts' conservative and risk-averse thinking may dictate that competitors accept the risk first, then suffer early adoption mistakes.

An industry-led research agenda should recognise and prioritise application over theoretical research. Given the limited amount of funds, prioritisation seems logical. This will produce more implementations of other industries' innovations. Companies in different sectors such as military, aerospace, computing, and engineering have budgets for robust and long-term R&D. Construction appears to benefit significantly from developing industry applications such as drones, information technology and materials. However, Leicht et al. (2014) analysed construction research activity as distinct from development and application activities. They found these latter expenses are three to four times the research expenses depending on the year measured.

RECOMMENDATIONS

Encourage more industry-led research partnerships

Due to low margins and high-risk factors, it must be realised that a more innovative environment needs to be created for construction to improve more quickly. This can start with formal partnerships between industry practitioners and university researchers. Public resources and industry knowledge should be synergised. As part of this, it is imperative to have contractor-directed research partially or fully funded by the industry. When categorised separately, funds for development are invested more than pure research in the AEC industry. Innovation centres can be a hub for spawning the practical from the theoretical.

As an example, some universities have actively developed funding for industry-directed research in Australia. Advisory Groups leading the sector should assist in govern the apportionment of expenditures toward relevant research. Construction Contractors should be able to focus their financial advancements on one of several research areas in this scheme. The atmosphere of construction invention should intensify.

Reform the patent process

Encouragement for the construction industry toward higher patent activity should be a priority for Australia. This increases the culture of innovation. Besides the obvious boost to safety, quality, and efficiency, patents can be an income stream for innovators and give the industry and its members incentive to improve rapidly. In addition, a patent's 20-year protection facilitates financial rewards for those who can create solutions to industry problems.

Additionally, the patent process is a healthy exercise in determining unique inventions. A patent is given only if the creation is a breakthrough or significantly improves an existing patent value. However, a patent focus might be criticised as selfish and potentially harmful to society. Some want to emphasise an open source focus on intellectual property. They see it as a better ethic. However, it will not incentivise the innovators to invest their time, energy and capital.

Construction's private and public leaders should focus more on innovation

All stakeholders appear to benefit from early review processes and monetary incentives for innovations. The role of government is critical. For example, the government could create and engage in a primary approval process that will provide a general critique of an inventor's submission. Also, to address and encourage invention, governmental agencies could use more performance-based specifications to permit innovators to design and produce new products to deliver design intent and desired outputs.

More government, university and industry-sponsored hackathons and incubators focused on the construction industry would increase the current pace of ideation and product development. Deal-making should follow.

As a further improvement, review the language in areas such as contracts, procurement documents, and specifications to encourage more performance-based criteria and capture of advances in processes after projects are completed.

CONCLUSIONS

These nine barriers appear to slow Australian construction's innovation (intellectual property and software) pace, and thus, it ranks below average compared to other sectors. The obstacles outlined in this paper make the overall lack of innovation understandable. However, taking the strategic view and acting in a targeted fashion can only help industry leaders facilitate future innovation and improvement in constructing shelter, infrastructure and processing facilities.

The industry's practitioners are sensitive to many things including risk and low return on investment.. There are many constraints this paper points to, and so adapting other industries' proven innovations may be a better strategy than greenfield invention. Regardless, once any solution is confirmed as valuable, it must be tailored, marketed and implemented. Overall, the cost for the contractor and the opportunity for the innovator appear to be adverse.

A new outlook is needed by industry, government, universities, inventors, and construction firms with these barriers in mind. Contractors are incentivised to strive for safer, higher quality, and cost predictable projects. Innovative solutions help create this end goal and minimise the risks undertaken. However, construction organisations need other groups' engagement to help overcome the barriers outlined. Each project stakeholder and interested third party can assist. An enthused and supported construction industry can create an innovation culture that benefits everyone.

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ROLE OF LEAN AND VDC IN REDUCING PHYSICAL AND OPERATIONAL WASTE AND ENVIRONMENTAL IMPACT

Musab Jamal Maraqa[1], Rafael Sacks[2], and Sabrina Spatari[3]

ABSTRACT

Lean construction focuses on eliminating process and operational wastes. The reduction of waste improves environmental performance by reducing GHG emissions. This research quantified the impacts of lean construction and VDC in reducing physical and operational wastes related to partition walls. The researchers observed worker activities at construction sites and compared them with observations from past projects. The activities were classified into value-adding and non-value-adding activities. The researchers observed the construction of different block types (gypsum, autoclaved aerated concrete, and concrete blocks) to estimate the operational wastes related to the construction method. The results showed that lean and VDC improved the value-adding activities using gypsum block to 68.4% compared to 25.8% in a traditionally managed project using concrete block, an improvement of 167%. Moreover, the embodied GHG emissions in the lean-VDC project per partition area are 12 kg CO_2e m^{-2} compared to 58.4 kg CO_2e m^{-2} in the traditionally managed project. The reduction in GHG emissions is due to reducing waste in the lean-VDC project and using more sustainable materials.

KEYWORDS

Lean construction, sustainability, waste, Life Cycle Assessment (LCA), Virtual Design and Construction (VDC).

INTRODUCTION

The construction industry is one of the most polluting industries in the world (Choi et al. 2019; EPA 2009; Horvath 2004; Li et al. 2019; UK-GBC 2018; IEA 2019). According to the International Energy Agency (IEA), the buildings and construction industry consumes around 36% of the global energy and releases more than 39% of the global greenhouse gas emissions (GHGs) (IEA, 2019). Those impacts primarily occur during building operation. In the United Kingdom, the construction industry uses more than 400 million tons of material per year, the majority of which imposes major burdens on the environment and large costs for waste management. For example, 60 million tons goes directly to landfill simply due to over-ordering, miss-ordering or poor handling, and

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breakages (UK-GBC 2018). Moreover, the U.S. construction industry accounts for 160 million tons, or 26%, of non-industrial waste generation each year (EPA 2009). It also contributes to 23% of air pollutant emissions, 50% of GHGs, 40% of drinking water pollution, and 50% of landfilled waste (Willmott Dixon Group 2010). Therefore, there is a need to improve the construction industry by implementing new construction paradigms like lean construction and BIM to reduce different types of wastes, which in turn can avoid unnecessary energy consumption and GHGs.

Lean construction focuses on eliminating waste, which represents any exhaustion of time, money, equipment, and energy that does not bring value to the customer (Womack and Jones 2003). Researchers from all over the world studied waste in construction, identifying and attempting to measure this waste and trying to find methods and ways to eliminate it (Lee et al. 1999; Formoso et al. 1999; Koskela et al. 2013; Golzarpoor and González 2013; Sajedeh et al. 2016; Maraqa et al. 2021). Elimination of these wastes plays an important role in providing the customer with the product in an efficient way, by reducing cycle time, time to market, and cost for the whole supply chain. Taiichi Ohno identified seven types of process wastes: transportation, inventory, motion, waiting, over-production, over-processing, and defects (Ohno, 1988).

Virtual design and Construction (VDC) is a practice that uses Building Information Modelling (BIM) for modelling construction products and their related construction processes (Kunz and Fischer 2012). VDC is used to assist multi-disciplinary project teams. It offers an incorporated method to plan production in construction, removing design clashes in the virtual world before they manifest in the real world.

Traditional management focuses on the transformational part of the industry and ignores the process and its associated operations (Koskela 2000). It views waste as the physical waste associated with the product. So, it misses the ability to quantify the process wastes and eliminate them. Lean thinking guides mapping the process and dividing the process' activities into value-adding and non-value-adding activities, which helps to improve the process by reducing the non-value-adding activities or eliminating them.

Life cycle assessment (LCA) is a practical tool and framework that can guide the sustainable design of products, processes, and activities. As a framework, it enables the systematic evaluation of environmental impacts associated with products, processes and activities (ISO 14040/44 2006). For decades, LCA has been used to understand the environmental impacts of products and engineered systems within the economy, including early-stage building materials, civil engineering infrastructure and buildings (Miller et al. 2019; Nguyen et al. 2018; Kendall et al. 2008; Junnila et al. 2006). Moreover, researchers have proposed methods to integrate LCA with BIM tools (Stadel et al. 2011).

During the last decade, many researchers have studied the relationship between lean construction, BIM, and sustainability to find the synergies between them. Koskela et al. (2010) suggested that synergy between BIM, lean, and sustainability is a considerable opportunity to achieve step-changes to address construction problems like delays, cost overruns, shortcomings of quality, and poor safety. However, this requires visionary and decisive action as well as persistence. Sacks et al. (2010) developed a BIM-Lean matrix, finding 56 interactions between the two and showing, through a survey of experimental and practical literature, 48 out of 56 intersections from documented evidence. The BIM-lean matrix can be used as a framework to understand practical issues faced by companies implementing lean and/or BIM.

Saggin et al. (2015) studied the relation between green costs and lean savings in a residential tower in Fortaleza, Brazil. Lean savings showed a reduction in material waste.

Results showed that the waste index in this project reduced to 10.93 cm/m^2 (height unit/area unit) compared with 13.53cm/m^2 in a traditional project without lean implementation, a reduction of 19.24% in construction waste. Carneiro et al. (2012) developed a matrix between lean principles and LEED interventions. They argued that LEED, as a rating system, does not allow the flexibility valued by lean construction, and it suggested the use of often expensive sustainability interventions without concern for process improvement and time and cost reduction. They noted that while LEED and lean construction contribute to the three pillars of sustainability (economic, environmental and social) since both share the waste elimination concept, the two methods differ in their application. Where LEED focuses on sustainability at conception, design, and construction phases, lean construction alternatively focuses on flow and conversion processes, aiming to improve production processes by removing all non-value adding activities. Another difference between lean and LEED is that the former focuses on reducing time and initial cost without specific concern for the environment.

This paper presents an extension of an experiment the researchers started in 2019 (Maraqa et al. 2020). It aims to measure multiple types of partition walls wastes by studying several blocks construction methods with several management approaches. The partitions studied in this work are gypsum block, autoclaved aerated concrete block (AAC), and concrete block. The blocks were studied with different management approaches; lean, lean and VDC, and traditional management. The overall objective is to present the effects of lean construction and VDC in reducing material and operational wastes and to present the role of the product in generating operational waste, which does not exist in other types of products. Also, (LCA) models were built for different types of partitions to evaluate the embodied GHG emissions in the different types.

This paper consists of four main sections. Section 1 describes the problem synopsis and the research objective. Section 2 describes the research method and the case study. Section 3 details the findings and results. Finally, section 4 concludes the paper, synthesizing the major research findings.

RESEARCH METHOD

A case study research method was selected for this research. Data were collected from three construction companies (A, B, and C) to study the physical and operational wastes related to construction of masonry partitions. Company A began implementing lean construction and BIM in 2012 by implementing Last Planner ® System (LPS) and BIM in the design phase, and since then they have made significant improvements in implementing BIM in the big room, virtual design and construction (VDC), 5S principles, centralized mixing, and supply of bulk materials. Companies B and C have worked conventionally without any implementations of BIM or lean construction practices.

This paper extends work described by Maraqa et al. (2020) and applies the same work study-analysis performed by Sacks et al. (2018) in company A's construction projects before the company implemented BIM and lean practices. The same observations and measurements were collected after the company implemented VDC and 5S practices. Recently, a new construction project built conventionally by company C with different block construction methods was studied to visualize the operational waste.

Life cycle assessment (LCA) following ISO (14040/44, 2006) was used to calculate the reduction in GHGs along the material supply chains of projects A3, B1, and C1. Researchers monitored the workers' activities every five minutes and classified the activities into value-adding and non-value-adding activities. The researchers monitored

450 worker-hours in three different projects (A3, B1, C1) under construction. The value-adding activities included: building, gluing, and leveling. The non-value-adding activities included: marking out, moving blocks, shuttering, cutting, moving between floors, steel fixing, cleaning, scaffolding, waiting, reworking, implementing design changes, and others.

A critical analysis was conducted for the raw collected data from the different construction sites. All the activities were classified into different categories, summing the time for each activity, and dividing it by the total time to identify its percentage. The aim was to test the impacts of different construction production systems in reducing wastes and improving environmental performance.

The following section of this manuscript describes the data collection activities for block works. The last section describes an inventory of GHGs designed to calculate the embodied GHGs of the blocks and the plaster layer, from cradle to installation.

LIFE CYCLE ASSESSMENT (LCA) OF THE PARTITION WALL

Life cycle assessment (LCA) following ISO (14040/44, 2006) was used to calculate the embodied GHGs for 1 m^2 of the finished partition wall in projects A, B, and C. To compare GHGs for different types of partition walls, LCA models were built using GaBi for the different types (Figure 1). The models include the block type with the related plaster types. The building materials used were autoclaved aerated concrete block (AAC), concrete block, gypsum block, gypsum plaster, and cement plaster. The embodied GHGs in these products were calculated based on values stored in the GaBi database (Sphera GaBi 9, 2020; Spatari et al. 2001) using the 100-year global warming potential (GWP) based on AR4 of IPCC 2007 (Forster et al. 2007) and measured in carbon dioxide equivalents (CO_2e). The system boundary for the projects studied evaluated the embodied GHGs in the block manufacturing and plaster materials.

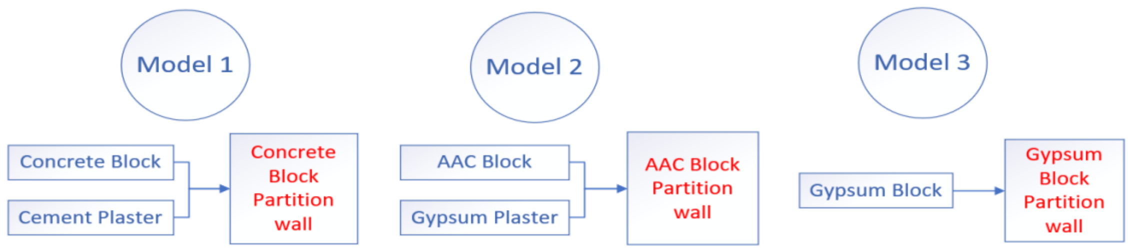

Figure 1: LCA models for different types of partitions using GaBi

CASE STUDY DESCRIPTION

A research team started an experiment for monitoring the block workers' activities in one of the construction sites related to company A in 2007 (A1). The results were interesting and motivated company A to start thinking about waste. Only 31.9% of the workers' activities were value-adding activities, while the rest were non-value-adding activities. The activities are cutting 24.1%, marking out 7.3%, scaffolding 2%, transporting blocks 4.4%, moving between floors 0.4%, design changes 7%, filling grooves 2.6%, and waiting and rework (Sacks et al. 2018).

Company A realized the importance of improving its process. They started to apply value stream mapping (VSM) for the masonry works (A2). They delivered the blocks before placing the concrete slab and avoided stacking two pallets on top of each other. They found that traditional block delivery is very wasteful (Sacks et al. 2018).

From a lean point of view, all these activities except building, gluing, and levelling are waste because they do not add any value to the final product. Avoidance of these activities is a necessity and can be reduced by mapping the process and eliminating these wasted activities. If the blocks are calculated precisely and delivered to the exact locations at the right time without stacking the pallets on top of each other, the workers will spend less time and effort in these waste activities. Also, material waste will be reduced, because stacking two pallets on top of each other increase the pressure on the bottom pallet and damage the blocks.

Block workers' activities were monitored in one of company A's projects in 2019 (A3) (Maraqa et al. 2020). Company A decided to implement VDC, LPS, and 5S (sort, set in order, sustain, standardize and shine), which is a systematic method for organizing the work environment and keeping the construction site clean and organized. A VDC model was built using Autodesk Revit. The VDC model produced a highly detailed model to optimize the number of block rows and reduce block cutting. Also, it improved the coordination between the different subcontractors and reduced the changes and rework. Three types of blocks were used in this project: autoclaved aerated concrete (AAC) blocks, water resisting gypsum block, and regular gypsum block. Company A decided to use gypsum blocks in their construction projects for many reasons. The blocks are relatively large (50 cm x 67 cm x 10 cm), lightweight, and smooth; thus, they do not need a finishing layer of plaster before being painted. From a construction method perspective, the gypsum block is considered a highly productive solution. VDC models helped in extracting the exact block quantities for each apartment and delivering them to the right location at the right time. Also, the VDC model helped in producing highly detailed partitions layout drawings for the workers. The site superintendent removed all the constraints by preparing the water and electrical connections and distributing the block drawings according to their apartments by hanging them on the wall. Removing the constraints helped the workers get the information from the beginning of the work instead of waiting.

A second project in which company A applied mainly the last planner system without VDC was studied (Maraqa et al. 2020). The reason for selecting this project is to test the marginal impact of different lean and BIM interventions. A third project was studied in 2019 belonging to company B (Maraqa et. 2020) (B1), which worked traditionally without any lean or BIM interventions. The company used AAC block. The blocks were delivered randomly to the different apartments, and block pallets were stacked on top of one another.

Finally, a fourth project was studied in 2021. The project was built by company C using concrete blocks (C1). Company C works traditionally without any BIM or lean implementations. Also, it did not either implement any technological construction method. Today, most construction companies do not use concrete blocks for many reasons. The blocks are relatively small (40 cm X 20 cm X 10 cm), heavy, and rough. Also, the concrete block construction method requires building concrete framing columns and beams. These beams and columns consume a considerable amount of cement and fine and coarse aggregate. Moreover, they need wood for shuttering, rebars for beams and columns, and more effort from workers.

In the fourth project (C1), all the block pallets, fine aggregates, cement, steel, and wood were delivered to the workspace on a temporary balcony after pouring the concrete and removing the shoring from the slabs. The general contractor prepared the balcony for delivery logistics, delivered all the materials, and the block subcontractor moved the materials inside the floor (Figure 2). Delivering the material in this way resulted in additional material relocation steps that wasted the workers' time. Numerous amounts of waste were observed. The workplace was not clean, organized, or even safe. Many of the works constraints were not ready such as drawings, water, and electrical connections. Lack of design visualization resulted in changing some partition wall locations after the workers finished them. Also, the different work packages were not planned well. This resulted in causing the subcontractors to leave and return to the project several times.

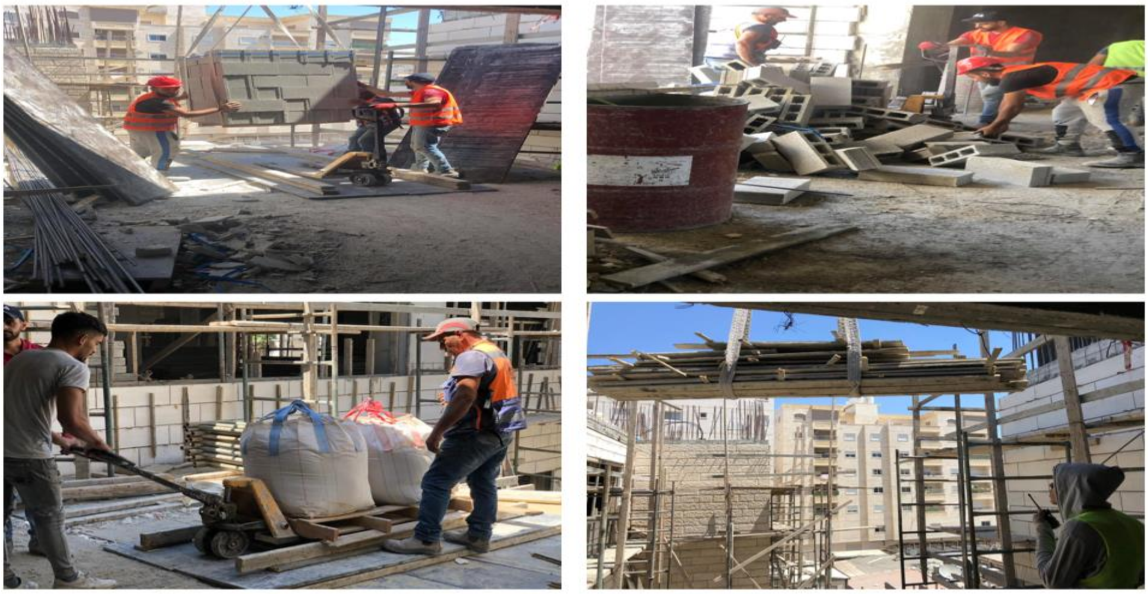

Figure 2: Delivering materials for project C1 using an open balcony

FINDINGS AND RESULTS

The four projects studied were analyzed for different categories: worker activities, material waste, and the embodied GHGs in the materials. Results indicate that lean and VDC interventions have a significant impact in reducing material and operational wastes. Value-adding activities have the highest value for the VDC-lean project with 68.4%, while non-value-adding activities have the highest value for the traditionally managed projects (B1& C1). Figure 3 shows the different projects studied. Project C1 was studied recently for concrete block, projects A1, A2, A3, and B1 studied previously (Maraqa et al. 2020). The value-adding activities in project B1 were 35.8% and in project C1 the results were worse.

In project C1 (traditional 2021), value-adding activities were only 25.8%, and the rest were non-value-adding activities. Non-value-adding activities are related to two aspects: the construction method, and the management approach. In concrete blocks (Project C1), some operational wastes do not exist as they do for the other blocks' types. These operational wastes include shuttering, mixing, drilling, and insulation. Waiting and rework and moving pallets activities were a significant cause of the block works operational waste of approximately 25% of workers' time. Also, the lack of design visualization due to designing the project traditionally resulted in rework. For example, after the workers finished a wall with an area of 25 m^2 between two inner sides of two columns, the client decided to rebuild the wall on the outer side of the columns to increase the room area (Figure 4). This required spending around 20 working hours demolishing the wall. Moreover, the concrete block requires activities that do not exist in the gypsum block or the AAC block. These activities are shuttering 9.2%, mixing 10.6%, steel fixing 4.9%, drilling 1%, placing concrete 6.3%, and insulation 0.3%. These activities form about one-third of the workers' time. Table 1 summarizes the value-adding and the non-value activities in the different projects studied.

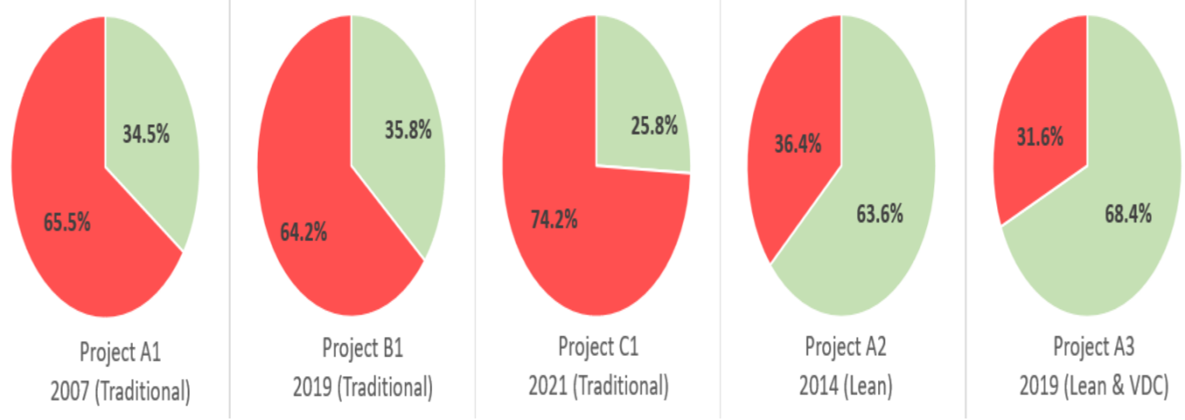

Figure 3: Results for five projects showing proportions of value-adding (green) and non-value-adding (red) activities for masonry construction operations. Charts for company A and B projects were reported previously (Maraqa et al. 2020)

Table 1: Summary of the results of activities observed in five work studies. Values are the percent proportion of the total working time spent on each activity

Worker activity	Project A1 2007 (Traditional)	Project A2 2014 (Lean)	Project A3 2019 (Lean & VDC)	Project B1 2019 (Traditional)	Project C1 2021 (Traditional)
Building, gluing and levelling	34.5	63.6	68.4	35.8	25.8
Cutting	24.1	7.8	1.3	12.6	4.3
Moving pallets	4.4	1.3	4.8	19.0	7.8
Move between storeys	0.4	1.3	1.9	3.7	-
Cleaning	9.9	5.2	4.9	5.7	2.3
Marking out	7.3	11.7	3.5	5.6	1.4
Scaffold	2.0	0.0	0.3	1.2	2.8
Waiting and rework	10.5	3.9	6.1	6.6	15.1
Design changes and others	7.0	5.2	8.8	10.0	8.2
Shuttering	-	-	-	-	9.2
Mixing	-	-	-	-	10.6
Steel Fixing	-	-	-	-	4.9
Drilling	-	-	-	-	1.0
Placing concrete	-	-	-	-	6.3
Insulation	-	-	-	-	0.3
Total	100.0	100.0	100.0	100.0	100.0

Figure 4: Lack of visualization for client review led to rework for a complete block wall

LIFE CYCLE ASSESSMENT AND GREENHOUSE GAS EMISSIONS FOR DIFFERENT TYPES OF PARTITIONS WITH DIFFERENT MANAGEMENT APPROACHES.

This section evaluates the GHGs for three types of partition walls. The partition walls studied consists of the block and the plaster layer. Concrete block with cement plaster was used in the traditionally managed project (C1). Also, AAC block with gypsum plaster was used in the traditionally managed project (B1), while gypsum and AAC blocks were used in the lean-VDC project (A3).

The functional unit studied in this research is 1 m^2 of a ready partition wall. The concrete block partition wall consists of the concrete block and a cement plaster layer. The AAC partition wall consists of the AAC block and gypsum plaster layer, while the gypsum block partition wall consists only of the Gypsum block without any plaster type. The concrete block partition wall has the highest value for the embodied GHGs because it depends mainly on cement. The embodied GHGs per m^2 equal 56.8 kg $CO_2e\ m^{-2}$. However, the gypsum block partition wall does not have any plaster, and the gypsum material is environmentally friendly. The embodied GHG per 1 m^2 have the lowest value with 9 kg $CO_2e\ m^{-2}$. This analysis showed that the gypsum block is the best alternative among the other three block alternatives. Table 2 presents the embodied GHGs in different types of block and plaster layers.

Table 2: presents the embodied GHGs in different types of block and plaster layers

Partition wall	Block Embodied GHG (kg $CO_2e\ m^{-2}$)	Plaster Embodied GHG (kg $CO_2e\ m^{-2}$)	Total Embodied GHG (kg $CO_2e\ m^{-2}$)
Concrete block	12.7	44.1	56.8
AAC block	17.4	3.2	20.6
Gypsum block	9.0	-	9.0

From an environmental point of view, lean construction and VDC had a dominant influence on reducing waste and GHGs. Table 3 presents the embodied GHGs for the different construction projects studied with the different management approaches. In the traditional management project (B1), the waste percentage is 22%, and in the project (C1), the waste percentage is 12%. However, these wastes were reduced significantly to only

6% in the lean-VDC project. In terms of embodied GHGs per partition, area built, in the lean-VDC project the embodied GHGs is 12 kg CO_2e m^{-2}, while in the traditional management projects (B1 and C1) are 25.6 kg CO_2e m^{-2}, and 58.4 kg CO_2e m^{-2}.

The results show that the embodied GHGs in the traditional management projects (B1 & C1) are greater than those from the lean-VDC project (A3). Some of the GHGs related to the material used in the partition walls, while others related to the management approach. Although the concrete block and the AAC block have higher embodied GHGs used in the traditional project, the lean-VDC project still has the lowest embodied GHGs since it generated the minimum waste.

Table 3: GWP and material waste for two traditional projects and lean-VDC project

Inventoried Data and Performance Metrics	Traditional management B1	Traditional management C1	Lean and VDC management A3		
	AAC Block	Concrete block	AAC block	Gypsum block	Total
Delivered quantities (m^3)	2,225	597	344	1,886	2230
Block volume built (m^3)	1,762	532	334	1,759	2,093
Waste volume (m^3)	463	65	10	127	220
Delivered blocks (ton)	890	597	138	1,603	1741
Blocks built (ton)	705	532	134	1,495	1,629
Block waste generated (ton)	185	65	4	108	112
No. of pallets	1,646	497	251	2357	
No. of truckloads	55	42	9	86	
Distances travelled (km)	5,500	4,200	900	8,600	
Transportation of unused blocks to site (km)	1,000	360	0	500	
Transportation of waste from site (km)	500	180	0	250	
Block embodied GWP (t CO_2e)	387.2	75.8	59.9	168.8	228.7
Plaster embodied (t CO_2e)	56.5	247.4	10.7	0	10.7
Block transport to site (t CO_2e)	6	4	0.9	10.7	11.6
Embodied GWP in transport to landfill (t CO_2e)	0.6	0.2	0.00	0.4	0.4
Total embodied (t CO_2e)	450.3	327.4	71.5	179.9	251.4
Total embodied GWP in waste (t CO_2e)	82.4	8.9	1.7	12.6	14.3
GWP per partition area built (kg CO_2e m^{-2})	25.6	58.4	21.4	10.2	12
GWP in block waste percentage (%)	22	12	2	8	6

CONCLUSIONS

Previous research has highlighted the benefits of lean construction in reducing different types of wastes. However, most of this research focused on measuring the environmental impact of reducing physical wastes. In this research, we proposed a case study research method to evaluate both the process and operational wastes. We showed that selecting the product plays a significant role in reducing environmental impacts, not only due to the embodied GHGs in the product but also because it can reduce the operational waste which has embodied GHGs.

The projects evaluated in this study revealed that lean principles and VDC play a significant role in reducing different types of wastes: physical wastes and operational wastes. In the lean-VDC project (A3), the value-adding activities increased to 68.4%, compared to the traditional projects B1 and C1 with 35.8% and 25.8%. Also, this study showed that the construction method itself introduces some operational wastes. The AAC and concrete blocks are both used in traditionally managed projects, but the operational wastes are much higher in the concrete block compared to the AAC block. Concrete block has shuttering, steel fixing, mixing, drilling, and concrete placing, which do not exist in the other block types.

From an environmental point of view, lean and VDC reduced the embodied GHGs significantly compared to the traditional projects. The embodied GHGs reduced in the lean-VDC project (A3) for two reasons; the first, use of an environmentally friendly product and second, reduction of the amount of waste in the blocks. The waste in the lean-VDC project (A3) was reduced to only 6% compared to 22% and 12% in the traditional projects (B1 & C1). The embodied GHGs in the lean-VDC project (A3) is 12 kg CO_2 e m^{-2}compared to 25.6 kg CO_2 e $m^{-2}$and 58.4 kg CO_2 e m^{-2} in the traditionally managed projects (B1& C1).

We conclude that lean and VDC management approaches are dominant in reducing different wastes types (physical and operational waste). The results showed that implementing lean and VDC with environmentally preferable products achieves optimum benefits. The proportion of value-adding activities increased, the block waste decreased, and the total embodied GHGs per partition area decreased.

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EFFECTS OF DAILY MANAGEMENT ON DESIGN RELIABILITY

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ABSTRACT

Building Design Management (DM) is challenging due to the fragmentation of project partners, the iterative nature of design and the tradition of informal management of designers. Therefore, many contractors do not trust the promises of designers and protect the construction schedule with schedule buffers that increase project lead times. To act upon this situation, several researchers have suggested using the Last Planner™ System (LPS) as a method for DM. Using two case studies, we present how the use of the LPS method as a tool for Daily Management (DAM) increases the reliability of the design and how, correspondingly, *not* using it can affect design reliability. So far, very little attention has been paid to the role of DAM in DM, and this short article seeks to provide new insights into this research gap for both researchers in the field and DM professionals. These early and exploratory results, despite the limited number of cases, can be utilised in further research as well as in practical project management, especially when the reduction of schedule buffers between construction and design is targeted.

KEYWORDS

Lean construction, lean design management, last planner, PPC

INTRODUCTION

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. One lean method is the Last Planner System (LPS), which is used for production control and Design Management (DM) after its development (Fosse & Ballard, 2016). The LPS is based on continuous pull planning sessions, measuring the promises made by the parties to each other, and continuous learning (Ballard et al., 2007). Several studies have shown that in construction production,

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where the LPS method is introduced, relatively high Planned Percentage Completed (PPC) values are generally achieved (Kim & Jang, 2005; Bortolazza & Formoso, 2006; Khanh & Kim, 2013; Hicham et al., 2016).

DM in construction is a complex process, and its failure can shatter the entire project. Challenges in DM are a multidimensional phenomenon involving project management challenges, communication challenges, guidance challenges, competence challenges and technological challenges (Coates et al., 2004; Addor & Santos, 2014; Alaloul et al., 2016; Pikas et al., 2013; Mehrbod et al., 2019). In addition, the field of construction is known to develop slowly (Koskela et al., 1997; Chen et al., 2017). Despite the widespread use of traditional project management methods in the construction industry, these methods have been found to be ill suited for DM (Gray & Hughes, 2001). One alternative to traditional methods in construction design is lean design management (LDM) (Koskela et al., 1997; Tilley, 2005; Uusitalo et al., 2019).

LDM comprises many methods and tools (Uusitalo et al., 2017). LPS has been used in DM for visualizing the design workflow, optimizing the sequence of design work and phases, increasing the transparency of the design process, tracking the amount of work in progress, and controlling the design process (Koskela et al., 1997; Fosse & Ballard, 2016). Several companies have also seen the importance of daily (“huddle”) meetings in the use of LPS, and DAM is considered to facilitate continuous improvement as an integral part of a lean philosophy (Salem et al., 2006). Behind DAM is the plan-do-check-act cycle (PDCA), also called the "Deming’s cycle" by its developer (Koskela et al. 2019). In these short meetings, called “huddles,” team members quickly report on the previous day’s situation regarding their own work and whether there is a problem preventing the work from being promoted (Schwaber, 1995). This part of the LPS method is analogous to the Scrum methodology developed in the software industry.

Scrum is so-called agile method that iteratively and incrementally develops a product with the goal of maximizing customer value return, and these methods have been developed since the 1950s as a reaction to the traditional bureaucracy of engineering methods and the ever-changing business environment (Abbas et al. 2008). What distinguishes agile methods from lean methods is that agile methods respond to the complexity of a change of continuity in an unpredictable environment, while lean methods are a collection of functional techniques that focus on productive resource use (Sanchez & Nagi. 2001). However, while scrum is developed for software product development projects, it can also be applied to complex projects and design (Streule et al. 2016). The scrum framework consists of roles, artifacts, and events (Schwaber & Sutherland. 2013). Many previous studies (Koskela & Howell, 2002; Owen & Koskela, 2006; Owen et al., 2006) have provided concepts for adapting agile methods from software development to the design phase of construction projects, and some engineering companies in the Nordics have implemented these methods as part of their processes (Føreland & Halvorsen, 2018; Uusitalo et al. 2017).

Although many researchers have recognised the benefits of LPS in DM, most design-related studies have focused on LPS sessions and described their benefits (Daniel et al., 2015). Thus, the role of daily management (DAM) in DM has not been adequately studied, and this study therefore focuses on showing how using DAM as part of DM improves design reliability. This exploratory paper focuses on highlighting the impact of the DAM on design reliability and seeks to highlight the importance of further research on this connection.

The purpose of the DAM is to bring the team together and provide the team with a common platform in which team members visit the day-to-day work, report on obstacles they have encountered and progress in their own work (Lianying & Xi, 2016). Typically, a DAM meeting, also called a "huddle," is held daily (Salem et al., 2006). DAM also has other effects. For example, Salem et al. (2005) highlighted the effective outcomes of a detailed review of acute issues in construction site daily huddles. According to Seed (2014), the DAM meeting can prevent the construction industry's inherent tendency to suspend work when problems arise and to look for a new direction at the next meeting. He also emphasised that the daily huddle meeting agenda should be focused on the tasks among the parties, i.e., what is the progress of the tasks, what is currently ongoing and whether there are any restraints to proceedings (Seed, 2014). Reducing the postponement of design work by DAM may also allow the shortening of buffers. This highlights new possibilities for the design of more efficient production that aims at small batch sizes and buffers, as proposed by Lehtovaara et al. (2021). One of these possibilities is the importance of reducing batch size and WIP to ensure the reliability of the design work (Ballard et al., 2002; Uusitalo et al., 2019; Lappalainen et al., 2021).

Also, as part of the DAM, LPS sessions include root cause analysis, in which tasks that were not completed, despite planning, are examined in more detail (Ballard, 2000). These analyses aim to systematically categorise the root causes of work interruption and eliminate them so that similar future tasks will not be prevented for the same reasons (Fauchier & Alves, 2013). Ballard (2000) led the construction industry towards root cause analysis and emphasised its importance in lean construction. The classifications presented by Ballard et al. (2007) can be used to systematically document the root causes identified and to determine their frequency. Resources can then permanently eliminate the most significant and common root causes of delayed tasks. The classification of root causes in this study is fourfold: (1) a lack of instructions or guidelines, (2) a lack of conditions for starting the work, (3) a lack of resources and (4) problems in process. Ballard (2003) also identified the importance of the DAM; however, its importance has sometimes been overlooked (Dave et al., 2015).

Despite some efforts (Streule et al., 2016; Zender & de Soto, 2020; Poudel et al., 2020), the research in the construction industry to date has not paid enough attention to the role of DAM in DM. This paper attempts to show that focusing on DAM in DM may offer more rigorous and reliable control of the design process than traditional methods. As the problem of poor reliability and predictability in DM is universal and common in the industry, our research also serves as an awakener for both researchers and practitioners. Thus, our study makes a relevant contribution to the construction industry.

METHODS

The research problem required an exploratory approach, and the case study method was chosen as the research strategy (Algozzine & Hancock, 2017). The case study method also made it possible to assess the differences and similarities between cases (Yin, 1981). In the case study, the validity of the study is achieved primarily by using multiple sources instead of single source data (Algozzine & Hancock, 2017). In this study, we used two primary data sources: PPC measurements and root cause analyses. Second, to ensure the reliability of the study and reduce prejudice, the data collection and analysis methods of the study are presented in a transparent and detailed manner; therefore, this research is replicable (Gibbert & Ruigrok, 2010). Third, research and data collection have been done by multiple authors (Gibbert & Ruigrok, 2010). Researcher bias and the bias of a small sample were also identified and considered in the conclusive part of this paper.

The data were obtained from two Finnish case studies, and an exploratory design was used to determine the effects of DAM on PPC values. Case study A was chosen because it used DAM for underground pipe DM in a greenfield industrial project. Case study B, which did not use DAM, was a hotel renovation project. In both case studies, the detailed design phase and construction work were ongoing. The active research work lasted 9 months. The authors used only two case studies for comparison, mainly due to the limited length of this paper. The data collected from the literature and other projects monitored by the authors also corresponded to the PPC level of case study B selected for this study, and thus the comparison between these two cases is a sufficient sample for this purpose. Data were first collected from digital sources provided by the design teams and then edited and categorised by the researchers. In case A, the data was stored in a table in the Microsoft Teams workspace, from where it was transferred to Excel by the researchers. In Excel, the data was organized so that descriptive statistics could be calculated and PPC charts could be generated. In case B, the data were obtained from a project bank from which it was downloaded for use by researchers. The data in the project bank were in Excel and pdf formats, and the researchers transferred the data to a separate Excel file and descriptive statistics and PPC diagrams corresponding to case A were prepared.

CASE STUDIES

Case A was an ongoing industrial plant site with a gross area of approximately 200,000 m2. The corresponding design organisation consisted of a client representative who supervised the design (sub-area project manager) and a design project manager who worked for the design team and designers. The design project manager independently led the daily meetings after the initial phase. The sub-area project manager represented the owner at these meetings and made the necessary decisions regarding the design work. The agenda for the daily meetings was simple: what the designers were doing and whether there were constraints to be removed. The maximum size of the design team during the study was nine people. The designers and team leader actively participated in the daily meetings, except for isolated occasional absences. One of the researchers facilitated the LPS method, but soon after the principles of the LPS method became apparent to the designers, the design team and the client's representative continued independently, and the researcher assumed the role of observer. The LPS method started with a joint LPS session, in which a phase schedule was prepared with the help of the master plan and preliminary task planning was done.

In the first session, the design team was introduced to the following LDM principles: (1) do only unhindered work, (2) remove all constraints before starting the task, and (3) publish drawings frequently and in small batches. Since the master plan had been assigned to the project before and without the use of LPS, the design team began scheduling in the first phase of the planning session. The first workshop lasted one working day, which was divided into two parts, and the phase plan was conducted in small groups. Because of the Covid-19 pandemic, the session was held remotely using teleconference software and an electronic whiteboard application. It was agreed that daily planning routines would include only the necessary planning tasks for the next five working days, and the size of the tasks was limited by scoring (maximum half-day job = 3 points, approximately one day job = 8 points, a couple of days job = 13 points, and a maximum of one week job = 34 points). The scoring method was borrowed from a similar method used by the facilitator in the IT field to steer the team's efforts towards evaluating the scope and complexity of the task and away from estimating the exact number of hours (Mahnič, 2015). At the beginning of the design, the tasks were mainly designed for one person, but exceptions to this principle were made during the work, and there were often other designers under one task who participated in the task. The amount of work in progress (WIP) was limited to 50 points at the beginning of the design, aiming for the design team to focus only on the agreed-upon tasks for a week and complete them during the week. The WIP limit also reduces the batch size of a task to a maximum of 50 points (approximately one week of work). The background to setting this limit is the intention to be familiar with lean and agile philosophies, where the amount of WIP is intentionally limited (Sutherland & Schwaber, 2013). Design work had started with limited resources in case A four months earlier without WIP restrictions and in the traditional way, although as construction approached, the parties decided to implement LPS as well as DAM.

Every fifth daily meeting on Fridays was 15 minutes longer than other daily meetings, and it was dedicated for planning the next week's tasks. Only constraint-free work was allowed to be placed on the next week's to-do list. In this regard, the designers followed LPS make-ready planning and weekly planning procedures. Learning took place in weekly meetings on Fridays, which always began by checking the implementation of the weekly work plan and PPC metrics. Tasks that were not completed despite make-ready planning were then reviewed through root cause analysis, and constraints were classified and removed during or shortly after the meeting. If the removal of the constraint took place, as was the case for a few tasks, no new tasks related to this constraint were taken under work until the constraint was removed. The duration of the weekly meetings was about 30 minutes, and the duration of the daily meetings was initially 30 minutes, although it was shortened to 15 minutes, as the group learned how to use the method. In addition to the DAM, the design team held normal design meetings with the client and other designers, with a focus on coordination issues with different design industries. The constraint log and to-do list were compiled on the digital cloud platform to which all parties had access. One of the authors observed 19 weekly meetings and 31 DAM meetings for 5.5 months. However, not all daily meetings were observed by the author, and at that time, the team met daily without the author's presence.

Case B was an ongoing hotel renovation site with a gross area of approximately 40,000 m2. The design of case study B was led by a construction management consultant, and LPS sessions were held with the design team on a weekly basis. In this case study, all design disciplines were represented. With a few exceptions, the design team regularly attended weekly sessions and planning meetings. The design work was planned according to the LPS method through the master schedule for phase scheduling, look-ahead planning, and weekly planning (Verán-Leigh & Brioso, 2021). The team used Excel spreadsheets at the beginning of the project, but as the project progressed, it switched to using a digital cloud-based whiteboard application to replace the traditional LPS board based on post-it notes. Also, during this project, the Covid-19 pandemic affected the work of the design team, and the sessions were held as remote sessions, except for the initial phase of the project. The exact number of designers was unavailable to the researchers, but there were dozens of them in the design organisations. The duration of the weekly meeting was about an hour, and one of the researchers observed 12 LPS sessions and went through the data of the LPS sessions for two years. The batch size was not limited in this case study, although the principle was that the tasks should be sized to be completed between the weekly sessions. Constraint logs were not used by the design team;

however, these constraints of design work were discussed in the weekly sessions with the aim of resolving them either in the session or shortly thereafter. In addition to the LPS sessions, the design team held separate design meetings, as the case study A team did, where they focused on technical design coordination issues rather than task management.

DATA ANALYSIS

The data consisted of weekly PPC measurement results as well as recorded root causes that prevented the completion of the planned design task. Both PPC results and root causes were compiled into tables using Excel. The root causes were classified in case study A into the following categories commonly used in the LPS method: (1) a lack of design instructions or guidelines, (2) a lack of conditions for starting work, (3) a lack of resources and (4) problems in process. The first root cause was, for example, situations in which changes were made to the design criteria while the design was already underway and ignorance of the design requirements and/or design guidelines. The second root cause was tasks in which the initial data or subscriber's decisions were missing or the previous work phase was in progress and prevented the work from being performed. The third root cause was related to tasks that could not be completed due to a lack of manpower or technical problems with the design software. The fourth root cause included tasks that were not completed due to miscalculation of time allotted for work, correction of errors and deficiencies in design coordination.

RESULTS

PPC

In case study A, PPC increased shortly after the start of daily meetings, with a mean of 91.8%. The amount of weekly estimated work was limited to 50 points, and the mean was 62.6 points. Figure 1 shows the evolution of PPC for case A over 19 weeks and weekly workload point estimates.

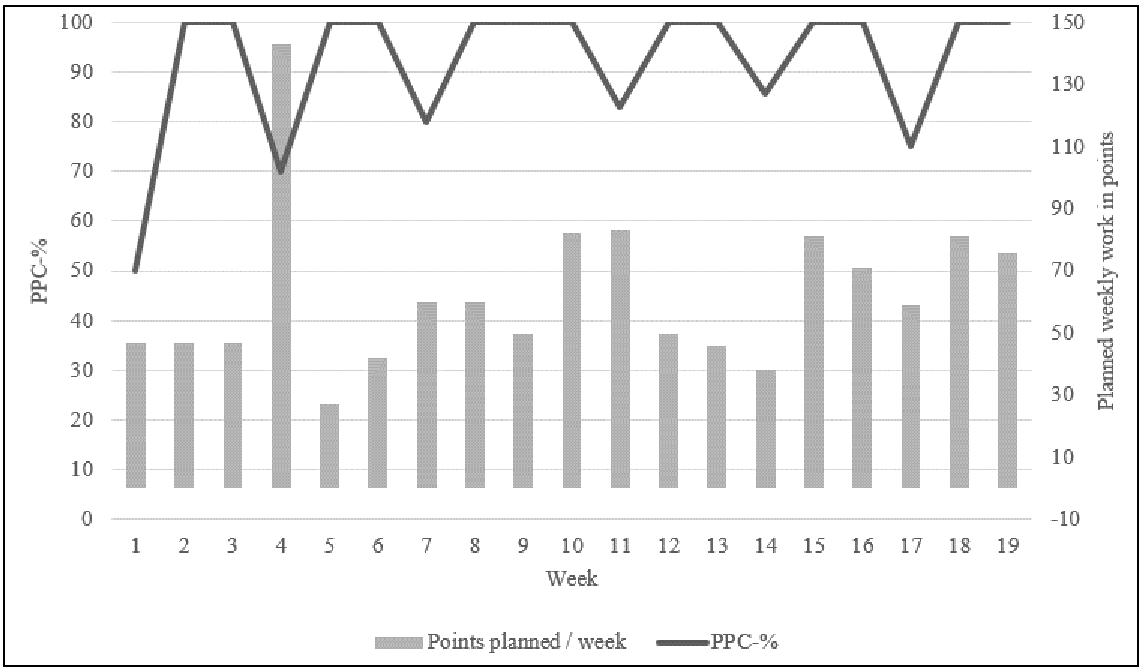

Figure 1. Case A – PPC and planned weekly work.

In case study A, weekly work was measured as points that reflected the estimated extent of work in approximate hours or days worked. However, it was not possible to determine from the data the actual work that had been done. In case study B, the PPC was clearly lower than in case A, with a mean of 58.8%. The amount of weekly estimated work was not limited, and the average number of weekly tasks was 29.9. Figure 2 shows the development of the PPC of case B over 42 weeks and the weekly tasks.

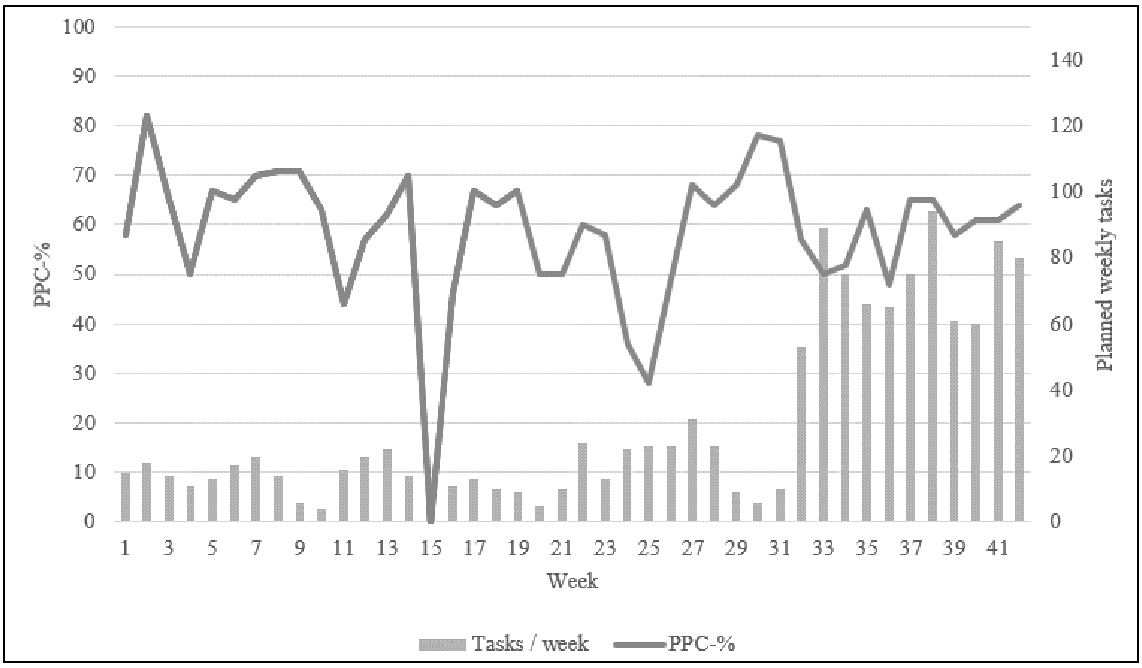

Figure 2. Case B – PPC and planned weekly work.

In case study B, weekly work was measured only as the number of tasks, so the estimated or actual workload could not be determined from the available data. The results also show that in both cases, there were no major improvements in PPC values, and the level of reliability was relatively constant in both. In case A, it is higher, and in case B it is lower.

ROOT CAUSE ANALYSIS

In case study A, which lasted only 19 weeks and involved only the underground pipeline design team, the number of root causes was naturally lower than in case study B, which had a follow-up period of 42 weeks and involved all design disciplines of the project. Table 1 summarises the data from both case studies for the root causes of the design assignments that were not completed as planned during the week.

Table 1. Root Cause Analysis Results

Root Cause	Case A	Case B
1	0	30
2	5	90
3	0	60
4	3	63
5	0	866

Root cause 1 = Lack of design instructions or guidelines
Root cause 2 = Lack of conditions for starting work

Root cause 3 = Lack of resources
Root cause 4 = Problems in process
Root cause 5 = Unknown cause

As can be seen from the table, in both case studies, root cause category 2, a lack of conditions for starting work, was the most significant factor hindering completion of the design tasks. Similarly, in both cases, deficiencies were found in the process that prevented the completion of the tasks. However, in case study A, no root causes 1 and 3 were found at all, while in case study B, these were identified, especially root cause 3, as problems in the process and as a common restriction to completing the tasks. In contrast, as a specific finding in case B, the number of unidentified root causes was remarkably high at 866 cases. It is evident that the coverage and purposive implementation of root cause analyses have suffered, especially in case B, due to the large number of discrepancies. Root cause analyses are laborious to implement, and if the number of anomalies starts to increase, as in case study B, the design resources will not be sufficient for detailed analyses. In case A, the daily processing of root cause analyses did not lead to a corresponding labour cost, which was naturally also affected by the smaller number of deviations.

SUMMARY

The results clearly show the differences between the cases, the most significant of which is the PPC value. In case study A, where DAM was used, PPC was at a higher level than in case study B, where DAM was not used. With the standard deviation of the PPC number being the same in both, the level of reliability in case study B was stable but lower than in case A. In both cases, the variation in workload does not appear to have affected PPC.

For root causes, similarities were found for root causes 2 (lack of conditions of work) and 4 (problems in process), but not for root causes 1 (lack of design instructions or guidelines) and 3 (lack of resources). The large number of unidentified root causes in case B and the researcher's observations of LPS sessions suggest that the root causes were not treated or handled with the same precision as in case A, with unidentified cases likely to have several root causes belonging to causes 1–5.

When comparing the discussions that took place in a project that used DAM to a project that did not use DAM, the most significant differences were that in a project that used DAM, each delay was addressed in daily meetings, and the root cause was eliminated. In a project where DAM was not in use, the root causes of the failure of the tasks were recorded weekly, but there was little discussion about eliminating them and no systematic effort to remove the root causes and restraints. The number of root causes in case A was small, which may be influenced by problem-solving practices resulting from the systematic and daily removal of barriers. The approach of case B, where the root causes were not systematically eliminated, seems to lead to a recurrence of the same work restrictions, and if the root causes are not eliminated, and thus PPC also appears to be permanently lower.

DISCUSSION AND CONCLUSIONS

Our findings imply that high PPC values are possible in design. Our exploratory study proposes that with DAM, it is possible to achieve a consistently high level of PPC. This result contributes to supporting, for example, the views of Koskela et al. (1997), Fossen and Ballard (2016), and Uusitalo et al. (2017) on the role of LPS in the use of LDM in construction projects. To develop a full picture of DAM, other researchers could replicate our findings in different projects, allowing the importance of DAM in terms of schedule buffer reduction, batch size, and WIP reduction to be assessed more comprehensively in this short paper. Further research should also investigate the possibilities of using DAM in takt production, in which case, for example, the pace of one-day construction production could be integrated into the daily management of design (Lehtovaara et al., 2021).

In case study A, which used DAM and prevented entry into work unless constraints were removed, the number of unfinished tasks was lower and PPC higher than in case B, where researchers found no systematic or daily process for removing constraints. Indeed, in the case of case B, it appears that the make-ready planning phase was missing the constraint removal process, and the reason for this needs to be further investigated. According to a previous study, it is possible that using make-ready planning would raise the level of PPC (Hamzeh et al., 2015). LPS was applied in slightly different ways in both cases. On the other hand, this has already been observed in previous studies and is partly human; different methods are applied in different environments and situations, individually and in different ways (Dave et al., 2015). Thus, we cannot say with certainty that DAM as such has a direct impact on a better PPC level, especially when the use of LPS in these cases differs in terms of make-ready planning.

The authors recognise that the sample is small and not random; however, through this short article, it is possible to share the experiences of DAM in DM. However, our research should be treated with caution, as our results are based on a small sample that is not random and is in a limited geographical area. Also, a research design comparing two distinctive projects – in one case monitoring only one relatively small design team and a single design discipline and the other tracking the entire design team – is a significant limitation on the generalisability of our results. It is conceivable that DAM might be easier when the design team is small and limited to a particular design field. It is also possible that factors other than DAM influenced the low PPC values of case study B; however, the researchers did not find anything specific in their observations during the sessions that could be the reason for the low PPC value. In this study, PPC was the only measure that would appear to be affected by DAM, but further research is needed, for example, on what other variables are affected. For example, the effects of differences in constraint log usage methods and the effects of differences in team leadership practices would be interesting areas for further research. Therefore, even though utilising DAM would improve the reliability of the design, the generalisability of our results should be treated with caution, and to achieve better generalisability, we recommend that researchers conduct similar studies in other project environments and in different countries.

Hopefully, this short paper will encourage design managers to experiment with DAM together with LPS in future projects. The organisation of similar studies is relatively uncomplicated and fast to implement, so comparative studies should be expected soon. This study will be complemented in the future by interview studies, which aim to discover the in-depth views of the designers and other parties involved in the study on the effects of DAM on their workdays. Future interviews will also provide additional information on the specificities of the cases and possibly other factors that may have contributed to the differences in PPC levels.

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FINDINGS ON THE USE OF THE LAST PLANNER SYSTEM—A CASE STUDY

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ABSTRACT

The last planner system™ (LPS) is a production control method used in lean construction projects that has offered good results to construction companies in terms of improving labour productivity, increasing collaboration and the possibility for developing continuous learning. This short study contributes to LPS research on the reliability of promises and how parties perceive their effects on schedule and productivity. The study was conducted using a case study on an industrial construction project in which LPS had been in use since its start. Research data were collected using a semi-structured survey conducted online due to the pandemic. The study also utilized project progress data and measurement data from the LPS sessions. The most interesting result of the study was how little the LPS participants felt they had to compromise their goals. We also found how scheduling methods used in parallel with LPS can frustrate users and contribute to reducing its usefulness. Our findings can be used in further research in several ways, either by utilising the questionnaire we developed or by comparing our findings to other studies. We believe that practitioners using LPS will benefit from our results and can use them to address these shortcomings identified in future projects.

KEYWORDS

Lean construction, last planner, reliable promises.

INTRODUCTION

Project activities have become more complex over time, and this complexity is reflected in the complexity of construction-related tasks, the growing interdependencies between tasks, cultural complexity, and social complexity (Girmscheid and Brockmann, 2008; Luo et al., 2017). There are also more and more employees from different cultures in construction projects, and the number of participants in the projects has also increased and spread geographically compared to previous decades (Ochieng et al., 2013). Partly because of this, terms such as collaboration, decentralization, commitment and trust are increasingly used in construction research and applications (Alves and Tsao, 2007).

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Solutions based on these factors have been sought in this complex world of construction, and one of them is the LPS method developed with lean construction. The LPS is a collaborative and commitment-based planning system with should-can-will-did planning at its core (Elfving, 2021). First, 'should' refers to the phase in which sections of the master schedule that define what should be done are scheduled. Next, lookahead planning is based on what 'can' be done once the constraints on work have been removed, while weekly work is planned in the LPS through reliable promises to agree on what 'will' be done (Ballard et al., 2002). Finally, 'did' in the LPS is continuous learning based on identifying and eliminating the root causes of failed task planning on a permanent basis (Liu & Ballard, 2009).

At the heart of the LPS, transparency between parties is essential, as it enables reliable promises to other parties and the building of trust (Howell et al., 2004; Fauchier & Alves, 2013). However, trust does not arise in an instant and is a complex phenomenon (Lühr et al., 2021). Moreover, the reliability of promises regarding the use of LPS has been extensively studied. For example, Tommelein et al. (1999) emphasized the key role of owners, architects, engineers, and construction managers in enabling reliable promises and preventing unreliable workflows. Priven and Sacks (2015) examined 12 residential construction projects through an action study and found that the use of the LPS strengthened the social networks of professional trade crews. In their study of 26 projects, Fernandez-Solis et al. (2013) found that the use of LPS significantly improved workflow and communication between the involved parties. However, focusing on a reliable workflow and promises also puts pressure on individuals to make and keep these promises, which can also reveal conflicting organizational practices (Koskela et al., 2007).

One important motivator for the growing popularity of the use of LPS in construction is the pursuit of better productivity, which has also been extensively studied. For example, Ballard and Howell (1998) found that the use of LPS significantly improved productivity in several projects. Further, González et al. (2007) showed that a high number of reliable promises led to higher labour productivity, while Liu et al. (2011) identified a similar relationship between productivity gains and workflow reliability in pipeline installation crews using the LPS method. However, several factors may limit the positive development of productivity despite the use of LPS. One common constraint is high employee turnover (Shang et al., 2012). High employee turnover can have a detrimental effect on both reliable promises and continuous learning, which are the two main components of LPS. Another important factor in the productivity of construction work is employee satisfaction (Sageer et al., 2012). Interestingly, for some employees, the use of LPS is evidently painless, and labour productivity has improved, but for some, the use of LPS itself has had the effect of even resigning from their work (Kalsaas, 2012). Therefore, the use of LPS is not one-dimensional and free from fears, restrictions, and boundary conditions in the construction industry.

The use of the LPS requires the involved parties to be willing to negotiate and even compromise on their own goals for the benefit of others and the whole (Ballard & Tommelein, 2021). However, the emergence of such willingness in a project is often challenging, as Jørgensen et al. (2004) observed in their study: construction professionals may not understand the concept of lean construction and slip back into old roles; project members do not generate a willingness to share information, they do not compromise on their own goals, and they consider suboptimization instead of the overall performance of the project. Negotiations between the parties in front of the LPS tables require the ability of individuals to enter into social agreements. Priven and Sacks (2016) proposed social subcontracting as a solution to the problem. Their idea is to improve communication, mutual respect, and co-operation between the parties between the main contractor and the representatives of the subcontractors (Priven and Sacks, 2016). Using the process and artefacts developed for this, a written agreement is created to express an understanding of how the site will behave, how the relationship can be strengthened, and how this agreement will be monitored (Priven and Sacks, 2016).

The role of the project manager while using LPS requires certain mental model changes. In the LPS method, the project manager must transform from a traditional command and control management model towards a coaching management approach (Bach, 2014). To succeed during the LPS sessions, the leader should be able to create optimism, hope, resilience, and, above all, openness and trust among the participants (Fauchier and Alves, 2013; Bach, 2014). For example, if a leader is unable to transform and does not act openly and shows distrust in LPS sessions, it will inevitably affect the success of LPS (Priven and Sacks, 2016).

LPS also challenges the old roles of developing schedules and shifts the focus of schedule planning from that of a solitary planner to a collaborative huddle (Hamzeh, 2011). However, in reducing the level of scheduling to the required last-planners level, gaps in the flow of information to higher-level schedules (such as master and phase plans) have been identified. Furthermore, project managers or other schedulers have to spend a lot of time compiling the LPS data and dividing it into other schedules (Dave et al., 2015).

The use of LPS has achieved positive results in the construction industry in several countries (Daniel et al., 2015). However, there are also gaps related to the precision of LPS and the reliability of promises that have not been adequately addressed in previous studies. Accordingly, this article aims to fill the gaps related to the precision of LPS and the reliability of promises that have not been adequately addressed in previous studies. Nevertheless, we are aware that previous research has highlighted the connection between reliable promises and improvements in productivity (Ballard, 2000; Liu & Ballard, 2008). However, only a small number have used large industrial construction projects as their research objects; thus, our research is an additional contribution.

METHODS

The semi-structured online survey method was chosen for one Finnish industrial construction site where LPS has been in use for a year. A semi-structured survey, combined with the opportunity to provide free feedback, was found to be suitable for this short survey, as such a method is time efficient for both interviewees and interviewers and is not overly resource intensive (Allen, 2017). On the other hand, the disadvantage is that some potential participants inherently exclude these types of methods, and in that respect, the sources of information remain less rich than in direct interviews between individuals (Johnson & Braun, 2016).

The research proceeded in phases. In the first phase of the study, the author, who acted as facilitator, observed LPS sessions and documented them with photographs and his own free-form notes. Sessions were held weekly, and at the busiest stage, the sessions were divided into two different days. During the first phase, PPC measurement data were also collected in Excel spreadsheets. The final phase was to conduct an online survey and analyse the results of the survey.

Moreover, one of the authors of this study also acted as a facilitator of the LPS sessions and observed the behaviour and actions of the involved parties. The PPC values measured in the LPS sessions were also available for the authors and were used as complementary data in this study. There were also features of action research in the observation, as the facilitator himself participated in conducting the LPS sessions. However, this was not done in a methodologically systematic and structured way, so it involved participant-observer bias (Given, 2008). His observations were used in this study primarily to evaluate the results of questionnaires and examine the meanings of open-ended responses. This paper reports the findings related to observations, and future work will continue to develop an improved plan and action through the findings and reflection reported in this paper (Baskerville, 1997).

The choice of research subject was influenced by the fact that two of the authors were working on the project under study, making it possible to acquire available data for research use. The construction work on the aforementioned project was led by a construction management consultant, whose staff was integrated into the client's organization, which had the responsibilities of the main contractor. The subcontractors were responsible for their own sub-areas, and the contractual relations had been concluded directly with the customer. The contracts included an obligation to attend the LPS sessions, and at the beginning of work, short training sessions were held by the consultant for those with no previous experience using the LPS. The project's total gross area was about 200,000 m^2.

At the time of the study, LPS sessions had been used in the project for 10 months. Specifically, the LPS consisted of two parts: 1) master and phase planning and 2) make-ready and weekly planning as well as learning. However, master planning had already been done before construction began, while phase planning was largely tied to a traditional phase schedule without collaboration with contractors. In the model used by the CM consultant, the LPS was used for part 2, and each contractor began the weekly LPS sessions upon arrival at the site. Specifically, make-ready and weekly planning were done on physical boards using sticky notes, while learning took place through root-cause analyses, which were held separately. The principle of root cause analysis was that each individual deviation was not examined, but recurrent ones were examined in more detail to eliminate the root cause. All root causes were classified and discussed in front of the LPS boards, but the analysis was done separately in a smaller group after the session.

In addition to the LPS, the contractors used the traditional S-curve (i.e., the progress curve) and three-week schedules, which essentially had the same content as the LPS tables. However, in the LPS sessions, the emphasis was on presenting tasks that had an impact on the work of others. This means that in situations where the contractor had a lot of work in his area but no other contractor had worked there yet, it was agreed that the number of tasks would be limited to those with an impact on the vicinity of the contract area or those requiring coordination. The typical duration of the session was 30 minutes, but it could be within the range of 15–60 minutes, depending on the difficulty of the tasks to be planned.

A total of 93 participants in the LPS sessions were selected to participate in the survey. The survey was sent to the participants via e-mail. Additionally, in two of the LPS sessions, a QR code was distributed on a sheet of paper, allowing the participants to answer the questions on their mobile devices. To focus the survey questions on the research problem, the questions were divided into six parts as follows: 1) experience using the LPS, 2) level of detail of the schedule, 3) compromising goals, 4) staying on schedule, 5) reliability of promises, and 6) work productivity. The answer scale for the questions was compiled using a Likert scale. Space for free feedback was given at the end of the survey and did not require answering. The interview questions and answer options are presented in Table 1.

Table 1. Questions and Likert scale of answers

Q1: How satisfied have you been with the level of detail of the schedule established by the LPS?					
Likert scale for Q1	1 Very dissatisfied	2	3 Neither dissatisfied nor satisfied	4	5 Very satisfied
Q2: How often do you have to compromise on your own goals in an LPS session?					
Likert scale for Q2	1 Never	2	3 Sometimes	4	5 Almost always
Q3: How often do other parties have to compromise on their own goals in an LPS session?					
Likert scale for Q3	1 Never	2	3 Sometimes	4	5 Almost always
Q4: Compared to your other projects, how well have you stayed on schedule for this project?					
Likert scale for Q4	1 Very badly	2	3 Neither good nor bad	4	5 Very well
Q5: Compared to other projects, how well have other parties stayed on schedule for this project?					
Likert scale for Q5	1 Very badly	2	3 Neither good nor bad	4	5 Very well
Q6: The other parties give you reliable promises in the LPS session.					
Likert scale for Q6	1 Completely disagree	2	3 Neither agree nor disagree	4	5 Completely agree
Q7: How did the use of LPS affect labour productivity?					
Likert scale for Q7	1 Very negative	2	3 Neither positively nor negatively	4	5 Very positive

It should be noted here that while it was mandatory to answer the structured questions Q1–Q7, the option ‘I can’t answer’ was also available.

RESULTS

Overall, there were three general observations regarding the LPS sessions. First, at the beginning of the project, participants were fairly involved in the sessions, participation was active and planning issues were jointly discussed. However, as the project progressed, the facilitator observed mild frustration with the LPS method among the participants. This seemed to have started at the same time as the mechanical installation work, for which separate coordination meetings were actively organised between the construction and mechanical teams. In these meetings, some of the same issues as those in the LPS sessions were discussed, and they resulted in an aerial view of the area, which made it easier for contractors to mark their own weekly work areas.

Second, the representatives of the company responsible for the main mechanical equipment installations at the plant were very sceptical about the dates indicated on the LPS boards. This was increasingly observed by the facilitator, especially as the end of the 10-month follow-up period approached (i.e., when the volume of the mechanical installations began to increase substantially). Furthermore, at the same time as the observation, the LPS level also eroded significantly. Figure 1 below illustrates the diminishing development of the planned percentage completed (PPC) in one of the main areas of the site.

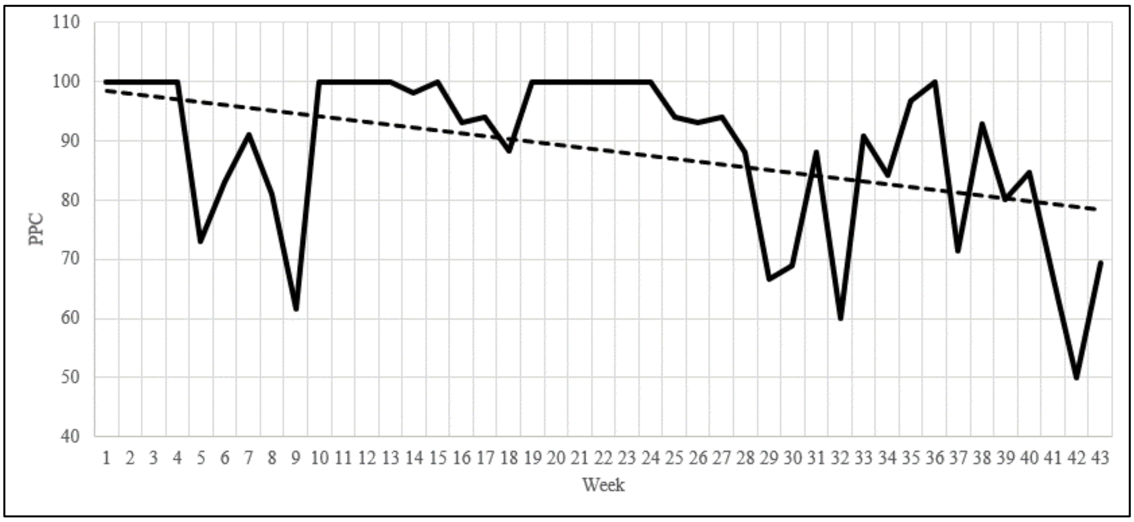

Figure 1. Decreasing PPC from one location as an example

The third observation relates to reliable promises. As the LPS sessions progressed, there was hesitation among the contractors regarding the tasks prepared by the others. Consequently, they began to postpone their own tasks to further away from those of the contractor performing the previous stage of work. In most cases, these findings were made using the information on the LPS boards, where it was clear that the contractors in the previous phase had not been able to keep their promises, and those in the next phase already had to postpone their own tasks due to a lack of reliability.

The interview survey was opened a total of 51 times, and responses were received from 19 individuals, which is a 16.1% response rate. The respondents were as follows: one foreman, three construction managers, three supervisors, seven responsible foremen, two site managers, two project managers and one site engineer. The majority of the respondents were well-experienced: 10 respondents had more than 20 years of work experience, three had 16 to 20 years, two had 11 to 15 years, two had six to 10 years, and only two had less than five years of experience. Of the respondents, one was an earthworks contractor, 10 were cast-in-situ concrete contractors, one was a prefabricated concrete contractor, and seven were other contractors. Moreover, 53% of respondents had previous experience with LPS, while 47% had none. Specifically, two respondents reported having used the LPS in previous project management contracts, two had used it at an industrial site and one at an infrastructure site. The results of the interviews are presented in Table 2.

Table 2. Survey results

Question	Min	Max	Average	Median	Std.dev.	Answers
Q1	2	5	3,3	3	0,7	19
Q2	1	4	2,2	2	0,8	18
Q3	1	4	2,5	3	0,8	15
Q4	2	5	3,6	4	0,7	18
Q5	2	4	2,9	3	0,8	15
Q6	1	4	2,9	3	0,9	17

Q7	2	4	3,2	3	0,8	15

Responses to the level of detail of the schedule were neutral. However, those to staying on one's own schedule were more positive (average 3.6) than 'perceptions of other parties doing the same (average 2.9). Respondents felt that, on average, they had to make a few compromises in their schedules (average 2.2), nor did they feel that other parties had to make substantial compromises (average 2.5). Nevertheless, they were neutral about reliable promises and the impact of the LPS on labour productivity. Comparing informants who had experience using LPS in previous projects with informants who had no previous experience using the method, interesting differences emerged. For example, for question 1, the group with no previous experience had a mean score of 0.6 points higher (3.0/3.6) and a median 1 point higher (3.0/4.0) than respondents with previous experience with the LPS method. Similarly, in question 5, the responses of these groups differed, and respondents with no previous experience using the method responded with a mean of 3.3 (more experienced group mean was 2.4) and a median of 3.0 (more experienced group median was 2.0). The groups also responded slightly differently to the reliable promises of the other parties (Q6); the group with no LPS experience answered the question with a mean of 3.2 (mean of the more experienced group was 2.6), with a median of 3.0 (median of the more experienced group was 2.5). In terms of labour productivity (Q7), the more experienced group also responded with lower means (3.0/3.4) and median (3.0/3.5) than respondents with no previous experience with LPS. In this response, more experienced responses also had a more variability than more inexperienced LPS users.

Free feedback was provided by nine respondents, and their open-ended responses are summarized in Table 3 below.

Table 3. Open-ended answers

Answer	Positive	Neutral	Critical
A lot of work has been done in other meetings and with other tools (memos, charts, to-do lists, sharing the traditional schedules). The LPS has been given a side role, although it could be the main tool. One reason is the impractical location of the LPS boards. Other coordination meetings could be held on the same board. The plan drawings added to the background of the boards are not quite enough to support the discussions. Maybe there should be a separate board on which the 'tightest' places could be added.			X
More post-it-notes should be included on the board.		X	
Underground pipeline design shortcomings / delays play a big role for every actor in the area in terms of cost and schedule.		X	
Six weeks is too long to evaluate as there will be so much change that such a forecast will not come true.			X
There were very few other contractors on the same board; for e.g., the benefit of the LPS has been negligible from the perspective of the contractor as it is being filled 'for oneself'.			X

From the point of view of the project manager, it is difficult to take a position on the survey. However, as an outsider, it appears that the LPS helps to better perceive the whole and ensures that no critical step is missed.	X		
That post-it-note 'doesn't work, it 'doesn't show the 'whole'. If a contractor does not stick to the agreed-upon schedule, then there is nothing useful in the LPS. No other schedules were seen in the sessions, and one could not properly compare the LPS to anything. I don't think it's a very good way to steer the project right now.			X
The LPS seems useless, and the S-curve is just OK.			X
There should be more post-it notes on the boards. Mechanical installations should also be included.		X	

As shown above, the open-ended responses were mainly criticism and neutral feedback. Specifically, the need to get more tasks on the LPS board was repeated in two of the answers. Similarly, two respondents stated that the LPS remains on the side lines due to the availability of other scheduling tools. The space reserved for boards, which is a construction site canteen, was also criticised in one response. Finally, two respondents specifically pointed to infrastructure work (piling and underground pipes) as a problem that was not adequately reflected on the LPS boards.

DISCUSSION

The most significant finding of this study was that the parties did little to compromise on their own goals and did not feel that others had to do so, either. This observation may indicate that they were able to negotiate a consensus during the LPS sessions that was acceptable to everyone and move forward in their work. The 'facilitator's observations, especially from the beginning of the project, also support this conclusion. This is in line with the findings of previous studies, such as Fauchier and Alves (2013) and Ballard and Tommelein (2021). In contrast, the results may also mean that the parties did not hold each other accountable and thus did not have to compromise on their own goals. However, this meant that they also did not have to resolve conflicts between the other 'party's goals and their own. Nevertheless, the observational findings suggest that during the session, the parties negotiated a compromise that everyone was able to work with in the following weeks and without having to significantly compromise on their own goals. Regardless, this can pave the way for more collaborative contract agreements that are beneficial for all parties (Chen et al., 2012). However, this requires further research and a more open-ended approach.

In terms of schedule, reliable promises and labour productivity, responses were neutral and similar to the observations of Power et al. (2021). When the open-ended answers were compared with those to the structured questions, the scheduling tools used in the project alongside the LPS seemed somewhat frustrating for the respondents and made the latter feel unnecessary as just extra work. It is also noteworthy that despite the long-term use of LPS among the civil contractors, its usage was adversely affected by the coordination meetings that began at the start of the mechanical installation, which partly overlapped with the LPS' agenda and therefore had a detrimental effect on 'its use. This may also be indicated by the 'facilitator's observations of a later stage of the LPS sessions, where overlapping methods were already in place and consensus-building or heated debate diminished, with the parties perhaps feeling that the session was no longer the' primary forum to coordinate ’schedules. These findings raise the following question: how does the use of overlapping systems affect LPS users? Earlier studies have suggested that the use of overlapping systems can confuse, frustrate, and impair the use of lean methods and often cause the return to previously used and familiar methods (Sacks et al., 2009; Simonsen et al., 2019). On the other hand, previous research proposes that even the partial use of the LPS improves workflow on site and that using it in combination with other methods does not impair site performance in light of research data (Priven & Sacks, 2015). Using overlapping methods can also impair group focus and performance. As the number of methods increases, mental activities become increasingly difficult and situational awareness of the ‘big picture’ becomes blurred (Rudolph & Repenning, 2002). The simultaneous use of several methods can also create increasing time pressure as the project progresses, which is normally experienced in projects, but when the time pressure increases sufficiently, it can impair group performance (Hansen et al., 2020). Future studies on this topic are therefore recommended.

Meanwhile, the authors did not see any signs of improved labour productivity or site performance in the responses, and this topic requires more quantitative data from the contractors. To improve productivity on a construction site, the manufacturing process must strive for optimal conditions. This is done by not only ensuring the presence of workers but also focusing on hiring the most skilled crew possible to perform tasks and ensuring optimal working conditions (Lindhard & Wandahl, 2013). However, in this study, although the LPS planning was done on a weekly basis, the flow of workers, materials, machinery, and space was not regulated or addressed in the LPS sessions, which was reflected in the open-ended responses, where most respondents criticized the use of LPS and doubted its usefulness.

Another factor that may have influenced the responses and criticisms about the use of the LPS among the interviewees was the general use of this system as a stand-alone tool without a broader understanding of lean philosophy (Hamzeh, 2011). As Hamzeh (2011) and Sarhan and Fox (2012) noted, the introduction of the LPS is not just in terms of its implementation as a tool in a project. Instead, it is necessary to change people’s thinking, ways of working, i.e., culture and enthusiasm to depart from the status quo. Moreover, in the LPS sessions, leadership has to nurture and support so-called ‘soft values’ that have been found to improve schedule reliability and thereby participants’ productivity as motivation, responsibility, and ownership increase (Lindhard & Wandahl, 2013). The responses of the interviewees contribute to the findings, as we found that there was little need to compromise on one’s own goals, and that several different schedule-related meetings and scheduling tools competed alongside the LPS, so there was no genuine shift in practices or culture towards the lean way of thinking.

On the other hand, the effects of social and cognitive phenomena were not the aim of this study, but the emergence of social agreements between participants in LPS sessions, for example, deserves further research. The importance of social agreements has been widely recognized (Gigerenzer & Hug, 1992), and their effects in social situations such as LPS should be studied. In particular, the importance of keeping reliable promises in situations where social contracts are violated (e.g. by cheating others) is an interesting topic for future LPS research.

CONCLUSIONS

Despite the small sample size of our research, we believe that our findings support those of previous studies on the challenges of using the LPS in project environments that focus on using individual tools rather than generating a lean culture. Additionally, our research also raised specific questions about how little the parties considered compromising their own goals in the LPS sessions. In this context, we suggest that further research related to the topic of compromising goals be carried out on projects where the LPS is used.

Moreover, our research findings cannot be generalized because the data was collected from only one Finnish industrial construction project. In addition, the small number of respondents relative to the number of participants in the LPS sessions may have affected the reliability of our study. Regarding the validity of the study, since the manner in which interviews were conducted and the kind of questions asked of participants are made clear, it is straightforward to repeat this study format in a different project. Further research on this topic would be of great help in understanding the challenges faced by LPS users.

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DEVELOPMENT OF AN EDUCATIONAL GAME TO TEACH INTEGRATED PROJECT DELIVERY PRINCIPLES

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ABSTRACT

Although IPD exists as a project delivery option especially for high complex buildings, the construction industry continues to use traditional approaches and methods for project delivery. The major barriers to the use of IPD are a general fear of change as well as a lack of knowledge and understanding. Educational games can be used to build knowledge and understanding. These games enable competence-oriented, experience-based, and motivated learning. Starting with the basics of game didactics, this paper describes the development of an educational game to teach IPD principles.

Existing educational games from the field of Lean Construction are used to convey an understanding of methods used in IPD. IPD cannot be reduced to a single method, the game developed takes a more holistic approach. Therefore, the game is intended to teach principles of IPD through experience-oriented learning and to show the necessary process of change that accompanies this type of project delivery. This is achieved by simulating a construction project that makes IPD principles easier to understand and more tangible. The participants independently gain experience in the field of IPD through active involvement and group reflection. The paper also includes experiences with first applications of the game.

KEYWORDS

lean construction, Integrated Project Delivery (IPD), action learning/research, educational game, live simulation game.

INTRODUCTION

Integrated Project Delivery (IPD) is increasingly gaining interest in some countries of Europe, such as Finland and Germany. IPD aims to optimize project execution as a whole so that projects are more likely to be completed with less conflict, within budget, and on time. To achieve this, IPD relies on, among other things, early integration of key stakeholders, joint risk management, and a joint incentive system aligned with customer

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goals (Ashcraft, 2010). In this paper, IPD refers to all integrated approaches to project delivery in construction projects.

Despite growing popularity, obstacles to the wider adoption of this approach persist. A major one is the general fear of change (Pishdad, 2012). Change involves the adjustment of behaviors and routines. It cannot be forced by simply providing information (Fench & Marrow, 1945). People need to be motivated to change (Steins & Haep, 2011).

Educational games represent an interface between the transfer of information and the implementation of theory (Thiele, 2020). In particular, we use the term "educational game" in the following to emphasize the educational nature. However, we still regard it as a synonym for e.g. "learning” and “simulation game". Applying or implementing theories generates motivation (Franken, 2019). Therefore, the goal of this paper is to describe the development of an educational game for teaching IPD. The educational game conveys the basic principles of IPD in a tangible way and thus eases the necessary change processes associated with IPD.

Figure 1 shows the approach used in our research. The following sections of this paper are based on this approach. The starting point of the investigations was a systematic literature research. Here, the aspect of the didactics of educational games was dealt with in particular. The development of an educational game is a creative process that requires innovative thinking. Therefore, two workshops were conducted. The participants in these workshops had different levels of knowledge in the field of Integrated Project Delivery. This creative process was structured with the help of the design thinking method. Through this, the needs of the client were put into focus (Osann et al., 2020). Clients in this case means the potential participants in the IPD educational game. The design thinking method is an iterative procedure for solving complicated challenges (Diehl, 2021). Workshops were planned and conducted using this method. Based on the results of the workshops, the educational game was developed and subsequently implemented and validated.

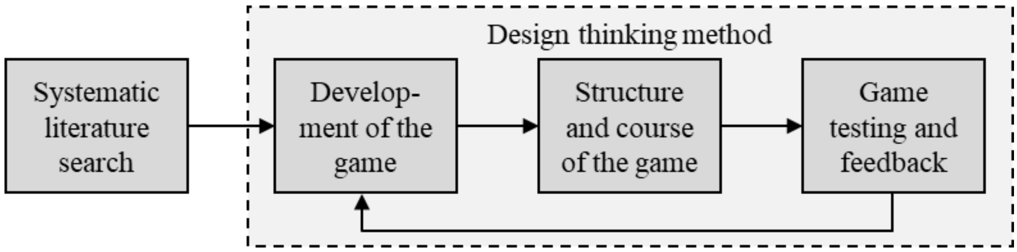

Figure 1: Game development approach

The game testing was intended to check the fit of the live simulation game with the requirements formulated in the research objective. The test was carried out with IPD experts as well as with IPD novices. This approach was chosen with the intent that on the one hand the experts check whether the necessary components of Integrated Project Delivery are taught, and, on the other hand, the novices check to what extent they build up competencies and an understanding of Integrated Project Delivery. IPD experts are familiar with the theory of this form of project delivery and have been or are involved in construction projects that have used Integrated Project Delivery.

DIDACTICS OF EDUCATIONAL GAMES

Didactics cannot be reduced to the science of teaching. It is a means for linking the contexts and structures at the level of the factual logic of a subject matter with the psyche of the learner (Siebert, 2012).

Learning is a cognitive process that is not immediately apparent from the outside. What can be observed is the behavior or action of the learner. The effects of the learning process are derived from these observations. From the pure observation of the learning results, however, no delimitation becomes apparent, what learning is concrete. There are different didactic ideas about this. One of these is instructional didactics. This says that the individual learning steps need in each case an impulse by the teacher. The teacher has a high proportion of speech and often intervenes in the learning process. The interaction with the learner is low (Hallet, 2009).

In the context of adult education, it is advantageous to place the topics to be taught in a concrete situational context. Especially for the teaching of behaviors, the learning content should be conveyed with the help of examples that relate to professional or social experiences already acquired by the learners. In this case, the learning process is perceived as meaningful by the persons, since the situations are personally known and the learning meaning becomes apparent. An important factor here is that the situations are perceived as realistic and authentic (Quilling & Nicolini, 2009).

In a simulated reality, as it is given in some forms of games, experiences can be gained without danger. A simulation aims to imitate elementary aspects of reality. Participants in the game can try out attitudes and strategies that are directly reflected upon (Kerres et al., 2009).

A simulation game has several characteristics. In general, situations are brought about, action decisions are demanded from participants and the effects of these decisions are examined. The setting can be based on a fictitious or real situation, and the objectives for the simulation are clear or implied. Participants are directly involved in the simulation and further development of situations is based on their actions (Holzbauer, 2008).

Figure 2 shows the correlation between the complexity of simulation games and the consequences for different parameters. With increasing complexity, the possibility of conveying larger amounts of information and depicting reality more accurately increases. The game stimulus also initially increases. However, the comprehensibility for the game decreases and has a negative effect on the game stimulus. The maximum learning effect for participants in a simulation game lies in a balanced relationship between the listed parameters. The complexity must not exceed a critical value, otherwise, the learning effect will decrease.

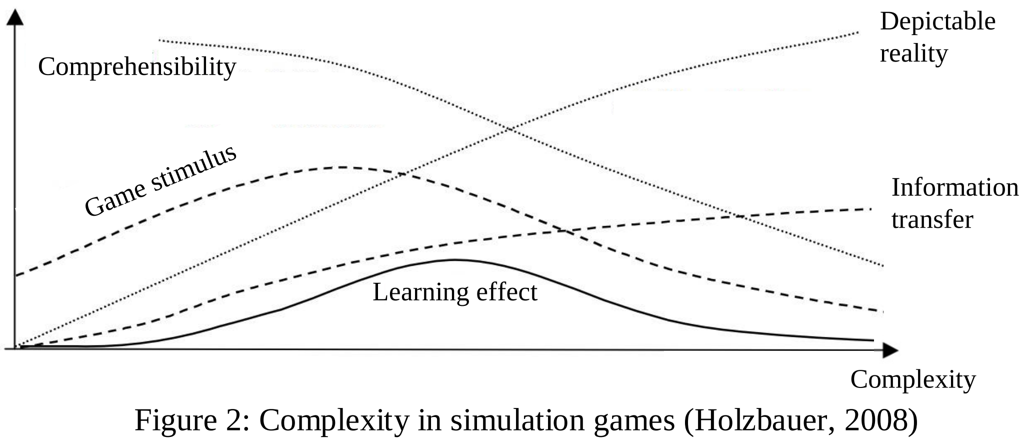

Figure 2: Complexity in simulation games (Holzbauer, 2008)

A simulation moves between a very abstract and realistic modeling. An exact representation of reality is not decisive in the learning of skills. The decisive criterion is an adequate didactic reduction of the real conditions. The model is brought into use and interaction by playful elements. The freedom within the interactions is given by the rules in the game and the defined roles (Kriz, 2011).

The necessity of a didactic reduction exists when there is a high complexity of facts to be taught. A reduction can be understood as a simplification. This must be done appropriately. The interdependencies and structure of the processes in the subject matter must be preserved (Weinberg, 1991).

The simulation of reality represents the first dimension of simulation games. The reason for using a simulation is that bringing about a real situation is not possible for time, cost or safety reasons. The second dimension is the game. In simulation games, not only is a reality recreated but a reality of one's own is created. This created reality is often characterized by a kind of competition and follows certain rules. The third dimension is the roles. Players take on roles of actors and can represent individuals, groups, or organizations (Kriz, 2011).

The general procedure of a simulation game is composed of three phases. In the instruction phase, also called “briefing”, the participants are introduced to the game. The contents include, for example, the framework situation, the roles, and the rules of the game. The game phase is the active element. The participants have to act and react out of their role and the associated mental background. They work independently and can make mistakes that remain uncommented from the outside. In the reflection and evaluation phase, also called “debriefing”, the experiences in the simulation are consciously worked through. The content and emotional experiences of the participants are reflected upon. Closing the simulation early after the game phase leads to a low level of competence building. Conscious reflection and evaluation in the group is an essential component for skill acquisition (Birgmayer, 2011).

Figure 3 shows the three phases according to Klabbers (2009) as a game circle. Within a game there is the possibility to repeat the phases if necessary.

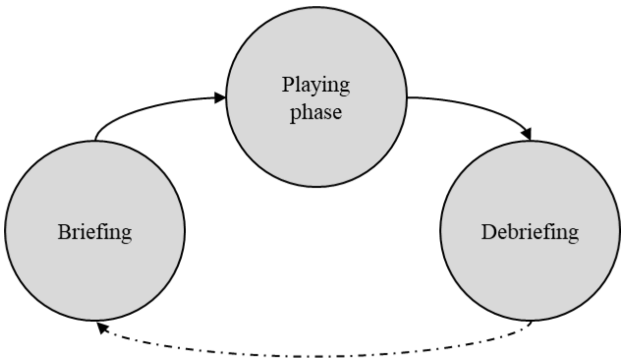

Figure 3: Simulation game course (Klabbers, 2009)

Interest concerning IPD and Lean Construction (LC) has increased over the last few years. Knowledge of LC is seen as beneficial in the construction industry (Forbes et al., 2018). Especially through the Lean Construction Institute or the Associated General Contractors of America, educational games such as the Airplane Game, Marshmallow Tower (Rybkowski et al., 2016) or the Parade Game (Tommelein et al., 1999) are used to teach Lean principles. Lean training with educational games also exists from within the Lean Community or in university settings (Tsao et al., 2012). The focus of the educational games is on LC or methods which are used by IPD. Playful learning approaches that are explicitly used for teaching IPD principles were not found during the research. This represents a research gap that this paper attempts to fill.

DEVELOPMENT OF THE GAME

OVERVIEW

The previous section dealt with the didactics that must be taken into account when creating an educational game. The game is a simplified representation of reality. In this case, it is the project execution with the help of IPD. A simulation game reality must be derived from this reality. In this reality, the structure of the educational game has to be defined and at the end, a detailed elaboration has to be created. This procedure is shown in Figure 4. The development can be divided into three steps. Each of these steps has a methodical focus. For the first two steps, two workshops were held using the design thinking method. In this way, ideas for the development could be generated and elaborated. After the workshops, the findings had to be translated into concrete game material. No further support from experts was required for the development steps described here.

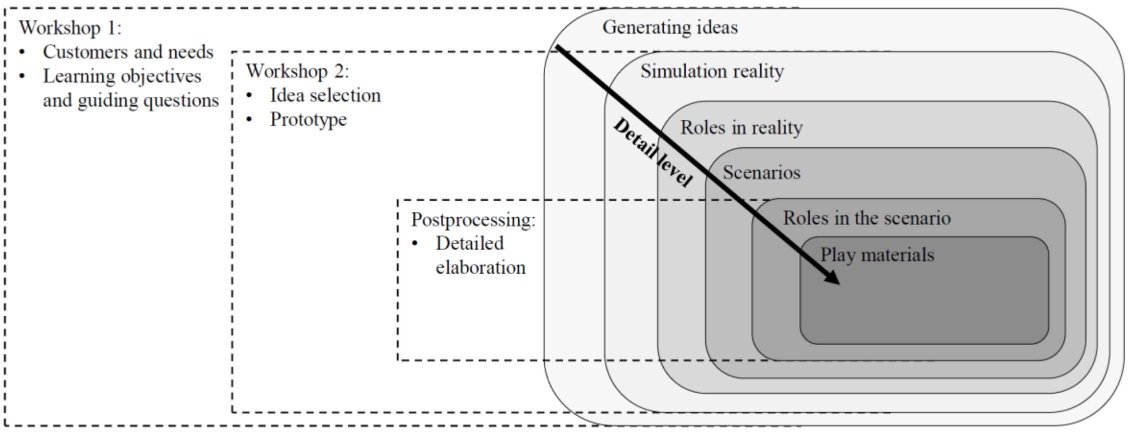

Figure 4: Approach to simulation game development

WORKSHOP 1

The overall goal of the first workshop was to generate ideas for the IPD educational game. The design thinking process was used in the workshop. The process can be divided into two sub-areas. The first is called the problem space, where primarily the challenge is investigated. It is specifically about understanding the problem, exploring it, and defining the core problem. The second area is the solution space. Here, creativity is a decisive factor. Ideas are generated, prototypes are developed and subsequently tested (Avenarius, 2012).

As shown in Figure 5, the overall objective for the first workshop is to capture the problem space, which is done in the first four steps, up to and including formulating guiding questions for the educational game. Furthermore, generating ideas is the first step in the solution space of the design thinking method.

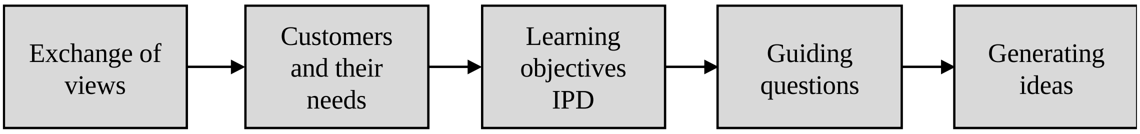

Figure 5: Procedure in the first workshop

Four experts with experience from IPD projects participated in the workshop. The workshop started with an exchange of views among the participants on the topic of the

IPD educational game. It became apparent that the workshop participants attach importance to the interaction of fellow players, the reference to practical examples of IPD and the use of an exciting implementation. A key statement from one participant is that an innovative project delivery model like IPD needs an innovative educational approach to teach its principles.

The next step was to identify potential customers of an educational game and their needs. It can be seen that the possible group of players for the educational game is large. For example, building owners, project controllers, planners, or contractors are represented. The fundamental needs of the users are to build trust in Integrated Project Delivery as well as the IPD team and to develop an understanding of IPD.

Based on the needs, the next step was to capture the learning objectives for an IPD educational game. Three learning objective clusters emerged. The cluster "IPD culture" includes learning objectives that are specifically intended to build trust. These include, for example, a "best for project" attitude, team building, and a collaborative attitude, among project participants. The cluster "multi-party contract" is a collection of learning objectives related to establishing an understanding of Integrated Project Delivery. These include, for example, the compensation model and decision and conflict management. The third cluster is the organization in IPD, for example focusing on the organizational structure.

In a further step, a guiding question for the IPD educational game was formulated for each cluster. The guiding questions are "How can the culture be actively experienced so that the participant builds trust?", "How can the functioning of the most important parts of the multi-party contract be experienced so that the participant understands it?" and "How can the processes and responsibilities in the different groups of the organizational structure be communicated so that the participants are aware of their task in the respective group?"

The guiding questions are a support for the subsequent idea brainstorming. The implementation of the educational game should answer the guiding questions. In addition to more detailed approaches for the educational game structure, such as the use of marble runs, the Froebel tower or Lego building blocks, three general approaches were identified:

- A learning simulation that teaches all IPD elements
- A modular structure of the game with individual teaching modules for elements of IPD
- The use of an adventure game as a teaching environment, such as an escape the room game, set up as a fixed or modular educational game

WORKSHOP 2

The results of the first workshop served as a basis for the second workshop, in which the design thinking process was continued. The aim of the second workshop was to select the general approach for the realization of the IPD educational game and to develop a prototype.

Two experts with experience from IPD projects and the application of simulations participated in the second workshop. In the beginning, the advantages and disadvantages of the solution approaches were discussed between the participants in the workshop.

The discussion on the choice of a fixed or modular setup is complex and a consensus is not available. One argument in favour of a fixed structure, for example, is that a standardized educational game consistently teaches participants the essential IPD elements. A modular educational game can be tailored to the wishes of the customer as well as to intended learning goals and thus be adapted as a product to the user.

In the discussion, ideas were considered which contained elements from the three general approaches. The educational game should have a fixed standard structure and be supplemented by modular elements. In the educational game, a common goal should be focused on by the participants, like in an escape the room game. A limiting decision towards one of the three general approaches becomes unnecessary by combining elements of the different approaches. A specific educational game approach was sought that meets this requirement.

The live simulation game was identified in the discussion as a form of game-based teaching. After a joint discussion of the live simulation game concept, this teaching and learning form was determined for the further procedure in the development of an IPD educational game among the workshop participants, since the required characteristics can be realized with it.

In the next step, taking into account the guiding questions for the educational game collected from the previous workshop, the cultural, organizational, and comprehension learning objectives for the simulation game were formulated. In the following, the most important learning objectives that were jointly recorded and discussed in the workshop are listed:

- Cooperation: Fast and open communication of information that only individuals possess
- Cooperation: Solution-oriented instead of searching for the guilty → "No blame culture"
- Cooperation: Appreciation for the perspective of the other → Interdisciplinary work
- Cooperation: Even in IPD there are conflicts
- Transparency: This leads to trust and better solutions
- Reflection: Recognizing the need to work on team behavior
- Compensation model: How the joint incentive system works
- Entrepreneurial action: Making "best-for-project" decisions and deciding under uncertainty
- Product optimization: Within the framework of the Conditions of Satisfaction (CoS), optimizations are desired
- Interests: Conflicting interests of the client and the other partners, especially in the validation process
- Creative role of the Project Management Team (PMT): The PMT has to create the conditions for successful work

DRAFTING

After the second workshop, the results were transferred into a concrete live simulation game. An example project for the game was being sought. The construction of a "Tiny House" represents a normal building project, only on a smaller scale. Taking up and transferring conflict scenarios from reality into a Tiny House project within the live simulation game seems to be possible. The didactic reduction seems to make sense and the idea is pursued further.

One goal in the live simulation game is that the players are mentally immersed in the project and that IPD can be experienced. This is realized through visualizations of the construction project and an exciting game story. A three-dimensional Tiny House model is built as part of the simulation development. Figure 6 shows an example of the exterior view of the model. The further structure of the simulation is presented in the following section.

Figure 6: Tiny House Model

STRUCTURE AND COURSE OF THE GAME

The framework of the simulation is the project "Construction of a Tiny-House". The construction project is carried out using IPD. The participants in the simulation are part of the PMT of the project. There is one owner, one architect, one interior designer, one timber constructor, and one interior constructor. Figure 7 gives an overview of the game process.

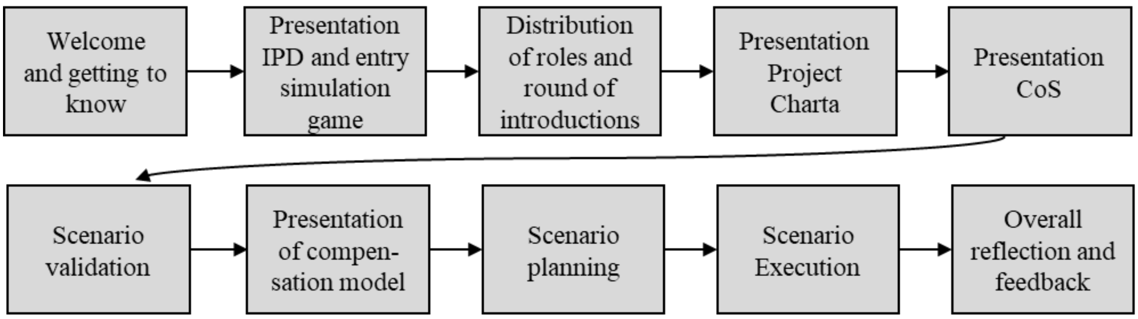

Figure 7: Simulation game process

With the PMT, the project is realized through the phases of validation, design, and execution. The simulation takes place in the "Big Room" of the Tiny House project. Materials exist for the visualizations in the simulation's seminar room to set up the Big Room. These include the Project Charter and the CoS for the project. Over the course of the project, additional visualizations and content are gradually presented in the Big Room. Five fixed roles exist in the project. Role cards for the five members of the PMT exist for the simulation. These cards contain general information about the person being played. Up to a number of participants of nine, all roles are doubled except for the owner of the building. From a number of ten participants, the simulation is implemented in duplicate.

There are then two teams that run the simulation in parallel. Two parallel visualizations of the course of the project are then displayed on two opposite walls. In addition, up to two observers can be used. The observers have the task of neutrally evaluating the course of the scenarios in the reflection rounds.

For example, a fictitious scenario is explained to the participants halfway through the validation. Individual roles are given additional information about the scenario that not everyone has. The PMT, as the administrative lead in the project, is tasked with solving the problem. Scenario and role cards exist for the individual scenarios. Situations are formulated on the scenario cards that initially cause problems or further conflicts in the PMT and are to be solved together. Furthermore, there are scenario-specific role cards with individual information about the scenarios and general information cards, where, for example, the learning objectives and possible reflection questions of the scenarios are recorded.

Over the course of the simulation, participants are given information about the project so that they can become familiar with it. At certain points in the course of the project, the PMT is presented with challenging situations.

After the participants have solved the problem, or after a certain time, the scenario is ended and a reflection round is held. The participants can reflect together on what impressions they have just experienced.

Afterwards, the facilitator continues to explain the course of the project until the next challenging situation occurs, for example in design. At the end of the simulation, an overall reflection is conducted with the participants to reflect on their impressions and experiences.

Figure 8 shows an example scenario. This scenario deals with risk management in the design phase of IPD projects. The learning objectives addressed to the participants in this scenario are the compensation model, entrepreneurial action, product optimization and the creative role of the PMT.

Scenario Card	Timber construction Enke
Risk management in planning We are in the IPD planning phase. In the validation phase, the Base Target Costs were determined on the basis of benchmarks of comparable products. Due to the high demands on weather conditions and approvability abroad, a reserve was formed in the risk/reward pool. In order to eliminate the risk in design phase, decisions are needed regarding insulation properties and other requirements for the structure.	**Risk management in planning** You saw a risk in the predefined floor construction and put an additional risk position in the risk/reward pool besides the benchmark value for the standard floor construction. The owner and architects should make decisions. The Project Implementation Team (PIT) - floor and wall construction cannot continue their design work until a decision is made. The PIT has given you two general options.

Figure 8: Example scenario in design

The IPD project and the process at PMT level provide the standardized setting for the educational game. The induced conflict situation forms the modular part and can be integrated into the game play depending on the learning objectives to be conveyed.

GAME TESTING AND FEEDBACK

The educational game has been conducted twice so far. Five people with experience from IPD projects participated in the first trial run. For example, the participants jointly developed a project charter and discussed individual problems as PMT within the simulation (Figure 9). The participants were able to identify a learning effect and only made individual suggestions for adapting the scenarios and role cards. The structure of the educational game was perceived as very good.

Figure 9: Game testing; Project Charter (left); discussion among participants (right)

The second simulation was carried out with people who had no previous experience with IPD. This showed a great learning effect. Based on the previous test runs, no further adjustments to the simulation are therefore necessary.

CONCLUSIONS

An innovative project delivery model like IPD needs an innovative educational approach to teach its principles. The innovative character of the developed IPD simulation game is shown by the combination of fixed and modular elements as well as fictional and reality-based components. Participants are supported by the moderation immersed in an IPD project wherein they are provided with a safe learning environment. They are given the opportunity to actively and independently from their actual company affiliation perform actions in the context of IPD without fear of consequences beyond the game. Over the course of the project, the change of mindset and processes associated with the use of IPD will be explained to the participants and visualized in a Big Room. Trial runs to date suggest that this goal can be achieved with the developed educational game.

The game is a snapshot. It needs to be continuously improved following the lean philosophy. For future developments, it would also be helpful to carry out basic research in advance on the legal and regulatory peculiarities of IPD in the respective country and the performance of IPD, so that an educational game can pick up on these. In addition, it would be useful to learn more about the functioning and interplay of IPD principles as part of further projects.

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DECREASING WASTE IN MECHANICAL, ELECTRICAL AND PLUMBING WORK

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ABSTRACT

Eliminating wasted effort is an important part of lean philosophy. Waste has typically been measured with time sampling or time motion studies, where the share of direct work is estimated. However, few studies have taken the next step and investigated the root causes of wasted effort. This paper reports the results of an extensive time and motion study and focuses on qualitative evidence on the root causes of wasted effort. 15 MEP workers and foremen on four projects carried a helmet camera for one calendar week and quantitative time-motion analysis was done based on these videos. All participants were interviewed, and video footage was reviewed together with the participants to evaluate root causes of waste.

The root causes of wasted effort were poor communication, issues with production planning and control, uncoordinated design, poorly organized material flow and a high share of preparatory work steps. The best direct work share was achieved in the only project which implemented takt production even though it was also the project with least repetitive work and largest distances due to large floor area. The biggest impact could be achieved with better constructability of design which would also enable just in time logistics and greater share of prefabrication. The results could be used to convince practitioners to adopt lean principles.

KEYWORDS

Lean construction, waste, workflow, time-motion study

INTRODUCTION

Eliminating wasted effort is a critical part of lean philosophy (Koskela 2000). Seven waste types have been introduced in lean literature (Santos et al. 2006) and lean construction researchers have proposed new ones such as Making-Do (Koskela 2004) and unutilized talent (Ansah et al. 2016). Waste can be eliminated by making sure that tasks have sufficient preconditions (Koskela 1999).

Waste and productivity have been often researched with the use of work sampling methods. Work sampling evaluates quantitatively the share of direct work and other types of work (Neve et al. 2020). Although time sampling can estimate the share of time spent on non-value adding activities, significantly less effort has been spent on studying the root causes of wasted effort. Time and motion studies have been used as an alternative approach and can also identify wasted effort and investigate root causes (Demirkesen et

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al. 2020). However, most reported time and motion studies have not approached the classification of time using lean concepts, such as waste categories and preconditions.

In this paper, our aim is to present findings on root causes of non-value adding work and the potential impact of lean interventions. These findings could convince more practitioners to adopt lean methods. The research is based on an extensive time and motion study, and focuses on mechanical, electrical, and plumbing (MEP) trades which have often been regarded as complex and have shown low share of direct work. The study aims to answer two research questions: 1) What are the root causes of wasted effort in MEP work in building projects and 2) What is the estimated productivity impact of lean interventions which target the identified root causes?

WASTE IN CONSTRUCTION

Transformation-Flow-Value (TFV) theory provides theoretical foundation to lean construction (Koskela 2000). In addition to looking at the efficiency of transformation, the theory recognizes the need to have better flow and increased value to the customer. Traditional ways to improve productivity have mostly focussed on increasing the efficiency of transformation, e.g., by developing means and methods or investing in automation to remove human labour. The flow view to productivity seeks to decrease the share of wasted effort which typically happens at the interfaces of transformation activities (Bertelsen et al. 2006).

Typically, transformation activities have been labelled as direct work (DW) in work sampling and time-motion studies. Higher share of direct work has been shown to correlate with productivity both on project level (Thomas et al. 1984) and on industry level (Neve et al. 2020). Although direct work is rather consistently measured across studies (Gong et al. 2011) research about waste is focused on analysis of categories which are not direct work.

Waste has been categorized by Ohno (1998) to seven different categories: overproduction, waiting, unnecessary transportation, unnecessary movements, over-processing, inventory, and defects. In construction context, Koskela (2004) added the waste of “making-do” – starting work without prerequisites. Although waste categories are often cited by researchers of lean construction, to our best knowledge they have not been used in work sampling or time motion studies. This is probably because waste can only be seen in context and work sampling classifies actions based on snapshots, taken for example every 5 or 15 minutes (Jenkins & Orth, 2004; Kalsaas 2011).

Another thing missing from previous time sampling studies is the analysis of prerequisites which is required to identify some forms of waste. It is understandable, that time sampling studies would not be able to identify missing prerequisites because they focus on snapshots. To know what the worker is missing when he cannot perform direct work, a longer sequence of events needs to be followed – i.e. what does the worker do next when direct work stops. Our interest in this research is to fill these gaps by not just classifying time into categories, but also observing longer sequences of work, allowing us to categorize missing prerequisites and the eight wastes. By doing that, we can estimate the impact of lean interventions, which typically attempt to increase the probability that certain prerequisites will be present at the right time when the worker is about to start a task.

METHODS

To get a broad understanding of wasted effort, several methods were utilized to get both quantitative and qualitative data. The main method was a time-motion study of 15 MEP workers and foremen, and a continuous survey of constraints and challenges experienced by the workers. The helmet camera study was conducted on four different projects with different characteristics. The research was carried out in spring 2021 and observation period was one calendar week per worker. Afterwards, each participant was interviewed. Clips of helmet camera footage were shown and the workers explained in their own words what happened in the footage, validating classified data from a workers perspective as well as developing a deeper understanding of connections between activities, waste and prerequisites. They were also asked whether their experience from the researched project and week differed from what they would consider a normal project and normal week, and for their opinions how to improve MEP productivity and key challenges related to their work.

At the time of this study, 170 hours of helmet camera footage have been analyzed in detail out of the total of 411 hours of collected video material. Time-motion data from helmet cameras was analyzed quantitatively by categorizing worker actions. In addition to classifying the time into categories, missing prerequisites and waste types were also identified from video footage. They could only be identified by looking at a longer sequence of events. For example, a typical issue was stopping work and moving away from the workplace. Video footage made it possible to see why the worker left the location and what was missing. Sometimes he went to look for materials, or tools or help from a supervisor. With longitudinal analysis of videos, it was possible to determine the missing prerequisites and determine why the work stopped.

In addition to video analysis, interviews were used to find out root causes for low productivity and propose recommendations. Root causes were identified by observing reasons why workers were engaged in non-value adding activities or why they wasted effort when doing direct work. This was determined mainly by reviewing the time-motion study classifications and by qualitative analysis of video material, confirmed with discussions with the workers. Quantitative evaluation of the impact of each cause was estimated by the share of time workers spent on a wasteful activity. Based on identified root causes, the potential impact of lean interventions were evaluated.

Projects available for study were limited due to the COVID-19 pandemic. Several candidate projects could not be studied due to COVID exposures on the project. Even though labor unions supported the study, finding consenting participants was challenging, especially due to additional stress caused by COVID-19 and need to catch up schedules on several projects. Therefore, the studied projects and workers had to be selected based on availability. The projects were all new construction. Two of them were residential construction, one was a hybrid hotel/office building and one was a large retail mall. Table 1 shows the key aspects of studied projects.

Table 1: Features of studied projects

	Residential 1	Residential 2	Hotel/office	Mall
No. of buildings	2 stairwells	1	2	1
Floors	6	5+1 underground	8+2 underground	5+2 underground
Size	7 023 m2 (79 units)	4 023 m2 (70 units)	12 000+ 10 000 m2	135 000 m2
Repeatability	High	High	High	Low
Lean implementation	No	No	No	Yes
Special notes	Normal residential	Design changes, modular bathroom	Major COVID-19 schedule delays	Takt production, minor COVID-19 delays

RESULTS

CLASSIFICATION OF TIME, PREREQUISITES AND WASTE TYPES

The quantitative analysis of time classification revealed that actual installation work was rare and fragmented. The electricians had slightly higher share of direct work (24%) while the plumbers and HVAC installers had just 15% share of direct work. The largest differences between trades were in discussions (electricians 7%, plumbers 16%) and in logistics related activities – namely hauling and searching (electricians 11%, plumbers 17%). The overall results for electricians and plumbers are shown in figure 1. When looking at project differences, the projects with delays (hotel/office) had a significantly higher share of discussions than other projects for both electricians and plumbers.

Most of the missing prerequisites were related to missing materials or parts. Residential 1 had well organized logistics, with materials on wheels, which can be seen in smaller share of missing materials and equipment in that project. All projects except the retail mall suffered from many interruptions caused by preceding work. This gives an indication about the benefits of takt production which was used in the retail mall but not in the other projects. Figure 2 shows the missing prerequisites per project.

90% of the wasted effort identified in the study could be explained by missing prerequisites. For example, movement represented 53% of the waste observed, and 83% of movement could be explained by missing prerequisites. Waiting was 20% of wasted effort and missing prerequisites were identified for 83% of cases related to waiting. Also waste types transportation (9%), defects (9%) and inventory (5%) were often associated with missing prerequisites. Delays in predecessor tasks led more often than other prerequisites to waiting, making-do and defects. Missing material very rarely led to waiting but was seen mainly as movement, transportation and searching from storage areas. Missing design information led more often than other prerequisites to overprocessing (additional work steps), movement and defects.

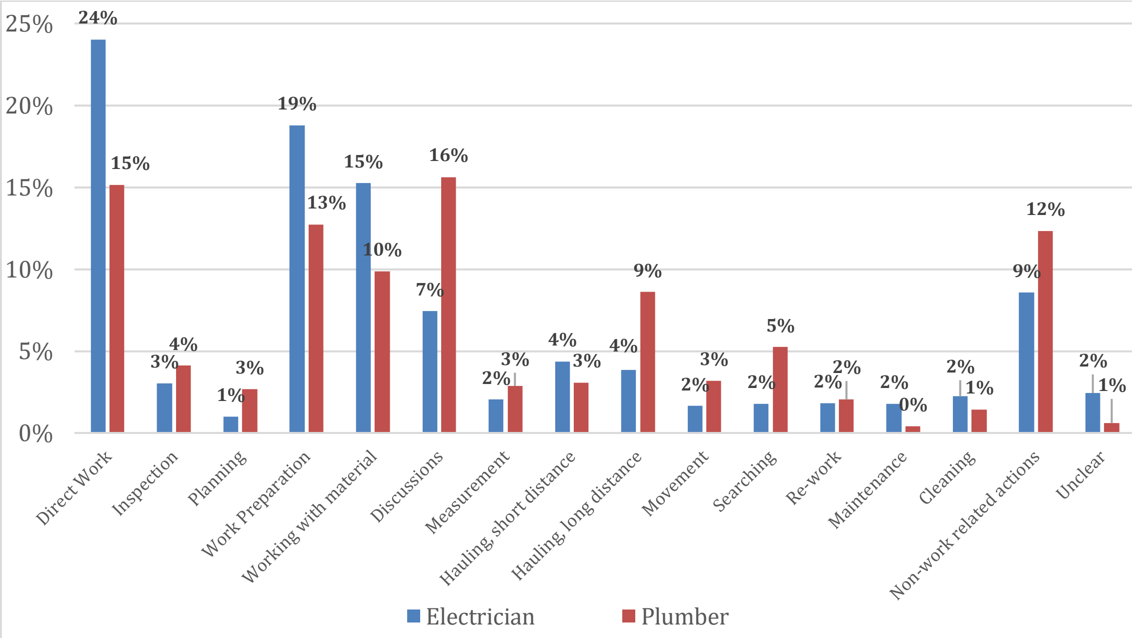

Figure 1: The share of time in different activities for electricians (blue) and plumbers (red)

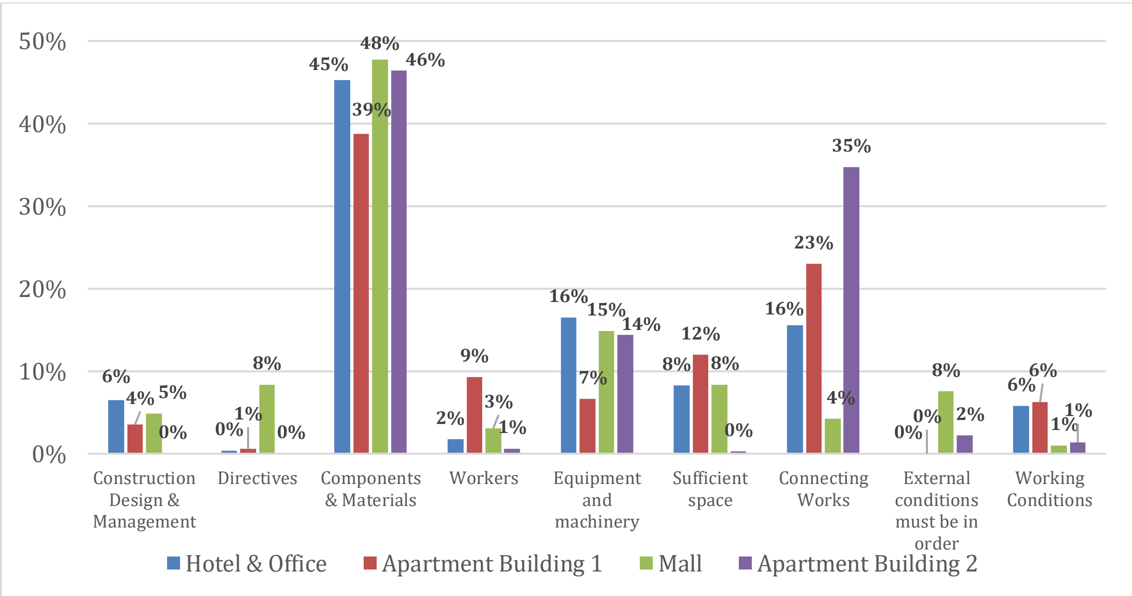

Figure 2: Share of missing prerequisites per project

ROOT CAUSES OF WASTED EFFORT

Based on quantitative data, interview results and qualitative observation of videos, five main root causes of wasted effort were identified. Generic root causes were related to communication, production planning and control, material logistics, design and the share of preparation work on site. In addition, several task-specific root causes were identified but due to space constraints, only the generic root causes are discussed here.

Communication

Much of the discussion happening on site was because the installers did not have enough information about their tasks. The overall understanding of the process was missing. The participating installers did not know what their part in the bigger picture was, and they did not know the impacts of their work. This led to hurried installations where another contractor needed quickly some work because they were closing a wall or pouring a floor. Missing information about dependencies was frustrating to installers and clearly led to wasted effort (especially discussions) in helmet camera data.

Interviews highlighted long and complicated command chains. For example, it was often faster for an electrician to make penetrations themselves rather than figure out how to get someone else to do the work. The installers did not know who to contact when encountering different types of problems. Problem solving took a long time or did not happen at all.

The importance of communication is shown by the large share of time spent on discussions. Because the sound was not recorded due to privacy concerns, interviews were used to get an understanding of the content of discussions. Although most of the discussions are within the own crew to coordinate tasks and materials or social discussion, significant share of discussions was coordinating work sequences and design with other trades. The share of discussions increased in the delayed project (hotel/office) because it was not clear how to catch up delays and the General Contractor's schedule did not help in coordination. The share of discussion was high in the other residential project because there were a lot of design changes due to modular bathroom pods of which the project team had no prior experience.

Production planning and control

The success with production planning and control had a significant impact on productivity. A large part of missing prerequisites was related to preceding works not being ready. The participants were frustrated about the deficiencies in production planning and control. The schedules used by General Contractor were not detailed enough and were not updated when there were delays. This led to the finding that installers are unable to use the official schedules. This was not a big problem for electricians who always had some other work to do if they could not do the scheduled work. Plumbers were struggling because they need very different materials for different tasks and locations, and they were unable to predict upcoming work and order required materials. Many installers were not aware of any schedule goals or deadlines, especially in projects with delays.

The difference of the shopping mall project which used takt production to other projects was very clear. Even though the project was less repeatable than others and installations were more complex, there were less delays caused be preceding tasks. The video footage showed a much more systematic process. Although the installers still thought that there was room for improvement, the differences to other projects were clear. The results also impacted the share of wasted effort. The largest and most complex project had the highest share of direct work, even though the distances were much longer than in other projects. Although the share of material hauling was larger in the project, the share of discussions was the lowest and explained best the increase in direct work.

Projects that did not use takt did not experience productivity losses dues to trade stacking. However, out of sequence work was constantly happening. Workers were jumping from task to task and had a lot of emergency work which led to disruptions of work.

Logistics and material management

Missing materials and equipment were the most common missing prerequisite. Material storages were far away from the work location in all projects. Interviews of plumbers revealed that material management is one of the biggest waste causing factors from their point of view. It should be noted that although the COVID-19 pandemic has caused increased material prices, none of the workers experienced lack of materials due to unavailability. Missing material was typically stored elsewhere or had not been ordered.

Plumbers were struggling with material management because if designs are not constructible, each improvised installation requires different materials (e.g. different angles of pipes). Material storages were not organized according to 5S principles and it was difficult to find the right material. There was one notable exception, in a residential project where an HVAC foreman spent working time to organize the storage. That crew had lower material hauling and searching times than other workers in the research.

Electricians had slightly different types of problems. Their material needs most often happened due to surprising and urgent assignments, which happened often based on the helmet camera footage and interviews. Electricians are often last in sequence and they are struggling with the materials of other trades which are blocking their scissor lifts and ladders. Much of the hauling time of electricians was used to move materials of other trades out of the way.

Design quality

Design quality and coordination was the second biggest concern of participants. All participants agreed that designs on Finnish projects do not consider constructability. There were often clashes in delivered BIM models. More common were problems where the designers had not used the actual parts available to installers. Hangers were missing from design, and often cable trays were designed right below large HVAC ducts, which is either impossible or very time consuming.

These deficiencies caused a lot of design discussions and improvisation on site. Detailing happened on site in collaboration with other crews. Deficiencies in design rarely prevented work but led to discussions, inspections (getting shared understanding) and improvised installations increasing the fragmentation of direct work. Design problems had cascading effects because improvisation also caused material-related problems.

Work preparation on site

Preparing for work and organizing materials took more time than the actual work in all projects. Productivity could be increased by decreasing the share of preparation work. Preparation included all material movements and organizing in the workplace (less than five meter distance). This took a long time and was inefficient. Several preparation tasks observed from videos could be done centrally and before the workers come to site. Short, less than five meter movements related to preparation took a large share of the installation time.

POTENTIAL IMPACT OF LEAN INTERVENTIONS

Several basic lean interventions from past lean research could be used to tackle the root causes. The proposed interventions to tackle the root causes are quite familiar to attendees of IGLC, so they are presented briefly, focusing on the estimated impact. The benefit of quantitative analysis is to estimate the impact of different interventions, and present data that can convince companies to make systemic changes.

Detailed MEP design and improved coordination

Design tasks have been successfully moved away from site in all construction markets where MEP is prefabricated (e.g. the USA, the UK, Australia). Typically, this has been done by giving more design and coordination responsibility to the supply chain so that they can prefabricate. Detailing and coordination on detailed level is done by workers from the trades. In Finland, there has been less interest in prefabrication because the workers work on a piece rate system, and negotiations about prefabrication with labor unions have been difficult. However, the study revealed that investing more in design could have significant benefits in addition to prefabrication.

Based on the study results, it can be estimated that proper detailing and coordination of MEP systems could increase installation time by four percentage points. Resolving most of design issues before on-site work could halve the discussions, decrease searching for material and decrease waiting. Productivity benefit for on-site work could be thus around 20%. Part of the saved hours must be invested up front in detailed design and coordination but naturally resolving problems virtually before going on site would take fewer hours than improvisation on site.

The role of improved logistics

The time spent on searching and hauling materials was a large part of the worktime (electricians 10%, plumbers 17%). Several interventions have been previously proposed in lean literature. They range from simple ("everything on wheels") to slightly more complex (5S principles) to complex (logistics service, kitting, just in time deliveries). Based on the quantitative results, some estimates can be given of potential productivity gains.

Easily movable material storage ("Everything on wheels") was shown to be beneficial in one of the case studies where workers had improvised such a storage – there the time spent on getting materials was notably smaller than in other comparable projects. Workers on other projects had also suggested similar innovations to their employers but their concerns were not heard. Based on the analysis of video footage, it can be estimated that hauling time would be reduced to 75% of current time, which would result in a 10% productivity improvement for plumbing and 5% productivity gain for electricians.

5S principles would eliminate a lot of searching through better organization of storage areas. It could be estimated that searching could reduce to 25% of current time. This would help the plumbers a lot due to their varied materials and could add 1 percentage point to their direct work.

If kitting and just in time deliveries could be implemented, at least half of the hauling performed by workers could be eliminated. This could add 3 percentage points to the direct work share of plumbers and 2 percentage points to electricians, and therefore major productivity gains. However, to be able to estimate exactly the materials needed in each work area, the design should be better coordinated first, and also the schedules need to be better controlled. For JIT deliveries, the process needs to be more stable.

Increased prefabrication

MEP elements are being prefabricated in several construction markets. Previous reports about the US market have shown that productivity benefits of prefabrication have been large (Khanzode et al. 2008) but companies have needed to invest in prefabrication capacity. Currently, the Finnish contractors are not ready to invest in capacity but in the short-term prefabrication could happen in a centralized location on site where all the required materials and tools are in the work site. Especially preparing ceiling installations on ground level could improve productivity significantly. However, before any increase in prefabrication becomes possible, the issues with detailed design and coordination must be solved first.

Production planning and control

The workers could not use the schedules of the project to understand what to do next. The schedules were not up-to-date and were not followed. On one of the sites, COVID delays had led to a major schedule update which had lasted for seven weeks – during that time there was no usable schedule on the project. This led to major improvisation and coordination among the trades. For most workers, this was acceptable and normal but there was a lot of stress on crew foremen who had to coordinate material deliveries and orders without being able to plan ahead sufficiently.

The impact of good planning and control becomes clear when the retail project with takt production is compared with the other projects. The project had very few issues caused by missing predecessor tasks. The qualitative analysis of video material showed a clear difference, and a systematic process while other projects seemed chaotic. Interviewed installers on the shopping mall project said that the biggest issues on that site were logistics due to the large size of the project and fragmented storage area but did not emphasize schedule related problems. The share of direct work was 25% in the shopping mall and just 14% on the hotel/office project which did not have a functional schedule at the time of the research. The largest differences were in the amount of discussions required (mall 5%, office/hotel 17%). Some productivity was lost due to larger amount of hauling on the shopping mall project.

However, there is still a lot of room for improvement. Although the Last Planner System is widely used in Finland and even in participating companies, there was no evidence of involving the crews in production planning on any of the projects. All interviewed workers were eager to participate and provide their expertise, but the schedules were still planned top-down and often missed the details required by workers.

Communications

Based on qualitative analysis of the videos, communication was not structured with continuous meetings (such as daily huddles) but happened when required through WhatsApp, phone or face-to-face meetings. All participating workers agreed that crews should have daily or weekly meetings where work is coordinated rather than interrupting work to do coordination every time there was an issue. It is difficult to provide a quantitative estimate of the benefits, but it is clear that a short daily meeting where all tasks of the day are reviewed would prevent many surprises and decrease the share of discussions. Surprising needs for coordination often interrupted the work and there were often hurried needs for work elsewhere which could have been prevented with better coordination.

DISCUSSION

Although there are hundreds of studies reporting shares of direct work in the literature, few researchers have combined qualitative and quantitative methods using time-motion study as a major source of evidence. The early results reported in this paper show that it is possible to get quantitative estimates of productivity gains resulting from lean interventions by comparative time-motion studies of different projects. Although the amount of data is small and the results cannot be generalized, this kind of data is beneficial in convincing practitioners about the magnitude of productivity problem and what kind of role lean methods could play in solving the issues faced by workers in their everyday life.

The share of direct work was just 25% for electricians and 15% for plumbers. This is much lower than the shares reported in work sampling studies, where the average seems to be 30-40% (Neve et al. 2021). This is not necessarily because of less direct work but could be explained by different granularity of methods. It can be hypothesized that work sampling exaggerates the share of direct work because if an observer checks the activity periodically, they do not have a longitudinal view of what is going on. It could take a few minutes to understand what is going on and the worker can transition between non value-adding and direct work tasks while the determination is taking place. This hypothesis should be evaluated in future research..

The proposed interventions themselves are not new. Better communication, involving crews in planning, improved logistics and implementation of 5S principles and takt production have been proposed and implemented by practitioners for a long time. It is more important to ask whether this kind of research is helpful in convincing more practitioners to adopt lean methods.

There is initial evidence that the research achieved its aims. New research has been funded which aims to solve the design constructability problem and involves the trade unions, MEP engineers and several major main contractors. The results about takt production have alleviated the concerns of trade contractors that prioritizing “work waiting on workers” would negatively affect their bottom lines. Trade unions have taken a positive view on resource tracking on construction sites to decrease the waste and representatives of workers are actively participating in coming up with solutions. Longer term impacts will be investigated in future research.

CONCLUSIONS

Root causes of wasted effort in MEP work (RQ1) were poor communication, poor production planning and control, deficiencies in logistics, lack of constructible and coordinated design and a large share of preparation work on site due to work spaces moving. The root causes are familiar and have been previously tackled by several proposed lean-based interventions.

It was possible to evaluate the productivity potential of different interventions by detailed comparison of missing prerequisites, project characteristics and patterns of used time (RQ2). The largest potential is associated with improving constructability and coordination of design (plumbers 20%, electricians 10%). Significant opportunities were found also with material logistics where just having everything on wheels (plumber 10%, electricians 5%) and organizing storages with 5S principles could result in substantial benefits (1 percentage point). More comprehensive industrial just-in-time logistics solutions could improve the productivity even more but would also require installation-level design to evaluate the right amount of materials. Installation level design would also give opportunities for prefabrication or at least more efficient work preparation on site. The study also indicates that takt production can substantially increase the direct work share of MEP workers, alleviating the concerns of trade contractors that capacity buffering would result in increased labor costs.

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ASSEMBLY PROCESS IN OFF-SITE CONSTRUCTION: SELF-LOCK DEVICE AS A KEY TO A LEAN APPROACH

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ABSTRACT

The implementation of lean construction in off-site construction is an ongoing combination aiming to improve the efficiency and reduce all forms of waste in the construction industry. Modular construction offers a high level of off-site value creation, and consequently leaner processes associated to the well-known off-site construction advantages as waste management, shorter project timeline, improved health and safety conditions for workers, better quality control, optimal material handling, and efficient working stations. Nonetheless, the on-site activities needed to connect the modules are often identified as critical sources of waste. In response, many connecting devices and models for calculations were developed in recent years, but very few present an automated locking mechanism for modular connection. While most connecting devices include the use of fasteners that need to be manually fixed to complete the connection of modules, an automated connecting device could significantly reduce the quantity of on-site activities by including an engineered mechanism that ensures self-lock. This research aims to evaluate the impact on leanness of an automated connecting device as well as to present a new plug-in self-lock device.

KEYWORDS

Off-site construction, Modular assembly, Connecting Device, Automated locking mechanism, Waste management.

INTRODUCTION

Off-site construction (OSC) is characterized by the process of manufacturing components in-factory before their transportation and installation on the construction site. Components can be of many forms, but in this research, only the modular form is of interest. More precisely, Modular Construction (MC) is defined by the Modular Building Institute (MBI) as an off-site process, performed in factory setting yielding 3D modules that are transported and assembled at a building's final location. Hairstans (2015) has divided MC in four subcategories; uninsulated modules whose surfaces have first skin on

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only one side, insulated modules without finished linings, insulated modules with finished lining on one side (either internally or externally), and modules fully finished on all sides with integration of services (i.e. with electrical and mechanical services, windows and doors). The fourth subcategory is considered throughout this study.

While the fourth category refers to *fully-finished* modules, the reality is that some work is left to be done on-site because of assembly considerations. Indeed, to permanently assemble modules together on the construction site, workers need access to the structural posts of the modules in order to install fasteners and complete the linkage, which leads to modules showing unfinished areas. While MC factories were designed to achieve a lean production with organized work-stations, controlled environment, and accessible material and tools, the assembly process interferes with the in-factory level of completion that could be reached, consequently causing non-lean activities (e.g. repeating finishing steps on-site for the specific areas left unfinished). Indeed, Zhang *et al.* (2020) have extracted from the published literature all key performance indicators (KPIs) of OSC supply chain in economic, social and environmental aspects, and the on-site modular assembly cost and time were identified as two KPIs frequently identified by researchers, highlighting the importance of the assembly process in the overall OSC supply chain. The results section of this paper lists all sources of waste (as defined by LC theories) in the assembly process of the OSC supply chain.

With the aim of improving the modular assembly process, many types of modular joints have been developed by researchers and are currently used to fix modules together. To name a few, Sharafi *et al*. (2018), Chen *et al*. (2020), Annan *et al*. (2009), Loss *et al*. (2016), Sendanayake *et al*. (2019), Bowron *et al.* (2014), Park *et al*. (2015), and Dai *et al*. (2018) proposed new connecting devices. As illustrated in Figure 1, modular joints are typically located in the corners of the modules, which allows to concentrate connection in specific points and to concentrate external load of the buildings to these transfer points.

Nonetheless, the literature presents very few modular connection involving an automated connecting device (ACD) (Ferdous *et al.,* 2019). An ACD refers to a mechanical device permanently fixed in the structural framing of all modules, in which a locking system is automatically engaged when the module being assembled to the others has reached its final position. Such a device could eliminate all fastening operations currently needed to link modules together. This research aims to evaluate how an ACD can reduce sources of waste, since its value addition to the final building is not the connecting device itself, but all the sources of waste it reduces. This paper also presents a new ACD developed accordingly to the potential waste reduction identified.

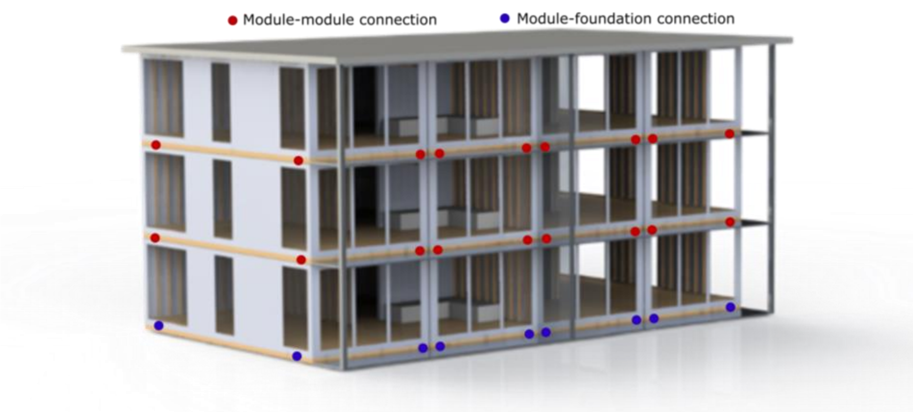

Figure 1: Typical location of modular joints to ensure vertical connection.

METHODOLOGY

To evaluate how an ACD can reduce sources of waste, the research approach is based on the development of appropriate Key Success Features (KFSs) to effectively manage Critical Waste Factors (CWFs) for a lean construction process through waste reduction. The CWF term is used in this paper to refer to specific characteristics of construction activities that are critical sources of waste. The methodology of the approach consists of five key phases: (1) identify CWFs through literature review and case study (field observations and interviews), (2) identify how to improve the CWFs by defining KSFs for an ACD, (3) design an ACD following state-of-the-art design methodology (2015), (4) evaluate the performance of the ACD with KSFs and (5) estimate the economic impact of the ACD.

More precisely, phase 1 consisted in field observations and interviews with members of OSC organizations combined with literature review. Field observations took place in Quebec, Canada, where modular construction is predominant with light-framed structures (Cecobois, 2020). The first project (study case A), located in Quebec City, involved a 24-unit residential modular building four stories high each containing seven light-framed modules (2019). The second project (study case B), located in the great area of Quebec City, involved a 6-unit residential modular light-framed building (2021). The in-factory visits took place in the factories of three different manufacturers, all located in Canada. During factory and on-site observations, many pictures and videos were taken for future consultation. Interviews were conducted with production managers, CEOs, and general managers of off-site manufacturers, as well as with a structure engineer, the CEO of an engineering group, and the director of creation of an architecture group. The literature review was divided in two major components: existing connecting devices for modular buildings, and lean construction principles. Phase 2 consisted in an analytical research approach to identify the key features the ACD must include in order to address the CWFs of the modular assembly process, while Phase 3 involved a state-of-the-art design methodology consisting of problem definition, design specifications, design iteration, prototyping, fabricating and testing. Phase 4 refers to a qualitative approach of evaluation, while phase 5 is predominantly based on assumptions.

RESULTS

CRITICAL WASTE FACTORS ON-SITE IN MODULAR CONSTRUCTION

In LC literature, Erikshammar *et al.* (2010) states that several elements must be managed to increase value in construction, such as waste reduction, quality, price and functionality, and more subjective elements such as design. The waste reduction approach defines eight forms of waste identified by Ohno as follows: Over-production, inventory, transportation, waiting, motion, over processing, rework, and not utilizing human resources (Howell, 1999). Table 1 presents how these forms of waste occur during on-site activities in OSC, with regard to on-field observations at both study cases A and B, interviews with OSC organizations members, and literature. Table 1 also presents association of these on-site activities with specific CWFs. A discussion follows.

Table 1: On-site activities in OSC, associated forms of waste and identified CWFs

On-Site Activities	Forms of Waste	CWFs
Modular assembly	Waiting	(1) Co-dependence of crews (2) Poor rate of machine usage / workers usage (3) Need of coordination
Positioning of module	Rework	(4) Alignment unpredictability
Structural connection	Over Processing	(5) Load bearing relies on many systems
Modules completion (*interior finish at connection points*)	Transportation and handling	(6) Multiple handling of tools and material (7) Reduced productivity compared to off-site
Building completion and rework	Material Waste*	(8) On-site material waste management is poor

** A more explicit form was chosen to simplify understanding, referring to the Over-Production form of waste.*

CWFs (1), (2) and (3) associated to modular assembly were identified when observing the following activities on field. Figure 2 illustrates crews B to F pursuing their activities. Crew A moves trucks for modules delivery. Crew B unwraps the module and attaches it to the crane. Crew C attaches and manoeuvers the cables for rotation control. Crew D, located in nacelles, controls the alignment of the module, corrects inter-modular gaps if needed, un-attaches the rotation control cables and ensures lateral fixation on the façade edge. Crew E, located on the highest walkable surface of the building, ensures the lateral fixation on the ceiling edge. Crew F, located one story lower, installs fasteners to complete the vertical fixation of the modules at the floor-ceiling interface. As seen on field, D, E and F can work simultaneously but depend on B and C, while B and C can work simultaneously but depend on A. Since tasks of crews D, E and F are labor intensive, the co-dependency of crews induce major wait-times prior to repeating the whole process of module assembly. Wait-times are responsible for workers and machines being inefficiently used (*e.g. the crane for assembly not operating for long periods)*. Moreover, this kind of complex crew synergy requires great coordination, and occasional failure in coordination can lead to major waste.

CWFs (4) refers to the un-assisted alignment activities that leads to frequent need of rework due to angular or positional inaccuracy. The unpredictability leads to rework taking many forms: lifting the module to re-align, and/or misfit of partitions, and/or incongruous façade form.

Crew B **Crew C** **Crew D** **Crew E** **Crew F**

Figure 2: On-site pictures of crews B to F executing their specific tasks at study caseA.

CWF (5) refers to the labor-intensive connection tasks, which add limited value for the project owner. With the actual assembly methods, the building structural stability depends on the shear wall continuity at various locations: at the façade edge, ceiling edge, and floor-ceiling interface. This complex connection process is considered over-processing since a single complete connection that does not require shear wall continuity could significantly reduce the labor needed for assembly, and be concentrated in a discrete locations in the module.

CWFs (6) and (7) refer to the module completion tasks induced by the need of accessing the connection points, typically numbered as four to eight per module. When connecting devices are non-automated, access is required at interior surfaces to install additional fastening to withstand tensile loads. Compared to off-site where workstations contain the right tools and are located immediately next to the appropriate material supply point, on-site modular completion requires substantial material and tool handling from module to module. Module completion can include the installation and finish of the drywall, the application of primer and paint, finishing the flooring, fixing mouldings, etc. Moreover, on-site labor productivity is significantly lower than that of off-site (Bosnich *et al.* (2001).

CWFs (8) refers to solid waste generated on-site. While off-site material waste management facilitates the reduction of un-usable remains, and/or encourages its recycling and sorting, on-site remains are most likely wasted.

ANALYTICAL REVIEW OF EXISTING CONNECTING DEVICES AND ON-FIELD ASSEMBLY PROCESS

Bowron *et al.* (2014) invented a new non-automated connector for steel MC. They founded a corporation named Vector Bloc, located in Toronto, Canada and have already sold multiple units that were used in high-rise modular buildings. The core of their design involves a three part connecting device for steel-modular assembly. The ceiling part is located at the top corners of modules, allowing the extruded parts to insert into the hollowed-square structural beams. Permanent linkage of structural beams and the ceiling part is achieved with welds. The floor part is located at the bottom corners of modules, allowing the extruded parts to insert into hollowed-rectangular structural beams, permanently linked to the floor beams with again, welds. Gusset plates were designed to achieve lateral connection between horizontally adjacent modules, and are installed on-site. Hence, related on-site activities that follow the positioning of the first floor modules are depicted as follows:

1. Placement of the gusset plates when all horizontally adjacent modules are placed;
2. Installation of fasteners to fix the gusset plates (two bolts per module);
3. Placement of the second story modules;
4. Installation of fasteners to link all three parts together (two bolts per module);
5. Completion of the inside of the modules to hide connection access points;
6. Completion of the modular joining areas at all locations in the building (corridors, open-areas overlapping on more than 1 module, elevator, exterior sheathing and finish, etc.).

The Vector Bloc products are often praised by literature because of the flexibility it offers despite its aim to standardize the modular assembly process. Indeed, the system can be combined with any post and beam dimensions and ensure vertical proper stacking for up to 60 stories high. While this innovation proposes a significant improvement to standardize the assembly process and achieve higher-rise buildings, it leads to question if an automated mechanism for vertical fixation can contribute to extend the lean benefits. What seems to oppose this innovation to LC principles is the need of a certain incompletion level of the modules, required for accessing the connection points. On this regard, Vector Bloc products can be compared to the Innov-144 connectors observed in Quebec, where the joints were non-standard as they were specifically designed for this project. It allowed the linkage of the modules through two metallic holders, one in a C shape containing the floor timber beams, and the other one fastened on the lower module wood post. When analyzing these two assembly solutions with the six forms of waste identified in Table 1, it seems obvious that the lean approach can still be improved through the development of an automated connecting device ensuring the vertical and lateral connection as well as maximizing off-site completion of modules while reducing on-site assembly activities.

IDENTIFICATION OF KSFS TO ACT AS DESIGN SPECIFICATIONS

Table 2 presents the results of an analytical exercise on identifying relevant KSFs to help reduce the impact of the CWFs identified and to act as design specifications for the ACD development.

Table 2: Identification of KSFs as design specifications to improve CWFs

CWFs	KSFs
Co-dependence of crews Poor rate of machine usage / workers usage Need of coordination	(k1) Automation of the locking mechanism
Alignment unpredictability	(k2) Ability to assist the alignment of the modules (k3) Ability to create predictability in module positioning
Load bearing relies on many systems	(k4) Integration of a complete load bearing system that includes shear, tension and compression
Multiple handling of tools and material Reduced productivity compared to off-site On-site material waste management is poor	(k5) Dissimulation of the ACD inside the framing to allow full interior completion of the module and reduce on-site work

A NEW SELF-LOCK CONNECTING DEVICE

In accordance with the KSFs identified, an automated connecting device (ACD) was developed to increase the leanness of OSC processes. The proposed ACD, illustrated in Figure 3, is composed of a lateral plate (LP) and two distinct assemblies respectively named floor connector (FC) and ceiling connector (CC). The FC contains a triggering mechanism that induces self-locking only if the male member of the CC has reached its final position. The final position of the male member is reached when the module is sitting at the right position above the lower ceiling. More details about the functional and technical design specifications met when testing the ACD are presented in Table 3. The

ACD meets all the specified KSFs, starting with a fully automated vertical locking mechanism which significantly reduces assembly time by reducing wait-times, co-dependency of working crews and coordination needs. (k1). The ACD also requires no access to connection points by a complete dissimulation of the ACD inside the framing, hence maximizing the off-site completion of modules (k5). The ACD needs to be precisely positioned off-site in order to increase the predictability of modules positioning earlier in the process (k3), and the FC presents a conic entry that guides the cylindrical CC member to the right location, which contributes to facilitate the alignment of the modules (k2). Moreover, the ACD was designed to bear considerable loads in tension, compression and shear which are detailed in Table 3. The values for shear, tensile and compressive capacities were obtained from an experimental study led by Picard *et al.* (2022).

For comparison purposes, related on-site activities that follow the positioning of the first floor modules when using ACDs are depicted as follows:

1. Placement of the gusset plate when all horizontally adjacent modules are placed;
2. Placement of the second story modules;
3. Completion of the modular joining areas at all locations in the building (corridors, open-areas overlapping on more than 1 module, elevator, exterior sheathing and finish, etc.).

a) b)

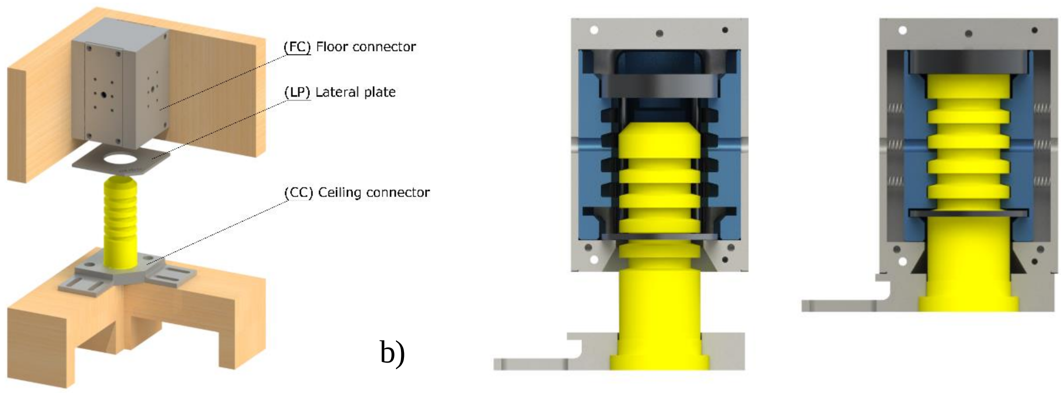

Figure 3: ACD device illustration, (a) identification of three major components floor connector, lateral plate, and ceiling connector, (b) cut-section in two states, prior to connection, and after connection.

Table 3: Design specifications of the ACD and resulting values

Characteristics	Resulting values	Comments
Movement of insertion	Vertical	The modules arrival on connecting site is always vertical.
Lock mechanism	Vertical and Automated	The mechanism replaces tensile bolts by restricting pull-out motion. Automation reduces workers activities at assembly.
Location	Adaptive	The ACDs can be located at the four corners of the module, or elsewhere if needed. They are located in the void space between the ceiling and the floor.
Module-mount offsite	Easy	The frame shape is adapted to the module type (*e.g.* light-framed module, steel module, concrete module, hybrid module).
Module alignment	Easy	The conic entry facilitates the alignment process.
Access needs	For lateral plate only	The connection needs access point for workers only on exterior surface of the ceiling, where the lateral plate is installed.
Unlocking	Possible	Holes on the sides of FC allow for bolt insertion, and when tightened, they compress the triggering springs and pull the locking clamps back in initial state. Ceiling opening is required.
Compression load path	Unaffected	Load concentrations at connecting points are avoided by allowing a continuous contact between rim joist and top plate of lower module.
Lateral fixture	Various plates	Three parts are designed for lateral fixture to accommodate all locations, as of the corner of the building (1-hole), the face of the building (2-holes), and the inside of the building (4-holes).
Tensile capacity	200 kN	Allowable for buildings up to 6 stories.
Compressive capacity	1000 kN	Designed to prevent collapse in case of beam failure (and load concentration).
Shear capacity	40 kN	Building response to lateral loads is a combination of ACD shear capacity and siding sheathing.

ECONOMIC ANALYSIS ON THE IMPACT OF THE WASTE REDUCTION

The lean processes inherent to OSC are responsible for a major increase in labor-productivity and resource usage. The optimization of workstations, the material and tools handling management, the jigs and standardized equipment for fast transformation of components, the controlled environment independent of weather hazards and more are believed to induce a major difference in labor-productivity. To quantify the cost difference between a task done off-site, and on-site, the hypothesis used assumes a 2:1 ratio of value creation per hour off-site to value creation per hour on-site. Differently said, the same task is believed to take twice the time to do on-site than it takes off-site. This 2:1 ratio is enhanced by the context of completing a module: since most of the tasks are started but unfinished at some locations (*e.g. drywall installing, finish, priming and painting)* it seems reasonable to believe it would take at least half the time to simply pursue the on-going task in-factory than to prepare tools and materials on-site and complete the task. Although it appears to be an optimistic ratio, the findings of Wandahl *et al.* (2021) state that on-site labor is being used at only 43% for direct work. Moreover, the rates of on-site workers is estimated to $65/h compared to $32/h for off-site workers in Province of Quebec (CEO of engineering group, 2022). Hence, the same 1-hour off-site task will cost $32 when performed off-site compared to $130 when performed on-site, which corresponds to 4-time increase between off-site and on-site.

The completion level of modules were observed to be of approximately 60% throughout on-field observations in study cases A and B. However, it has been reported that the level of completion can reach up to 80% off-site in the Swedish OSC environment, with the Timber Volume Element (TVE) method (Hook *et.* Stehn, 2008). Considering 10% of activities will be needed for building completion (junction areas of modules) with, or without the use of ACDs, there is a 10% to 30% additional completion that can be potentially reached with the use of ACDs.

The following paragraph sets an example of cost variation induced by off-site completion level and use of ACD in assembly activities. The example is illustrated in Figure 4. If constructed off-site or on-site, the material cost will not sustain a major difference, hence noted independent. Transportation is also independent of the ACD usage, as well as the building completion, which corresponds to approximately 10% of the module completion (*e.g.* esthetic continuity in halls and corridors, at façades, etc.). The labor cost, for its share, highly depends on the level of completion off-site and the remaining task to be completed on-site. Taking as example that a 60% off-site completed module induces a $20K labor cost, and following the 4:1 ratio highlighted previously, the remaining 30% can either cost $10K if done off-site, or $40K if done on-site. The cost of completion activities become $30K apart with, and without ACD. The waste reduction associated with KSF (k5) is substantial and highlights the potential impact of using an automated connecting device in MC.

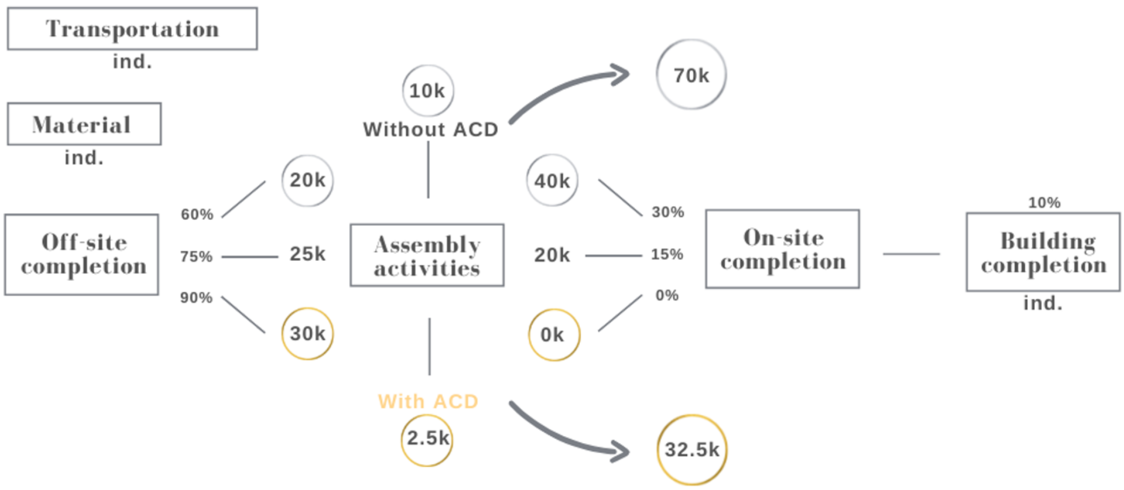

Figure 4: Economic example of the impact of using an ACD.

On the other hand, the waste reduction associated with KSFs (k1), (k2), (k3), (k4) is harder to evaluate and less predictable. Field comparison of similar buildings being built with, and without ACDs could help quantify the waste reduction in terms of assembly time. Indeed, all four KSFs are expected to facilitate the assembly process and consequently reduce the assembly time. Based on field observations only, the wait-times, the connecting operations of Crews D, E and F as well as the lack of coordination are assumed to represent 75% of the work-time. Hence, assembly process is estimated to be four times quicker with the use of ACDs, leading, again, to major cost reduction.

Sutrisna *et al.* (2019) presented the findings of their work on the off-site manufacturing cost analysis based on three study cases in Australia. To compare with this research, all cost components values were divided by the number of modules involved in each study case, mean values were computed, converted to CAD$ and are presented in Table 4.

Table 4: Construction cost in Sutrisna *et al.* study case, mean values

Cost Components	Mean Value (CAD$)	% of Total Cost
Module manufacturing cost (72% completion)	44.3K	71.9%
Module transferring cost (transport, unwrapping, attaching, lifting and connecting activities)	2.9K	4.7%
On-site Construction cost (module and building completion)	12.7K	20.6%
Engineering / permits / fees	1.7K	2.8%
Total cost / module	61.6K	100%

To compare with the results of this paper, the impact of an ACD is evaluated by computing the hypothetical total cost/module if off-site completion was maximized to 90%. The findings of Sutrisna et al. (2019) state that for the study-case under consideration, on-site construction cost represented 20% of the total cost and allowed for 28% of the module completion. By interpolation, if on-site completion was reduced from 28% to 10%, the cost would reduce from $12.7K to $4.6K. Following the 4:1 rule, the $8.1K reduction in the on-site cost corresponds to an $2K increase in the off-site cost, since 28% of the tasks will be done two times quicker, at a two times smaller hour-rate.

Hence, the savings associated to an 18% higher off-site completion are estimated to $6.1K per module. This represents a 10% cost reduction of the total cost/module since the mean total/cost per module of their findings is $61.6K. In addition, the module transferring cost of $2.9K can also be reduced to contribute in improving the total cost reduction.

CONCLUSION

The implementation of lean construction principles to the off-site construction industry is of growing interest in the literature and while many researchers have pointed out the connecting systems for modular linkage as a critical waste factor, few have evaluated its impact on the project cost nor have tried to identify a potential way to improve its efficiency. This research aimed to evaluate the impact on leanness of using an automated connecting device for modular assembly as well as present a new plug-in self-lock connecting device. The methodology consisted in five key phases: (1) identify CWFs through literature review and case study (field observations and interviews), (2) identify how to improve the CWFs by defining KSFs for an ACD, (3) design an ACD following state-of-the-art design methodology (2015), (4) evaluate the performance of the ACD with KSFs and (5) estimate the economic impact of the ACD.

The critical waste factors identified are the following: co-dependence of crews, low rate of machine usage / workers usage, need of coordination, alignment unpredictability, load bearing relies on many systems, multiple handling of tools and material, reduced productivity compared to off-site, on-site material waste management is poor. The key success features identified are the following: (k1) automation of the locking mechanism, (k2) ability to assist the alignment of the modules, (k3) ability to create predictability in module positioning, (k4) integration of a complete load bearing system that includes (tensile, compressive and shear capacity), and (k5) dissimulation of the ACD inside the framing to allow full interior completion of the module and reduce on-site work.With its automated locking mechanism (k1), the ACD allows to reduce on-site connection activities from six to three, and allows to maximize the off-site completion of modules to up to 90% (k5). Moreover, its conic entry and precise positioning in factory helps assist the alignment of the modules (k2) and helps to create predictability in the positioning (k3). Finally, the ACD can bear important loads, as of 200 kN in tension, 40 kN in shear, and 1000 kN in compression (k4). When estimating the impact of the ACD on total project cost, the usage of an ACD in the Australian study cases studied by Sutrisna *et al.* (2019) leads to the possibility of reducing the total cost per module by up to 10%.

This research highlights the potential impact of automating the modular connecting systems on the reduction of sources of waste in the modular assembly process of OSC. To confirm the results of this study, field analysis shall be conducted to confirm hypothesis and confirm the cost of similar buildings built with, and without an ACD.

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RETHINKING PROJECT DELIVERY TO FOCUS ON VALUE AND INNOVATION IN THE PUBLIC SECTOR

Patricia A. Tillmann[1], Stuart Eckblad[2], Fred Whitney[3], and Niall Koefoed[4]

ABSTRACT

With the intent to move towards value generation, public organizations have been increasingly searching for alternative procurement and project delivery routes. Countries like the U.S., Finland, U.K., Norway, and Australia are pioneers in adopting alternative means to project delivery in the public sector. Past studies have documented the benefits of more collaborative arrangements in that sector. However, their impact on project performance and their ability to generate value still lack evidence and documentation. In addition, little is known about project management practices that helped organizations focus on value and achieve better project performance within this context. Thus, this paper aims to provide evidence about the impact of alternative delivery methods on generating better project outcomes in the public sector, highlighting fundamental mechanisms and lean management practices that have contributed to these results. This research follows a multi-case study approach, reporting the journey taken by The University of California San Francisco (UCSF) Health to rethink its project delivery methods in the public sector. A close collaboration between the University of California Berkeley (UC Berkeley) and UCSF allowed data to be collected throughout the years. This paper results from a reflection of collected data and new insights gained through focused group discussions.

KEYWORDS

Lean in the Public Sector, Value generation, Integrated Project Delivery.

INTRODUCTION

The challenge of changing the focus to value generation in the construction industry has been widely discussed. Past research points out the historically fragmented and sequential approach to construction, impacting the industry's ability to generate value (Forgues and Koskela, 2009; Tillmann, 2012). The industry's incapacity to move from a sequential to an integrated approach resides in inefficiencies associated with traditional methods of procuring and delivering construction projects in the public sector, e.g., the price component taken as the most important (if not single) component of contractor selection, and the adversarial business context created by transactional contracting methods.

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Maximizing value at the project level is difficult when the selection process is based on price and increased value, quality, and speed are only considered for a premium. In addition to that, the type of contract generally inhibits coordination, stifles cooperation and innovation, and rewards individual contractors for reserving good ideas and optimizing their performance at the expense of others (Matthews and Howell, 2005).

Collaborative construction project arrangements have been the subject of many development efforts in response to the frustration toward the opportunism inherent in traditional contracting (Lahdenperä, 2012, Hietajarvi, 2017). Lahdenperä (2012) describes three multi-party contractual arrangements that are currently predominant in the industry: (a) project partnering, emerging in the US in the late 1980s and then used in the UK and Australia; (b) project alliancing, emerging in the UK in the mid-1990s and disseminated to Australia; and (c) Integrated Project Delivery (IPD), emerging around 2005 and most popular in the US. These alternative arrangements use mechanisms to incentivize companies to work as one team, e.g., balancing risk allocation, rewards tied to collective performance, integrated governance structure and team organization, and an agreed-upon operating system. Within this context, the lean philosophy has been a fundamental element of success on IPD. Project teams not only pursue a lean mindset but also adopt techniques and tools to establish an operating system that incentivizes companies to develop and achieve common goals.

Some of the benefits of alternative project delivery models to focusing on generating value in the public sector have been reported in the literature. Chen and Manley (2014) observe that the choice of procurement model has a significant impact on project outcomes due to the governance mechanisms chosen to organize work, shape the scope for goal achievement and determine innovation potential. In collaborative arrangements, owners are more directly involved with project delivery (Love et al., 2010) and seem to have a more active role in championing innovation and influencing improved outcomes (Namand and Tatum, 1997; Loosemore and Richard, 2015).

Within this context, around 2007, the University of Berkeley started holding the 'Lean in the Public Sector' annual conference, bringing practitioners from all over the world to discuss and share advancements in their countries around the topic. Throughout the years, some of the reported advances included (LIPS History, 2016): (a) Introduction of lean philosophy and methods to Australia’s project alliancing; (b) Pioneering work of Finland’s government organizations applying lean and IPD to over 35 projects; (c) Integrated Project Delivery (IPD) was legalized under EU construction procurement regulations; (d) UCSF led the development and testing of alternative contract structures and methods of aligning commercial interests, leading to the approval of its first IPD project in the public sector in 2022 and inspiring other University systems to apply lean methods and follow a similar path (i.e., California State University and community colleges and the University of Washington and Michigan State U).

While the benefits of more collaborative arrangements have been documented in the public sector, including the use of lean practices to focus on value generation, the impact of these practices on project outcomes still lacks evidence and documentation (Lahdenperä, 2012; Vilasini et al., 2014). In addition, although there is anecdotal evidence that lean practices have been used in the sector, there is little understanding about how they support focus on value and improved project performance.

A few studies have provided evidence on how Target Value Design contributes to an increased focus on value generation in the public sector. Among these studies is a paper published by Melo et al. (2015), which documented the first UCSF case study under a collaborative contractual arrangement. More than seven years later, this paper builds on that study and provides additional evidence about the impact of alternative delivery methods and lean management practices on improving project outcomes in the public sector, even when multi-party contracts are not permitted. The paper highlights fundamental mechanisms and lean management practices and discusses their impact on project outcomes.

The contributions of this paper are two-fold. The paper hopes to inspire other practitioners in the public sector to embark on a journey towards alternative delivery methods to support a better focus on value generation in the public sector. This discussion also hopes to reveal new insights into the underlying theory of project management and how concepts from different knowledge areas may play a key role in advancing construction project management as a discipline.

The research method adopted in this study was a multiple case study approach and encompassed the analysis of three projects. Data from the first project started to be collected from 2013 to 2014 through a collaboration between UC Berkeley, UCSF, and the general contractor. Data gathering techniques included analysis of documents and semi-structured interviews with selected project personnel from different companies, including UCSF, the project manager representative, general contractor, architectural firm, and structural engineering firm. Data collection continued from 2016 to 2019, when one of the researchers joined the UCSF Real Estate team. The focus was on Case 2 and sources of evidence were field observations, additional interviews with the owner and owner representative, as well as analysis of documents on UCSF policies shaping project delivery methods, the contract, documented lessons learned and project documentation. In 2021, with the eminence of UCSF’s first IPD project, the co-authors of this paper regrouped again for a series of focused discussions with the intent to reflect on the current state, past achievements, and expectations for the future. This paper summarizes the main lessons learned resulting from this reflection.

UCSF HEALTH’S JOURNEY TO IPD

UCSF is 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. 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, this department 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. Every step of this journey involved myriad negotiations with the University of California Office of the President (UCOP). It ultimately resulted in the entire university system accepting new delivery methods and changing California’s public contracting code. Once restrictive of alternative procurement methods, the California Public Code now allows organizations in the public sector to choose Integrated Project Delivery (IPD) to deliver major capital projects. This section will review UCSF's value proposition and then summarize the steps of this journey towards a more significant impact on value creation and innovation.

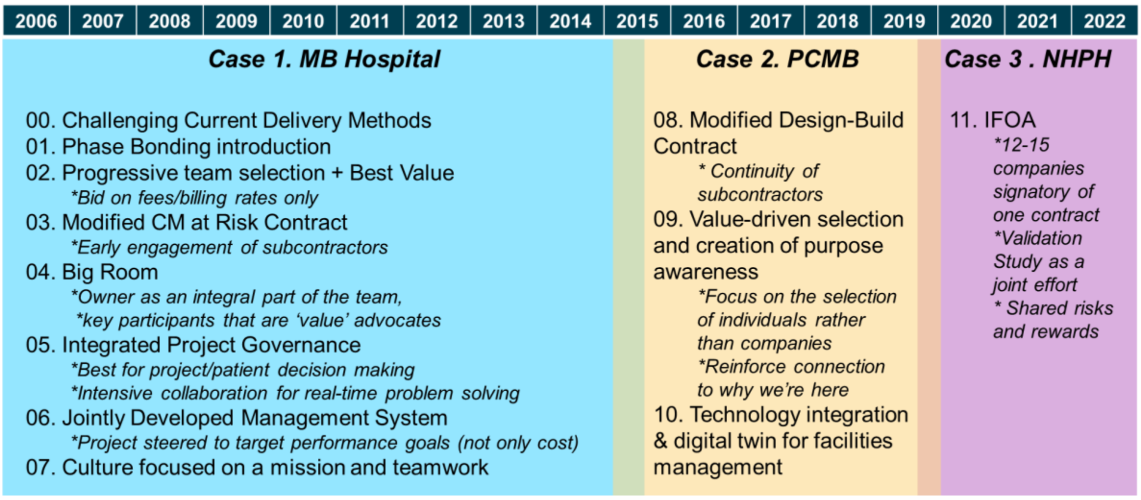
The pursuit of increased value

Project management organizations face a few challenges in supporting healthcare delivery. Firstly, models of care are rapidly changing with new understandings from science and technology. Secondly, an increased focus on operations design in care delivery poses several implications for the design of healthcare facilities – increasingly, designers are challenged to consider how the design of the built facility impacts the delivery of care – i.e., patient safety, care delivery routes, co-location of services, etc. Thirdly the rapid advancement of information technology and automation in providing care is generating new requirements to be considered when designing healthcare facilities.

By the time facilities are designed and built, medical equipment and technological requirements have often changed, causing rework on facilities that are already halfway through construction—not mentioning opportunities related to business revenue that often need to be incorporated late in the project delivery process.

In addition to these changing demands, it's often challenging to accommodate so many requirements from multiple stakeholder groups, which sometimes are conflicting. Requirements from various stakeholders need to be met, i.e., users, community, the city, the city's workforce development program, seismic requirements, facilities management, the university's sustainability policies goals, while also (and most of the time) attending to donors needs and the university's aspirations to contribute with iconic landmarks of health care in San Francisco.

These complexities and need for adaptation and a high level of customization make it very ineffective to use a traditional delivery method, such as DBB, which the University was using. Several problems are associated with using DBB in such a context: poor ability to manage risk, make changes, limited contractor participation on bids when projects are too large (bonding capacity[5]), and a litigious environment. UCSF health's journey started with a critical analysis of the current state and a desire to change into a delivery method that better fits the university's needs. The picture below provides a summary of this journey (Figure 1). The journey will be described under three main case studies.



[5] Construction bonds are a type of surety bond that protects against disruptions or financial loss due to a contractor's failure to complete a project or failure to meet contract specifications.

Figure 1: Removing barriers to focus on value and innovation

Case 1: The Mission Bay Hospital

The Medical Center at Mission Bay was *awarded ENR Best National & California Health Care Award*. The Center is UCSF's newest state-of-the-art hospital complex that has been designed to ensure top-notch patient care. The new hospital was built focusing on the patient's experience and is seen as *"An iconic landmark of health care, built from the ground up with care and compassion in mind."* The Center offers treatment with the latest technology, including telemedicine, robotics, intra-operative imaging, and space to accommodate future innovations.

The $1.5-billion integrated hospital complex includes a 183-bed children's hospital, women's specialty hospital, cancer hospital, and medical office building. Designers met the challenge of integrating three separate hospitals within the 878,000-sq-ft structure by incorporating shared support services and diagnostic treatment spaces arranged along a common spine to boost efficiency.

Nearly 18 months after construction began, UCSF drastically changed the project by adding cancer-treatment services, which required re-scoping 175,000 sq ft of the building to accommodate the new cancer center. When finished in 2014, the project claimed a $200-million reduction in budget from the initial estimate; even with the increased scope - $55 million in changes were made without impacting the opening date. The facility uses 50% less power than the average U.S. hospital. Work included an "unprecedented" analysis of materials to screen out from patient rooms those that were toxic or unsustainably manufactured. The outstanding outcomes of Mission Bay set the precedence for other projects to use collaborative contractual arrangements within the UC system. The main mechanisms that supported these outcomes are described below[6]:

00. Challenging current delivery methods

Influenced by the engagement with the American Institute of Architects (AIA) project delivery initiative, the first step taken on this journey was an honest conversation about the inefficiencies of the current University's practices and a proposal to move toward more collaborative project delivery methods. The proposal was to adopt Design-Build with a cost-plus fee and Guaranteed Maximum Price (GMP) type of contract, allowing early engagement of contractor and subcontractors. However, for different reasons, it took more than 18 months for the University to approve the request to use a more collaborative structure, and a modified Construction Manager at Risk contract was selected.

01. Phase Bonding introduction

Another aspect that was hampering the participation of a larger pool of contractors was the bonding requirements. The scale of projects was prohibitive for many contractors to participate in the selection process for projects, due to bonding capabilities. Phase bonding allowed the participation of a larger number of contractors.

02. Progressive team selection + Best Value (bid on fees/billing rates)

Progressive team selection refers to the gradual selection of team members based on consensus. The project teams get involved in the Request for Proposals (RFQ) and interview process of prospective parties, increasing the chances to build a well-

[6] Melo et a. (2015) presents a preliminary analysis of this case when the project was still ongoing. The focus was on describing the Target Value Design process and some of the supporting mechanisms. This paper focuses on additional elements and new insights that adds on and complements the reflections on that previous paper.

functioning team. Throughout the selection process, people get to know each other, and partners are selected on their ability to contribute to the team and the likelihood of working well together.

The use of Best Value (BV) contractor selection has been a key mechanism used by UCSF since 2007. This practice allows the university to consider the additional value a contractor may offer in concert with their bid price, thus determining the bid that delivers the best value. There is however a problem with this process: the cost of work is still considered as a key element in the contractor's selection, not mitigating the challenge of potential unrealistic bids upfront. A modification of this process allowed the team to establish the cost of scopes of work as a common denominator among bidders, allowing companies to set their overhead and profit amounts only. This modification excludes the cost of work as a factor in the selection process – and is a key element to eliminate competition based on the lowest price. Once this foundation was set, the team worked on altering the contracts and setting a different environment for project delivery. These changes will be described below.

03. Modified CM at Risk Contract

The contract used on the project was rewritten to enable design-assist major subs to engage earlier in the project. This type of contract, however, has a downside: the trades that are chosen for the pre-construction/early design phases are not guaranteed to continue during the construction phase, resulting in an undesired fragmentation.

Unlike an IPD project, the team was not able to implement a shared risk and rewards structure, to work together on validating the business case or limit liability for companies that are signatories of the agreement. A feasibility study is carried out by the University's construction management team. The team analyses historical data about other similar University projects and carries out a market benchmark analysis to validate this business case. As a result, the allowable and target costs were set and shared with the project team, but not developed collaboratively.

As an alternative to support the achievement of common goals, an incentive program was set. The incentive included 11 criteria to be met, i.e. schedule milestones achievement, change order mitigation, community workforce development, and quality. If criteria were met, the project team (contractors and subcontractors) would get an additional 2% of the project's construction budget. As already reported in Melo et al. (2015), the project team was little incentivized by the program. The importance of continuing the project during an economic downturn and the purpose and mission of the building were greater motivators to improved performance.

04. Key Participants in the Big Room

For the Mission Bay Hospital, the owner, owner's rep, general contractor, architect, engineers and subcontractors created a "big room" set up onsite and worked collaboratively during the design and construction phases of the project. Other participants of the Big Room who made a difference in achieving improved project outcomes included: (a) Inspectors from the Office of Statewide Health Planning and Development (OSHPD) - responsible for the reviewing and inspecting all healthcare construction in California [7]; (b) Two full-time UCSF employees from facilities management were full-time in the project for 7 to 8 years: their participation allowed for

[7] The participation of OSHPD inspectors in the big room allowed the project team to achieve a 99.92 % success rate on a total of 9047 inspections. The project had on average 16 full-time inspectors who oversaw approximately 45 inspections per day.

a comprehensive analysis of the BIM model development and easy hand-off to operations. They verified every submittal in the project and made sure all equipment received their approval. This project was the first one at UCSF to generate a BIM model for operation; and (c) A full-time liaison with clinical experience: an ex-nurse from UCSF was a liaison between the users and the project team and an important asset to the project team

The participation of these "value advocates" in the Big Room, allowed for the project team (including builders) to be exposed to their multiple and sometimes conflicting requirements from an early stage. The multi-disciplinary team worked to incorporate those requirements while considering constructability and cost/schedule constraints.

05. Integrated Project Governance

The owner, architect, general contractor, and key subcontractors were part of the Project Solutions Group (PSG). One cardinal rule that this group established was to make decisions on what was best for the project and for the patients first, without talking about money. This allowed a focus on realizing value without being constrained by budget and schedule concerns too early. Later, during construction, the PSG became a key problem-solving hub. Meeting on a daily basis, the group provided close support for field personnel to solve any emerging problem. It was an effective forum to solve conflicts between construction, design, and inspectors, minimizing delays, rework, and re-inspections.

In order to escalate issues that the PSG couldn't solve, a meeting called DAM (Dispute Alignment Meeting) was set up. In this meeting, principals from the participating companies would meet to resolve any remaining items the project team could not find a solution for, i.e., resolve contingency use, risk allocation, and budget impasses.

Owner participation was not limited to these upper levels of decision-making. There was also owner representation (with decision-making authority) in the cluster and other day-to-day meetings. In addition, the owner team was fully collocated in the Big-room. This allowed intensive owner participation, reducing the latency of decisions and also increased influence on decisions, especially on important ones with potential impact to project outcomes. The team feels this was the most important mechanism to be able to advocate for value and champion innovation in the project.

06. Jointly developed management system

In the Mission Bay Hospital project, the team developed common goals, management protocols, and a mission statement through a series of workshops. It took six months of team building and organizational integration in order for the team to agree on methods and techniques to use. One of the agreed methods was the use of Target Value Design with the Project Modification and Innovation (PMI) process, already described in Melo et al. (2015). What is important to note, which was not captured in the previous study is that along with target costs for each cluster, the team also established value criteria to assess the impact of innovations, namely, improvements to maintainability, sustainability, operability, and aesthetics. Schedule impacts were also considered.

One aspect that hasn't been mentioned in the previous study is the power of co-developing these processes and procedures together and the positive impact that it has on a team's performance. Every process was co-designed and agreed upon by the different parties. This was a major lesson learned when the University team started a new project and tried to use some of the best practices with a different team. Other design processes include the agreement to use the last planner system and the establishment of agreed KPIs.

07. Culture focused on mission, teamwork, and collaboration

Intentionally building a culture focused on collaboration and innovation was also an important element introduced alongside co-developing the project's processes and procedures. In a week-long exercise facilitated by Stanford University, the team worked together on developing the project's mission, goals and processes, as well as discussing what it means to work collaboratively. This, and other team-building exercises played an important role in developing a cohesive team. The successes achieved in Mission Bay led the team to adopt the same model on their next project. In the next session, we will focus on describing only the differences between the cases.

Case 2: The Precision Cancer Medicine Building

The PCMB was awarded the *ENR California Health Care Award of Merit*. The building consolidates UCSF's solid tumor practices to a single location on the Mission Bay Campus. In addition to clinic space for most cancers, PCMB has 47 infusion bays, 120 exam rooms, radiology, pathology, radiation oncology, blood draw, a patient resource center, and support services. There are 19 imaging modalities dedicated to cancer diagnosis, staring, and treatment. Bringing these practices together at Mission Bay, further integrates research and clinical care, encouraging collaboration between researchers and medical teams. PCMB has the space and equipment to offer the newest treatments, such as infusion with genetically engineered viruses that target specific cancer cells, and cutting-edge tests, including genetic sequencing of tumors and germline testing to look for gene mutations associated with cancer risk.

The project's budget was 275M project budget with $163M for construction. When the project was complete in 2019, $19M savings were recognized.

08. Modified Design-Build Contract

To mitigate the potential fragmentation of subcontractor participation in the design and construction phase, the team chose a Progressive DB contract for this project. This model also has its downsides. Collaboration and opportunities for innovation are susceptible to the general contractor's culture and managing style. It's a model that does not support full transparency and collaborative problem-solving culture. As a result, issues may remain unsurfaced, increasing the probability of disputes.

This contract also had an incentive program. During the course of the project, the team opted to use these resources toward meeting the target cost and the program was extinguished.

09. Value-driven Team Selection and Creation of Purpose Awareness

The PCMB project selected its team members based on their affinity to the higher purpose of the project. The team developed focused questions in the RFQs and selected individuals who demonstrated a genuine commitment to improving healthcare and patient-centric outcomes. The traditional RFQ responses given by contractor's marketing departments were discouraged and interviews were carried out with individuals that would be the day-to-day contributors on projects, not executives that are typically involved only 5%-10% of their time in the project. From the beginning, the RFP literally spelled out: *"we want to work with individuals who want to cure cancer."*

Another initiative to bring awareness of the project's mission to each individual on the team was multiple presentations done by UCSF medical staff. On a monthly basis, different staff members that will work in the hospital came to the big room and presented on topics that helped the team reflect on the whole purpose of why we're here. The same ideas were conveyed during the onboarding process. Each team member onboarding the process would get exposed to the project's mission and its desired collaborative culture focused on value and innovation.

The idea behind this was to create greater awareness of the project's mission and touch individuals on a personal level to be advocates for health and healing and invested in making decisions that better consider patients and caregiver perspectives. Knowing the project's aspirations regarding its culture and goals also sets the right expectations for new team members. This focus on value becomes the team's unifying element.

10. Technology integration and digital twin for facilities management

Increasingly, the University prioritized the need to consider technological requirements in the design of new hospitals. At PCMB, the team was able to have full-time staff from the UCSF's IT department. Besides rethinking the delivery of care from a technology standpoint, the use of a digital twin to support a hospital's operations gained more attention and the team developed a robust plan for its adoption at UCSF.

Case 3: Expectations for the Hellen Diller Medical Center

The new hospital (estimated at $4bi) will strengthen UCSF's world-renowned clinical, research and training mission. The hospital will be designed to integrate with the natural setting of the surrounding Mount Sutro Open Space Reserve, focusing on the total patient experience to promote healing, wellness, and recovery. Expected to open in 2030, the plans for the hospital call for designing an architecturally outstanding, energy-efficient, and environmentally sustainable facility that will accommodate the advanced technologies UCSF uses in clinical and surgical settings, including robotics and intra-operative imaging, as well as the space needed for a modern Emergency Department.

11. The shift to Integrated Form of Agreement (IFOA)

A multi-party contract allows the mitigation of limitations observed on previous projects, i.e., fragmentation and discontinuity of subcontractor participation in projects, and lack of direct access to all team members to incentivize a value-driven mentality and champion innovation. A multi-party contract is expected to provide an open forum for innovation and implementation of value-driven ideas, allow for increased communication, and support a more proactive approach to issue identification and resolution.

The IFOA will bring 12-15 companies together, with shared responsibilities, goals, risks, and rewards. Different from other projects where the team had to work within the boundaries of best value selection, this time companies were chosen based on their qualifications only, taking the cost component completely out of the selection process.

Another major shift is that now, the team is working together to validate the business case (as opposed to a validation made by the university's construction management team). The team will finalize its validation study in May 2022 and has been working together on a virtual big room for more than a year to accommodate the complex program of a state-of-the-art facility in what will be a truly iconic landmark for the city of San Francisco. All of this is within stringent time and budget constraints.

DISCUSSION

Previous studies observed that the direct involvement of owners and their investment in the project shape the scope for goal achievement and determine innovation potential, influencing improved outcomes in alliancing projects. The cases presented here are evidence that such engagement and its benefits can happen even in non-alliancing projects.

Building on the findings of Melo et al. (2015), this paper also evidences the contribution of lean management practices to achieve better outcomes in the public setting, arguing that along with Target Value Design, the co-creation of common objectives, KPIs, processes, and procedures help teams to be more aligned improved performance.

This paper demonstrates that there are valuable insights from contract theory and production theory to the management of construction projects. It also brings to light underlying contributions of social science to the discipline of construction management that need further investigation.

CONCLUSIONS AND FUTURE RESEARCH

The aim of this paper was to provide evidence about the impact of alternative delivery methods on generating better project outcomes, highlighting fundamental mechanisms that had contributed to these results. The journey taken by UCSF Health to rethink its project delivery methods in the public sector was used as a case study. Ten different mechanisms were described, and their contribution to value generation. For hospitals with such complexity, facing a dynamic environment susceptible to change and consideration of additional requirements, an integrated form of agreement is expected to be the most supportive project delivery method. The next steps of this research will be to monitor and document the achievements of this new case study.

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TOWARDS INTEGRATED IMPLEMENTATION OF IPD AND DFMA FOR CONSTRUCTION PROJECTS: A REVIEW

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ABSTRACT

Integrated project delivery (IPD) and Design-for-Manufacturing-and-Assembly (DfMA) are emerging topics in the construction literature, which have attracted considerable attention in recent years. DfMA is known as a philosophy and a method whereby products' designs are optimized for downstream manufacturing and assembly. Similarly, IPD, is known as a philosophy and a method which enhance integration throughout the project life-cycle. Although literature identified the ability of both DfMA and IPD principles to enhance project performance metrics, little research has investigated their potential synergies. Keeping in view the opportunities accruable from this combination, this paper conducted a systematic literature review of papers that discuss minimum one of these two methods, and identified common principles or practices shared among IPD and DfMA. Finally, a framework is developed based on synergies between IPD, and DfMA in construction projects.

KEYWORDS

Integrated Project Delivery, DfMA, IPD, Design-for-Manufacturing-and-Assembly, Architecture and Construction, Lean, Literature Review.

INTRODUCTION

Conventional project delivery methods have performance issues due to their segmented structure (Fischer et al., 2017). Frustrations with conventional delivery methods and lower than expected end results, have led to the development of the Integrated Project Delivery (IPD) (Abdirad et al., 2019). IPD aims to address the problem of fragmentation in construction projects. In this contractual method, a new single purpose entity or limited liability company is created; consisting of the owner, the lead designer, the construction manager, and other key stakeholders in the design and construction of a project (Mesa et al., 2016; Yee at al. 2017; AIA, 2010). Design for manufacture and assembly (DfMA), is a methodology which, similar to IPD, seeks to resolve the problem of fragmentation in the industry by connecting design, manufacturing, and construction from early in the design process (Tan et al., 2020; Gao et al., 2020; Ng and Hall, 2019). This method aims

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for facilitating manufacturing and assembly, boosting productivity, improving quality assurance, and reducing projects' cost, time, and waste (Boothroyd et al. 2002; Bao et al., 2020; Montali et al. 2018; Lu et al., 2020; Bogue 2012).

As emerging topics in the construction management domain, we still know a little about IPD and DfMA. From a practical perspective, their adoption in the construction industry is still low and the awareness about them is still marginal (Yee et al, 2017; Bao et al., 2020). From a theoretical perspective, the conceptual aspect of IPD and DfMA practices are yet to be discovered (Mesa et al., 2019; Hall et al., 2019). Although IPD and DfMA represent two different domains of research and development, there are evidences that they have parallel principles and practices which seek to enhance integration in construction projects. The term "principle" here refers to a fundamental proposition that serves as the foundation for a system or a concept (Ng et al., 2019), while "practice" refers to shared behavioural routines which lead to the procedure of practical understanding (Hall et al. 2018). However, little research provide insights on identifying and describing these shared principles and practices in details.

In order to benefit from the full advantages of IPD and DfMA methods and understand the risks associated with implementing their synergy in construction projects, more research is crucial. The aim of this paper is to report on a systematic literature review that aimed at identifying common principles and practices of IPD and DfMA.

METHODOLOGY

This study employs a systematic review methodological approach. As shown in Figure 1, this methodological framework consists of two phases: (1) data collection: identify the search keywords, identify the search databases, and search, screen, and select the relevant articles; (2) data analysis: content analysis using VOSviewer, synthesize, and developing a framework.

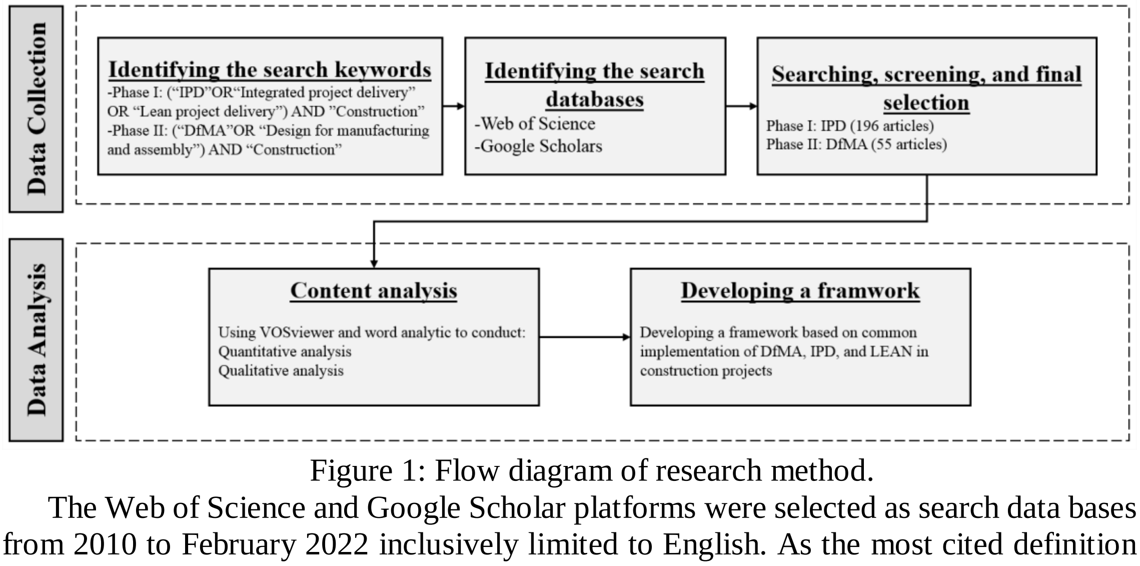

Figure 1: Flow diagram of research method.

The Web of Science and Google Scholar platforms were selected as search data bases from 2010 to February 2022 inclusively limited to English. As the most cited definition of IPD was proposed by AIA in 2010, we chose this time period to capture the most number of IPD relevant articles. For consistency, we covered the same search period for DfMA literature. As shown in Table 1, each keywords include controlled vocabulary and terms related to IPD and DfMA in the construction engineering domain.

Table 1: Search keywords.

IPD	DfMA
IPD	DfMA
LPD	Construction
Construction	Design for assembly
Lean Project Delivery	Design for manufacture
Integrated Project Delivery	Fabrication-aware-design
Integrated Design and Construction	Design for manufacture and assembly

The Lean construction community conducted significant research on IPD and DfMA. Therefore to grasp the true nature of the topic and assure the comprehensiveness of the review, in addition to electronic journal databases, conference databases related to Lean construction (i.e., proceeding database of the International Group for Lean Construction (IGLC)), are reviewed

The final selection and inclusion of relevant studies is done through: selection of articles by reviewing their titles and abstracts; primary screening the full texts to assure the relevance to the topic and the construction domain; and secondary screening of articles in circumstance of doubt about the relevance of a study. As shown in PRISMA diagram shown in Figure 2, a total of 196 papers for IPD and 55 papers for DfMA are included in this review. Among these articles, we have found a few papers (Lu et al., 2021; Langston & Zhang, 2021) which referred to the combined application DfMA and IPD in construction projects, but did not conduct further studies about it, as their principle research focus.

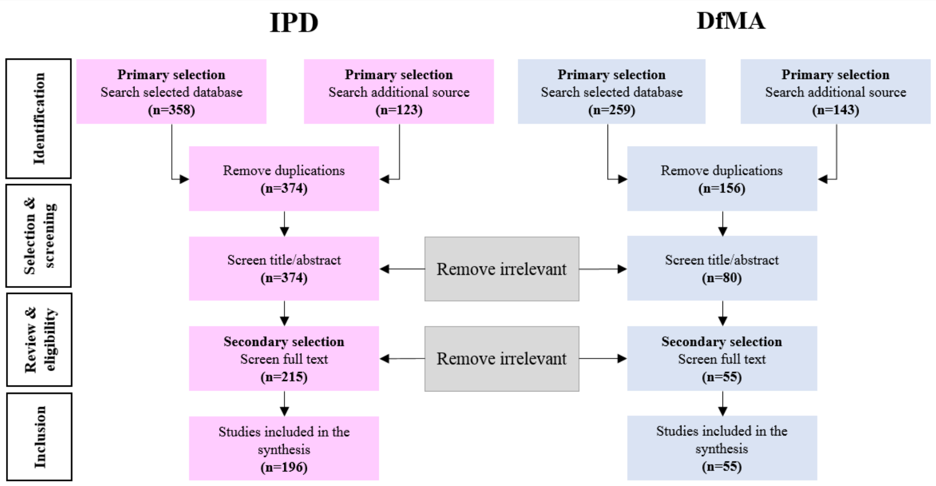

Figure 2: PRISMA diagram of the selected articles.

CONTENT ANALYSIS

RESEARCH TRENDS

The distribution of articles by the year of publication is depicted in Figure 3. As shown, there is an increasing interest toward IPD and DfMA research since 2010. In particular for the DfMA, in the year 2021, the number of publications doubled compared to the previous year. This shows a trend towards research about DfMA in the construction industry.

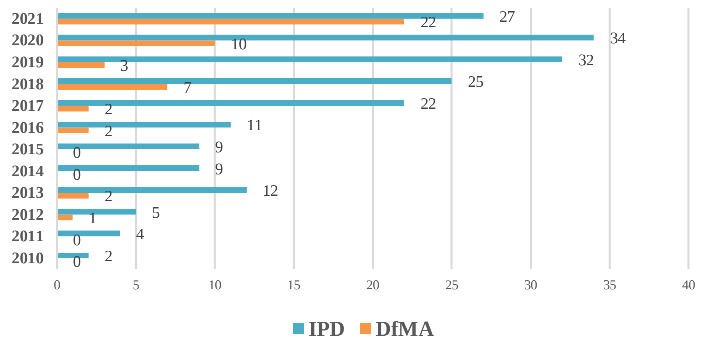

Figure 3: Distribution of articles by the year of publication.

The Sankey diagram in Figure 4 illustrates the IPD and DfMA research focus overtime, with respect to construction projects' phases. As shown, the volume of studies (width of blocks) has gradually increased over the past decade. Regarding research focus, IPD and DfMA studies focused more on the whole life-cycle of the project since 2015, while from 2010 to 2014 studies mostly focused on projects' design and construction stages.

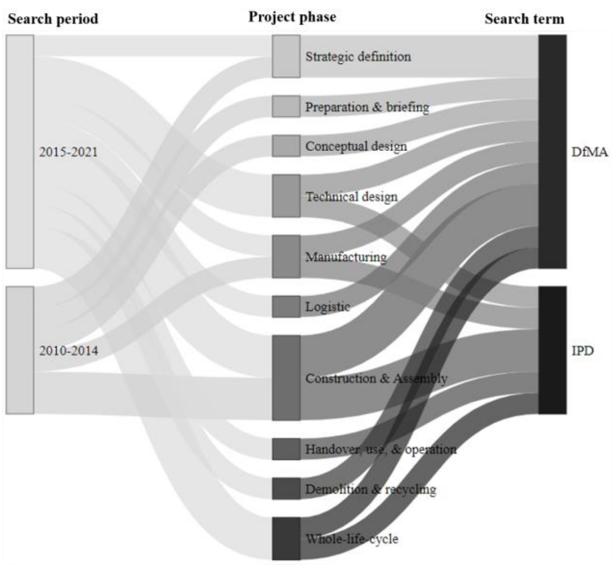

Figure 4: Sankey diagram of IPD & DfMA studies with respect to project phases.

WORD ANALYTIC

We used VOSviewer to conduct a word analytic and visualize the co-occurrence of keywords in IPD and DfMA literature. As shown in Figure 5, several keywords have co-occurred in both topics frequently; *Lean*, *BIM*, and *integration*, are discussed in this section.

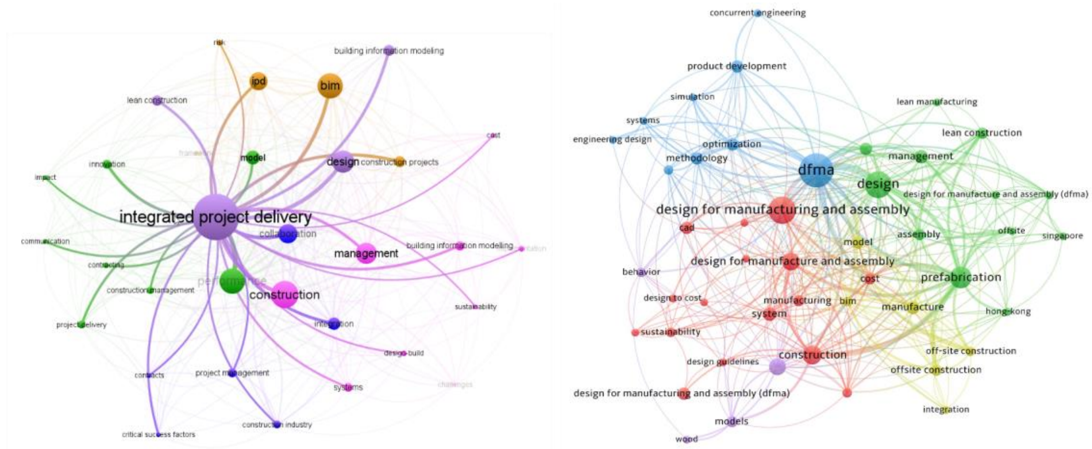

Figure 5: Co-occurrence of IPD (left) & DfMA (right) articles' keywords (VOSviewer).

Lean Construction

The keyword "Lean" has co-occurred frequently in both IPD and DfMA literature. It matches the procedural and cultural principles of both concepts. Lean Construction is a method of planning and optimizing the supply chain to minimize the waste of time, materials, and labour and maximize value (Koskela et al., 2002). Lean principles originated from car manufacturing and the Toyota production system (reference) and then adapted to the particular characteristics of construction projects, such as uniqueness, complexity, and 'one-off' project-based production processes. Lean construction principles are currently more diverse and focused on waste elimination, user-satisfaction, value-addition, and improved communications (Lu et al., 2021).

Literature shows that IPD and DfMA key principles are rooted in Lean principles and practices such as supply-chain-integration (SCI), just-in-time (JIT), automation (Jidoka), pull-planning, early contractor involvement (ECI), standardisation, waste reduction in cost, and labour, concurrent engineering (CE), client's commitment, target value design (Miron et al. 2015; Koskela et al 2002; Gerth et al. 2013; Kim and Lee 2010).

A few scholars investigated similarities and differences between Lean and these two approaches. Mesa et al. (2019) conducted a comparative analysis of IPD and Lean project delivery (LPD) methods through analysing of organizations, contractual relationships, and operational systems in projects. They found that the core difference between IPD and LPD is related to their operational system. Both approaches are similar in terms of encouraging the application of integrated organizations, relational contracting, and integrated delivery process. DfMA and Lean principles are also interrelated and mutually supportive in construction literature (Gerth et al.,2013). For instance, DfMA supports Lean construction practices by helping designers optimize design, reduce waste, and eliminate non-value adding activities in the project supply-chain, through minimizing the number of parts, and maximizing ease of handling and assembly. Ng and Hall (2019), conducted a review of Lean and DfMA literature, and concluded that the three Lean concepts of: JIT, quality improvement, and concurrent engineering (CE), are the most influencing factors in the adoption of DfMA.

Scholars conducted various studies on the mutual impact of these concepts on each other. Some report DfMA facilitate Lean process (Gbadamosi et al., 2018), while others report Lean enhances DfMA philosophy (Banks et al., 2018; Ramaji et al., 2017). Regarding IPD, some studies apply IPD and LPD perceptions interchangeably (Do et al., 2015), while some studies indicate that Lean Construction is a set of techniques which supports IPD (Mesa et al., 2019). In summary, while IPD, DfMA, and Lean principles are conceptually different with different focuses and scopes, they can bring common benefits and values to the construction industry, such as maximizing value, reducing construction cost and efforts, and improving construction productivity (Ogunbiyi et al., 2014).

Based on the review, we have identified all principles and practices of IPD, DfMA, and Lean cited in the literature. The Sankey diagram in Figure 6, illustrates the relationship between these principle (left column) and practices (right column), and how they are associated with the studied concepts (middle column). As shown, integration is the most cited principle, which relates to all three concepts. Also, several practices such as maximizing value, reducing costs, and eliminating wastes are shared between IPD, DfMA, and Lean.

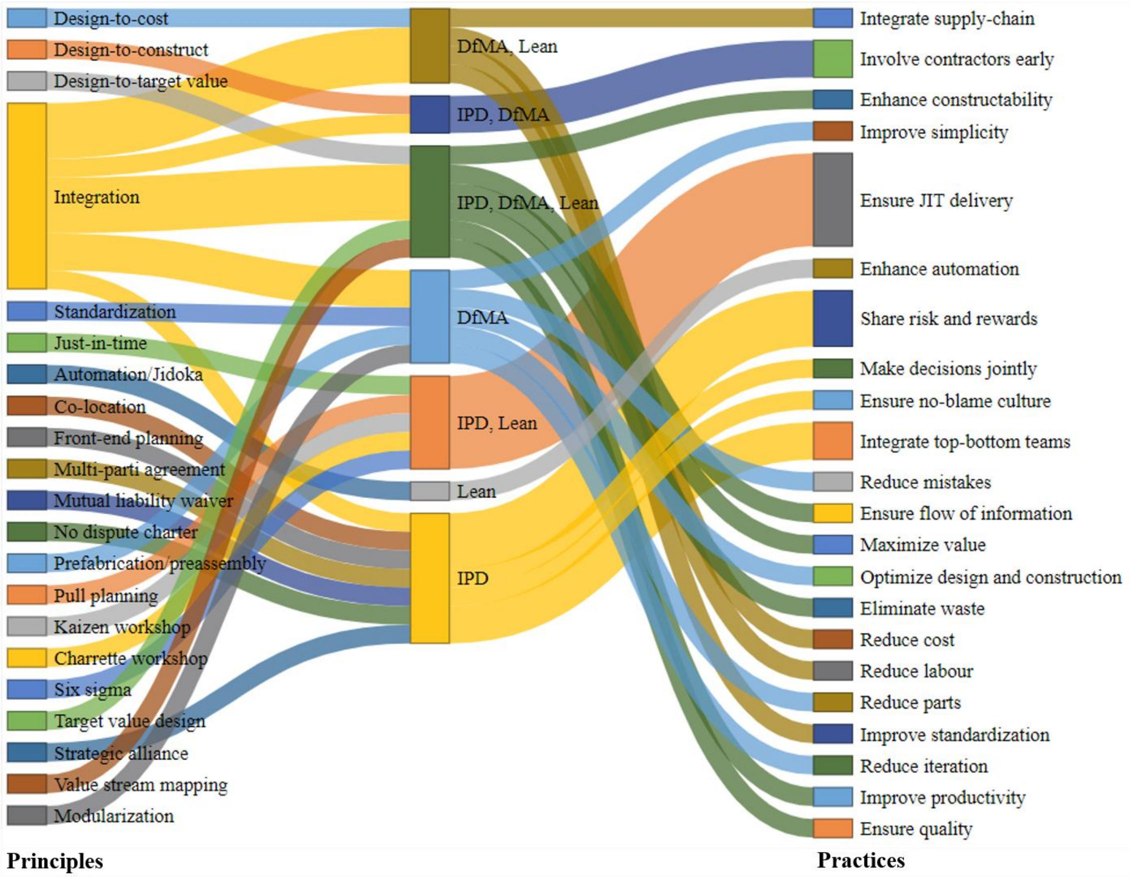

Figure 6: Sankey diagram of relationship between IPD, DfMA, and LEAN.

BIM

The term "building information modelling" or "BIM" has occurred frequently in both IPD and DfMA literatures. BIM is associated with the technological aspects of both concepts. A building information model is the digital representation of a building with its components characterized by parametric objects (Yin et al., 2019). Several studies identified that there is a trend toward the integration of DfMA, and IPD with technologies like BIM (Gerth et al. 2013; Lu et al., 2019; Bogus et al. 2006). There is a growing attention to the connection between IPD, BIM, and Lean construction in the literature, particularly for their application on large and complex projects (Langston et al., 2021). In both IPD and DfMA approaches, a high level of communication, collaboration and real-time data transfer among different stakeholders is required (Ng and Hall, 2019; Gerth et al. 2013), which can be addressed through various dimensions of BIM (2D, 3D, 4D, nD).

BIM can provide designers, engineers, suppliers, and contractors a seamless collaboration environment, as the digital model provides a platform to exchange ideas and share knowledge (Lu et al., 2021; Chen et al., 2017; Zhong et al., 2017). BIM facilitates the implementation of DfMA through acting as a design analysis tool for improving manufacturing and assembly processes. This platform can be used in IPD projects to verify whether DfMA principles are applied correctly to optimize the design for fabrication and construction (Lu et al., 2021).

Integration

The term "integration" also co-occurred frequently in both IPD and DfMA literature. This is due to the fact that both IPD and DfMA emphasize enhancing integration throughout the project life-cycle. Figure 7, provides a summary of IPD, DfMA, and LEAN individual and joint principles cited in the literature, which can improve integration from four perspectives: informational, organizational, geographical, and cognitive (Dallasega et al., 2018). As shown in grey, various digital tools and technologies can contribute to informational integration, and enable project participants to share knowledge while integrating project information.

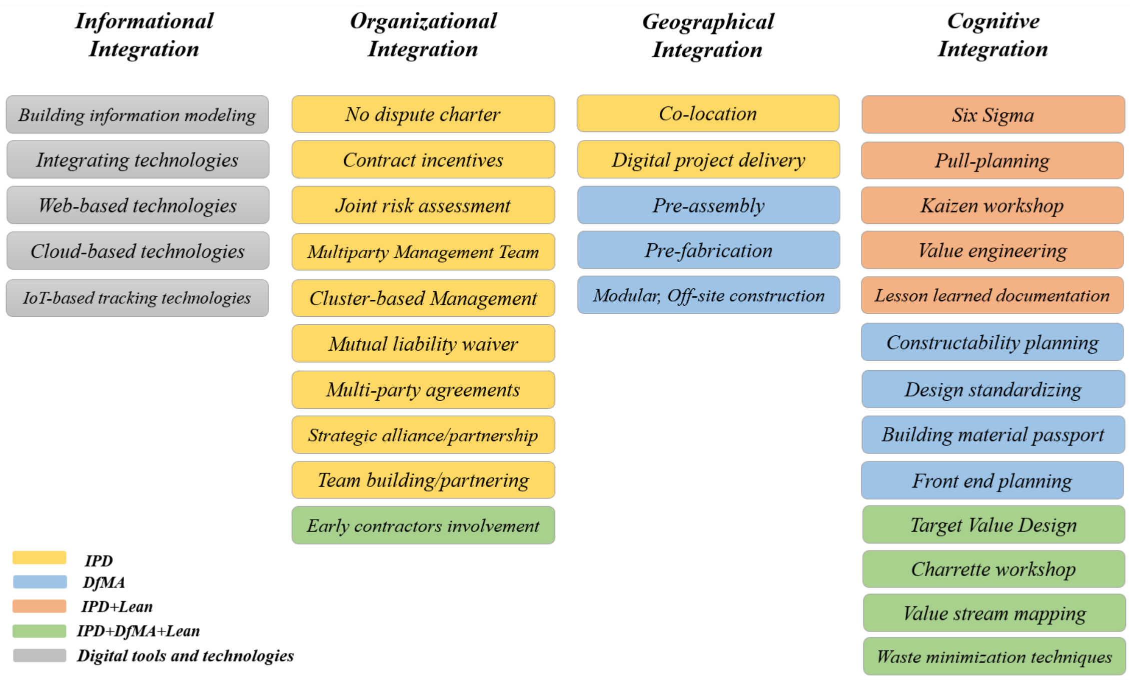

Figure 7: Various modes of integration based on IPD, DfMA, and Lean principles.

DISCUSSION

Based on the results of the literature review on synchronicities between DfMA, IPD and Lean a conceptual framework is proposed in this section (see figure 8). This framework outlines (I think this is better) future developments of these concepts, and helps improve their application in construction projects. The combination of these principles enhances supply-chain-integration and ensures stakeholders' collaboration for improving productivity from the initial design phases to the construction-closeout phases. The central part of the framework illustrates the implementation of DfMA concepts in different stages of a typical construction project. For instance, in the manufacturing and delivery phases, design-for-(additive)-manufacturing (Df(A)M), design-for-assembly

(DfA, for off-site construction projects), and design-for-logistics (DfL) criteria must be respected. Table 2, provides a full list of DfMA abbreviations with their complete name and description (Arnette et al., 2014). As shown, the core of the proposed framework is supported by Lean procedures, IPD contracting method, and an information sharing platform.

The Lean strategies in the platform emphasize on maximizing value, minimizing waste, creating an efficient workflow production system, and no redundancy (Langston & Zhang 2021) throughout the project life-cycle. Applying Lean principles and practices, improve value-based design, supply-chain-integration, just-in-time delivery, and construction automation in various phases of the project.

The contractual relationships are based on the IPD method, which emphasizes team integration, a no-blame collaborative culture, and shared risks and rewards. As shown in the framework, several standard forms of IPD contracting are available in North America, among which, CCDC30 (in Canada) and AIA C-191 and ConsensusDocs 300 (in USA) are the most cited contracting guidelines.

The technological platform, is based on applications which support the flow of information in various stages of a project, including BIM, Internet of Things (IoT), reality capture (RC) technologies, and smart logistics tracking applications. The digital platform assists with visualization (3D-BIM), schedule optimization (4D-BIM), cost management (5D-BIM), sustainability (6D-BIM), facility management (7D-BIM), health and safety (8D-BIM), maintenance (9D-BIM), and recycling (10D-BIM) (Lu et al., 2021).

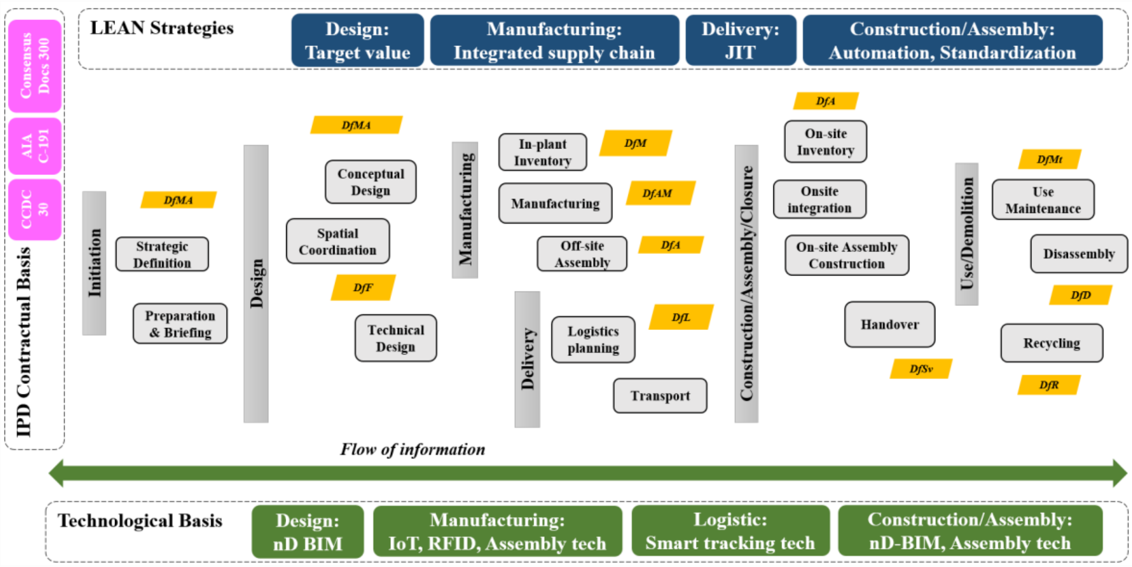

Figure 8: The proposed conceptual framework.

The combination of DfMA, IPD, and Lean along with the application of digital platforms, enable an efficient knowledge sharing, communication, and productivity monitoring throughout the project, and support a streamlined alignment of tools and techniques with people and processes as the basis for a new integration strategy. The proposed conceptual framework helps elucidate synergies and outlines future opportunities for the mutual application of DfMA, BIM, and Lean strategies in IPD construction projects.

Table 2: DfMA abbreviations, full names, and their descriptions.

Abbreviation	Full name	Description
DfMA	Manufacturing Assembly	Design products that can be fabricated efficiently
DfF	Flexibility	Create products and fabrication lines that are flexible to meet customers changing requirements
DfM	Manufacturing	Focus on the manufacturing stage of production
DfAM	Additive Manufacturing	Focus on the additive manufacturing of products
DfA	Assembly	Focus on the assembly stage of production
DfL	Logistics	Focus on designing products that can be shipped effectively
DFSv	Serviceability	Create products which can be repaired upon failure, by the consumer, company, or third-party
DFMt	Maintainability	Create products which can be maintained, and its life can be extended with proper maintenance
DfD	Demolition	Focus on disassembly of parts, components, or materials
DfR	Recycling	Focus on recycling of materials

CONCLUSION

In summary, the results of this review show that IPD and DfMA are expected to be increasingly adopted in the construction industry. The implementation of IPD methods, Lean principles, and information technology platforms such as BIM, can facilitate a smooth adoption of DfMA principles in construction projects. This study contributes to the existing body of knowledge by synthesizing IPD and DfMA similarities, and identifying common principles and practices, practices, to define potential synergies for increasing efficiencies in the design and construction of buildings. The results show that both IPD and DfMA have common Lean principles. They both aim to enhance integration across various stages of the project and both stress the importance of digital information sharing platforms for their successful implementation. Furthermore, this paper proposed a DfMA framework based on a synergy between IPD, Lean, and BIM. The proposed framework can improve future developments of DfMA method, when the implementation of BIM-based digital platforms, IPD, and Lean practices become routine in the construction industry.

ACKNOWLEDGMENTS

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VALUE-ADDING INDEX - SHARE OF DIRECT WORK INCLUDED IN UNINTERRUPTED PRESENCE TIME

Christopher Görsch[1], Zhao Jianyu[2] and Olli Seppänen[3]

ABSTRACT

Continuous improvement depends on appropriate productivity measures. Productivity can be measured through time-motion studies but relies heavily on manual efforts and therefore contributes insufficiently to real-time awareness in dynamic environments such as construction. Indoor positioning shows potential determining shares of construction workers VA (Value-adding), based on Bluetooth Low Energy technology in real-time. Different studies show positive correlations between VA and productivity.

However, it is unknown from location data how much workers engage in VA work while being present. Applying both methods simultaneously to one worker, this paper shows how to numerically quantify direct work (DW) and VA. Such combined data can show how much VA and DW occur when uninterrupted presence is detected while applying thresholds, indicating minimum durations spent inside work locations.

Utilizing a small data sample enabled proof-of-concept testing and resulted in numerical quantifications of DW and VA. Preliminary findings show larger proportions of DW and VA when uninterrupted presence time is higher. Future research needs to enlarge the included data. If findings hold true, uninterrupted presence with higher thresholds could predict more accurate workers´ VA levels in real-time. The study also contributes to knowledge positively impacting construction by bridging workers' behaviors on-site with monitoring technologies detecting movement.

KEYWORDS

Time-motion study, indoor-positioning, continuous improvement/kaizen, flow, lean construction

INTRODUCTION

Continuous improvement is a key principle in lean construction. Alarcón & Serpell (1996) as well as Jonsson & Rudberg (2017) reported that a principal barrier improving construction projects is the lack of appropriate productivity measurements. Different studies have reported a lack of comprehensive key performance indicators (KPIs) in construction industry (Alarcón & Serpell, 1996; Beatham et al. 2004; Costa et al. 2006). Metrics, in addition to cost and time are needed, since they are not capable of measuring

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VA, Value-supporting (VS) and non-value adding (NVA) time (Alarcón and Serpell, 1996), as the share of time spent on VA activities and construction labour productivity (CLP) are known to be positively correlated (Neve et al. 2020). Hereby, VA is understood as activities creating value for a requested product for a client, VS as necessary activities in supporting the value creation and NVA as inefficient processes, not creating value for a requested product (Ohno 1988). Noted in different studies (Beatham et al. 2004; Costa et al. 2006), current performance frameworks and indicators lack in compatibility, applicability and rationality, since most of them assess performance only from a certain perspective, which corresponds with the researchers´ technical background (Meng and Fenn 2019).

Over many decades, one method which has been frequently used is work sampling (Thomas, Guevara, and Gustenhoven 1984). The method quantifies time shares of DW and other work activities, by using a set of activity categories. Different researchers have applied different classification systems (Kalsaas, 2011; Neve et al. 2020; Thomas et al., 1984). Although a correlation between the proportion of DW and CLP has been demonstrated in work sampling studies, the observed proportion of DW had a high standard deviation between studies and there was no noticeable increase as a function of time (Neve et al. 2020). Work sampling has been further criticised for its snapshot-based approach e.g., every 5 minutes, and workflow interruptions of participants due to presence of the observer on-site (Dozzi & AbouRizk, 1993; Luo et al. 2018). Time-motion studies have been used as an alternative concept overcoming certain work sampling shortcomings e.g., reducing workflow interruptions, due to indirect site observations via filming with helmet mounted video cameras (Demirkesen et al. 2020). Nevertheless, both methods, rely heavily on manual data collection and analysis methods, which are still prone to error and labour intensive, insufficiently contributing real time monitoring and decision making (Goodrum et al. 2006).

In the light of these shortcomings, many approaches capturing on-site data in an automated way have emerged (Costin et al. 2012; Lin et al. 2013; Olievieri et al. 2017; Park et al. 2016). Several proposed technologies are applicable, but only a few studies demonstrate how a real-time tracking system can be applied to determine the share of VA of construction workers. Zhao et al. (2019) applied an indoor positioning system based on BLE technology, estimating presence indices, representing uninterrupted presence time of workers in work locations. The presence indices used to provide only limited information on whether workers engage in VA activities when being present in work locations, which does not provide accurate information on the share of VA time spent during workers' daily activities. Nevertheless, the study suggests that uninterrupted presence is strongly correlated with VA time and can therefore be used as a metric for measuring productivity on the project level, based on two basic assumptions:

1. If work gets interrupted, these are mostly NVA activities
2. If work is uninterrupted in work locations, VA activities are possibly taking place (although NVA can happen also in work locations).

By applying simultaneously, a time motion and an indoor positioning study on a mechanical, electrical and plumbing (MEP) worker, this paper combines video data from head mounted cameras and location data from indoor positioning Bluetooth Low Energy (BLE) technology. With this approach we try to find a methodological approach how to test these assumptions and how to answer the following research question: How much VA and DW really occurs when uninterrupted presence is detected by indoor positioning?

INDOOR POSITIONING & ITS LIMITATIONS

The location tracking solutions have been applied in many construction projects across the world. A common goal of implementing location tracking technologies in construction is to monitor site occurrences of workers and other site resources by knowing their movement and working patterns in terms of time and location. Typical tracking solutions include, for instance, BLE, Radio-frequency identification (RFID), Wi-Fi mesh network and Ultra-Wideband (UWB). All these tracking methods can be applied in an indoor environment. RFID has been proposed by Costin et al., (2012) where the research team studied this tracking method to be implemented in high-rise buildings to record workers' timestamps and movement patterns during the workdays. Another example is BLE, which has been applied in indoor construction projects in the past where workers' task progressed can be monitored based on time and location detected by this tracking method (Olivieri et al. 2017; Zhao et al. 2019).

Taking indoor BLE technology as an example, the advantage of this monitoring methods is notable. First, it has been shown to be reliable and relatively accurate for indoor continuous monitoring of workers in construction (Park et al., 2016). Second, the monitoring method is also cost-efficient and easy to set up and use. In one previous study the BLE tracking solution was successfully used for workers' time and location information onsite (Zhao et al. 2019). More specifically, presence of workers has been also analysed intensively based on this technology in the previous case, where it is believed to have direct correlation with VA of workers performing their tasks. For example, the presence index was examined to determine the amount of absenteeism that workers spend within their working hours but outside their work location. This indicates, workers spend a lot of time on NVA activities at work (Zhao et al, 2019). Building on top of the previous application in using BLE method to be able to detect workers' presence, we think it is a suitable tracking solution in the current study where we aim to analyse the relation between workers' presence level connected with their VA.

However, the connection of time spent of workers in work locations and their actual VA times have not been clearly studied in a quantifiable matter. Without ground-truth data, it is difficult to evaluate the exact proportion of workers' presence which is VA or NVA (Zhao et al, 2019). However, it is reasonable to assume that task interruptions should have notable impacts on workers' VA activities performed onsite, because a worker should stay at one work location for an uninterrupted period in order to perform VA work. When the work gets interrupted and is fragmented into small time durations and several locations, waste and NVA activities are more likely to happen during these times. Therefore, it is reasonable to assume that the more task interruptions there are less likely for uninterrupted presence to accumulate at one work location. However, it is not known how much of the uninterrupted presence is really VA and can it happen during interruptions. One way to identify NVA times in construction is to use a time-motion study approach based on camera data to provide ground-truth data of workers' real behaviours.

METHOD: EVALUATING PRESENCE TIME WITH VIDEO DATA

Two methods were utilized to collect quantitative data via time-motion study and an indoor position beacon tracking within a research project considering productivity issues in MEP work, which often has been considered complex and has shown low shares of direct work. The research project´s focus, as well as needed data form both methods simultaneously set exclusion criteria for possible participants. In spring 2021 in a hotel and office construction project, both criteria were met, a MEP installer voluntarily signed up for a time-motion study and indoor position tracking simultaneously.

Time-motion data from helmet cameras was analysed quantitatively by categorizing the participant´s actions. Table 1 provides descriptions of the used categories and their classification as VA, VS, NVA and Unclassified (UC).

Table 1: Activity Classification Categories

Nr.	Category	Description	Value Category
1	Direct Work	Consist of activities, which increase the value of a building, component, or product.	VA
2	Inspection	Quality control measures that reduce the risk of recurrence.	VA
3	Work Preparation	All the preparatory work steps required to begin the work phase. Includes arrangement of tools and material on site (<= 5m from installation point). Includes a review of plans (as well as technical plans, material lists, schedules, etc.).	VS
4	Working with Material	Includes all work on material that prepares it for installation or holds it in place (e.g., cutting, joining with cable ties, etc.).	VS
5	Measurement	In addition to measurements, it includes recording measurement data in notebooks or on walls, for example. Includes small movements needed to take longer dimensions.	VS
6	Maintenance & Cleaning	Includes activities needed to continue working. For example, replacing tool batteries, repairing broken tools, cleaning during work, or cleaning after work.	VS
7	Hauling, short Distance	Transfer of material, equipment and tools, distance 5-30 meters from installation area.	VS
8	Hauling, long Distance	Transfer of material, equipment and tools, distance 30+ meters from installation area.	VS
9	Searching	Any activity looking for materials, tools, and equipment, which are not considered as work preparation (e.g., it takes a long time to find a missing tool).	NVA
10	Movement	Any activity involving movement without a clear purpose and not included in other categories. For example, aimless movement without material, equipment, or tools.	NVA
11	Re-work	Activities that need to be done again. Usually related to an error in the installer´s work, previous work steps of others, or changed plans.	NVA
12	Non-work-related Actions	All other activities, which are not included in other categories. E.g., waiting times and times spent walking to the site, but not discussions (category 13).	NVA
13	Discussions	All conversations with other people (including phone conversations). The content of the conversations cannot usually be deduced due to muted recordings.	UC
14	Unclear	Activities, which cannot be identified due to footage quality of angle of camera, etc.	UC

Due to ethical consideration, footage including “Discussions” was classified as UC, since the video material was muted. Furthermore, unclear video sections were also classified as UC. During the recording time workers were equipped with the set up shown in Figure

1. Filming from an installer´s point of view, covering an area of approximately 180°, gave the possibility to follow the worker´s workflow continuously. At the beginning of the data collection, the participant was sceptical about the approach, which clearly changed into a proactive attitude over the course of the week. Due to the weight of the attached camera and power bank, the installer reported some discomfort at the beginning of the data collection, which became irrelevant as time went on. In addition, it should be mentioned that the approach required daily time to set up and maintain the camera equipment, which counts for 1% of the total working time. Attention should be also drawn to video material that was classified as "Unclear" because it could not be identified from the footage (e.g., changed camera angle, insufficient brightness in working areas, too close to an object - overhead work) (< 0.5% of total working time).

Figure 1: Used camera and helmet equipment

The analysed video data set includes data from one plumbing worker, covering about 50 % of one working day (representing 3:49:07 hours). Reasons for such a subset, including less filming time than actual work time are the exclusion of break times and interruptions by research project staff, as well as unrecorded footage due to bathroom trips and technical problems with camera equipment (e.g., run out of battery). The worker´s working day was occupied with installing drainage pipes on different floors and re-work on the installation of a drainage system. The installer´s work was characterized by a high degree of customize installation work, which require a variety of small components and materials. Throughout the working day, needed materials went often short, so the installer spent long durations on material organization tasks like discussing, searching, and hauling. Tasks were carried out in a hotel and office building construction project with a total scope of 22.000 sqm on eight floors and two underground floors. The project was additionally using two outside elevators and off-site storage areas, which impacted the amount of hauling on-site. Furthermore, during filming, the work situation became increasingly tense as the installer had to catch up on backlogs of work after returning from a two-week Corona quarantine.

Simultaneously, the filmed worker wore an indoor positioning beacon which provided information of workers' location. Due to the installation of gateways on each of floor of the office building, the worker´s presence time was analysed at floor level. The reason for targeting at floor level is due to the availability of power supply at floor level, therefore we were able to place gateways near the stairwell and workers' main working areas. The corresponding data set represents a 7,5 hours of location data. Due to various difference in the data structure of both data sets, manual adjustments had to be made e.g., synchronizing time stamps, or applying Zhao et al.´s (2019) developed heuristics to location data. Due to the use of new filming devices, their time settings did not match the actual recording dates and times. Therefore, time information of the location tracking system (using actual date and time) was applied to the video data by finding a common starting point. Such a starting point was detected by matching time data in the video footage from computers and smartphones with the time stamp of the location data.

Table 2 shows an example of the merged data structure. Columns A-E show categorized and observed data from the helmet cameras, an activity of getting to the installation area, and gathering tools and materials from there classified as work preparation and VS. The activities lasted in total 114 seconds, whereby the worker changed its position based on the tracked location status. Columns G-J indicate the installer went from an undetected status to and detected status at 7:23:49 in the morning, and here the worker was located at gateway 83, which represents the entrance on the south-west site of the office building.

Table 2: Structure of merged Video and Location Data

Nr.	Activity Classification	Description	Value Classification	Time Stamp	Duration in Seconds	Heuristic applied	Gateway adjusted	Detection Time	Gateway Detection
1	Work Preparation	Walking to Installation Area	Value Supporting	07:23:39	10	presence	basement 1 stairs		undetected
2	Work Preparation	Walking to Installation Area	Value Supporting	07:23:49	26	presence	basement 1 south west	7:23:49	83
3	Work Preparation	Walking to Installation Area	Value Supporting	07:24:15	27	presence	basement 1 south west	7:24:15	undetected
4	Work Preparation	Gathering of Tools	Value Supporting	07:24:42	81	presence	basement 1 south west		undetected

If only video data would be considered, Table 2 would show two lines: 1. Work Preparation (walking to the installation area) and 4. Work Preparation (gathering of tools). Due to data merging and the detection of a changed location in the middle of activities, line 2. and 3. have been added. After applying Zhao et al.´s (2019) heuristics (Column G) this example was considered at 114 seconds being present on site. Heuristics aim to look for undetected durations of workers and put some of those time intervals back to assigned work locations according to different scenarios. For instance, if a worker leaves from a work location for some undetected time and then returns to the same location, it is reasonable to assume that the undetected time should be the time spent at that work location as well (but just not detected by our system).

SHARE OF VA & DW INCLUDED IN UNINTERRUPTED PRESENCE TIME

The video material was watched and classified by researchers. Figure 2 shows the classified activities accumulated, how much time in percentage the participant spent on different activities during his working day. The share of direct work was just 10.6 % and the share of VA was 14.6 % for the analysed footage, which is lower than percentages reported in work sampling studies, where the mean appears to be 30-40% (Neve et al. 2020).

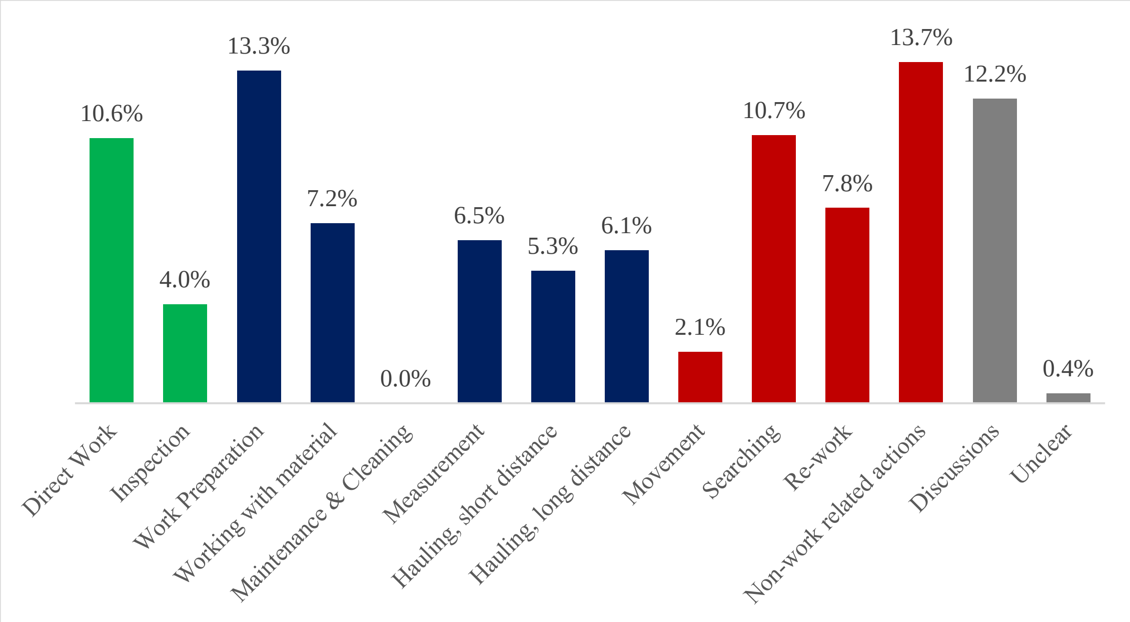

Figure 2: Share of Activities in per cent during one working day of Sewage Piping, Note: green bars = VA, blue = VS, red = NVA, and grey = unclassified activities; Break times are excluded from classified materials, not included in category "Non-work related Actions"

Time motion data requires a huge manual effort classifying the material. For production planning and control, it is important to find measurable and available data sources that can be processed in real time in order to influence decision making in a dynamic and fast progressing on-site environment to improve CLP.

Indoor positioning data is believed to provide a series of capable KPIs for the above-mentioned aims. Indoor positioning allows detecting presence of workers in work locations. However, from this data, it is unknown whether installers engage in VA work while being present, but it is believed that installers achieve less VA work, when briefly visiting work locations or spending time in non-work locations. Installers' presence time in work locations as a measure can be seen as a necessary but not sufficient KPI measuring VA time. In earlier research indoor positioning was applied without considering differences between tasks in their set up time (length of time a worker needs to be present before value can be added) (Zhao et al. 2019). Therefore, different THs were introduced to see their effects on the share of uninterrupted presence time, based on the work from Zhao et al. (2019). Here, uninterrupted presence refers to a period a worker spends constantly in a designated work location. A TH represents a minimum period of time spent within a work location before that work duration is considered as uninterrupted presence time. Applying the different THs can be seen as filtering time intervals of interrupted presence out of the data set, according to the applied TH level. This procedure is intended to filter out UC, NVA and VS activities in order to obtain an indicator that represents VA time as accurately as possible, since we have the assumption that more DW and VA occurs when longer uninterrupted in a work location. Figure 3 shows the amount of excluded data (in minutes) related to each category (VA, VS, NVA, and Unclassified activities).

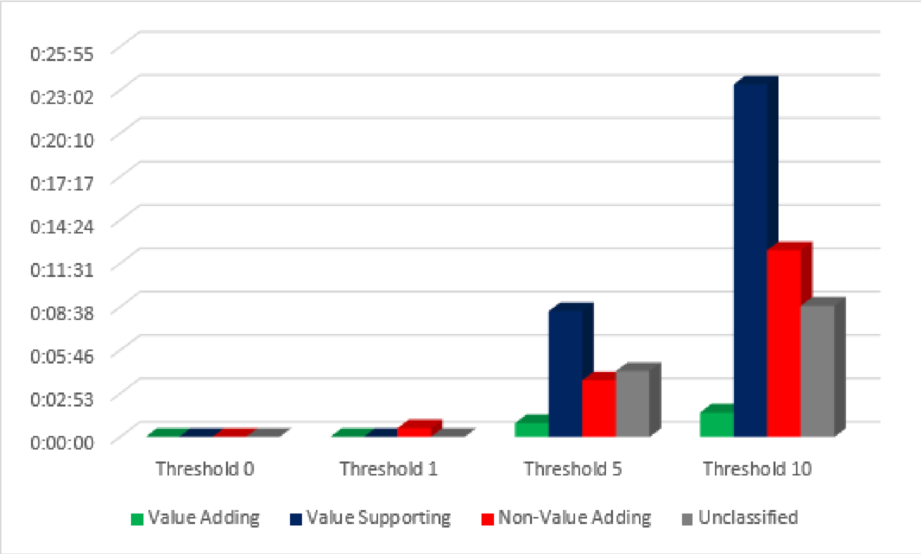

Figure 3: Time exclusion of value categories due to rising TH level

THs 0 and 1 are not showing a significant difference because the share of filtered activities is low while setting the TH to 5 minutes filters out 8.2 % and the TH of 10 minutes filters out 21.8 % of the activities. In both higher THs, VS activities are excluded the most (approx. half of the excluded material), which is surprising and in contrast to the first assumption since it is not NVA activities that most often occur when work gets interrupted. Within in this data set, VS activities took place mostly when work gets interrupted. In conclusion, the analysed data does not indicate support for the first assumption (1. Assumption: If work gets interrupted, these are mostly NVA activities).

Figure 4 shows the amount of excluded data from the different classified activities. Activities excluded the most are “Work Preparation”, “Measurement”, “Hauling, long distance”, “Searching”, “Non-work-related actions”, and “Discussions. Logistically necessary changes between work locations were classified as "work preparation" e.g., moving from one work location to the next after completing an installation task. Gather tools and setting them up at the next work location were also considered as "work preparation." On such occasions, "measurements" often take place along with reviewing plans to verify completed installation work or to verify conditions at the next work location. These operations often result in short location changes, e.g., to obtain additional or different materials and tools, which in turn require short work preparations to match the materials with the plans and measurements in storage areas. The activities "work preparation" and "measurement" account for 36.3 % of the excluded material of TH 10.

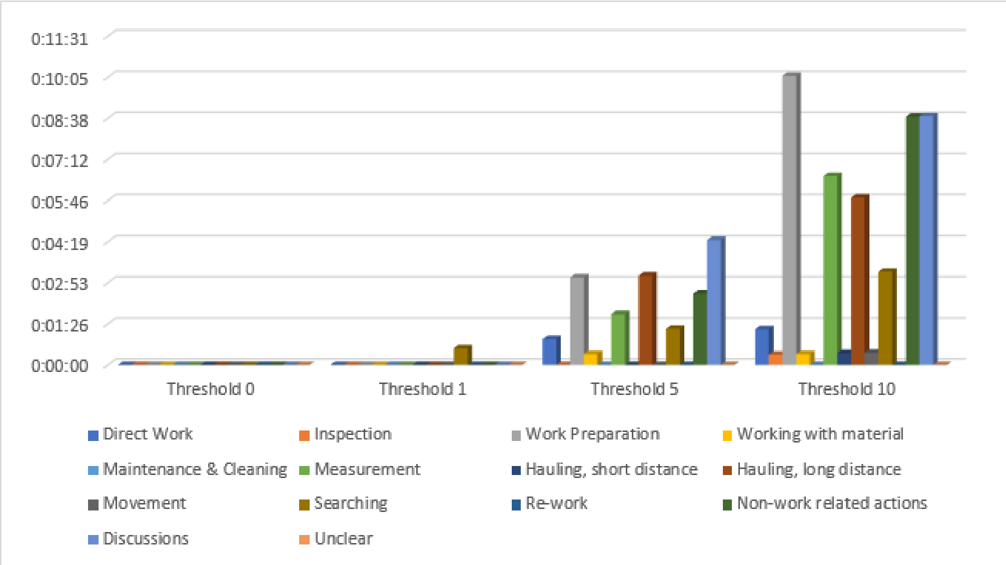

Figure 4: Time exclusion of activities due to rising THs

The above-described scenarios also explain excluded shares of "Searching" and "Hauling, long distance" activities (account together for 19.8 % of excluded material of TH 10), which often occur consecutively. Time spent on all activities depends on a variety of factors within this observed work set up e.g., logistical arrangements for storage, installation, transportation, and work areas; tidiness in these areas; worker´s awareness of these arrangements; or the degree of on-site work with the need for customized solutions. An outcome if these factors are unbalanced can be an additional need for clarification and build-up of understanding e.g., through on-site communication in form of face-to-face and phone discussions (accounts for 18.9 % of excluded material at TH 10). Another large portion (18.9 %) excluded while applying TH 10, are shares of "Non-work-related actions" in form of unintentional movement or smartphone checks, often happening while a workflow gets interrupted due to location changes, missing tools or materials, unclear plans, etc.

With the merged data it was also possible to calculate the share of DW and overall VA work included in the different THs of uninterrupted presence.

Table 13 shows the share of DW and VA time at TH levels 0, 1, 5, and 10 min. The table tells us, for instance, that when the TH was set to 10 minutes, DW took up to 14% of total uninterrupted presence while 19.2% of VA time (sum of DW and inspection times) inside of total uninterrupted presence.

Table 1 Share of DW and VA when TH is 0, 1, 5, or 10

	TH 0	TH 1	TH 5	TH 10
DW absolute	24:20	24:20	23:25	23:05
DW %	11.5%	11.5%	12.1%	14.0%
VA absolute	33:25	33:25	32:30	31:48
VA in %	15.8%	15.8%	16.8%	19.2%
Uninterrupted Presence Time	221:25	220:50	193:59	165:16
Uninterrupted Presence Index	92.3%	92.3%	84.7%	72.1%

The uninterrupted presence index was calculated based on the operation time of 3:49:07, which corresponds to the amount of video material with simultaneous location data. The analysed data indicates that higher THs include higher shares of VA and DW, because of the exclusion of shorter interrupted sequences, which contain higher shares of NVA, VS, and UC activities than longer sequences (VS activities occur most in shorter sequences, see above). Although the small data sample does not allow conclusions to be drawn, it indicates support for the second assumption that DW and VA activities are more likely to occur when work is uninterrupted in a work location over longer periods. Thus, higher THs seem to represent an indicator for measuring DW and VA more accurately than lower THs.

It is worth mentioning, although being present in a work location over longer periods, containing higher shares of VA and DW, other activities take place. Another interesting viewpoint is the amount of excluded DW. Whereas THs 0 and 1 don't exclude any shares of DW, THs 5 and 10 do exclude some of it. It accounts for less than 1 %, but still practically means VA and DW happening while not associated as present.

From a practical standpoint, this particular data set indicates the installer performed more DW and VA activities when uninterrupted presence time got less often fragmented. Accordingly, to increase CLP, we assume construction managers and other on-site players should aim for measures increasing the uninterrupted presences index at higher THs, whereby THs can vary depending on tasks and trades. With other words, measures to increase CLP need to focus on process coordination and logistical supplies in such a manner, installers have the chance to stay for longer periods inside the work location.

CONCLUSIONS

The study has presented a numerical result where uninterrupted presence, VA and DW time were analysed based on indoor positioning tracking technology and video monitoring in construction. We found that work sequences with higher uninterrupted presence time, TH was set to 10 minutes, hold 19.2% of VA time and 14% of DW. If also work sequences with lower THs (0) were considered, lower shares of DW (15.8 %) and VA (11.5%) were detected. The drop in percentage goes back to higher shares of VS, NVA, and UC activities in more frequent interrupted work sequences.

The small data does not allow to make conclusions based on these findings, which is the limiting factor to the meaningfulness of the results. It contains location data and video material of one specific worker from one specific construction project in Finland over the course of one working day. Future research needs to enlarge the volume of data and address what amount of data is needed to make more accurate conclusion on a project and industry level. We followed Zhao et al's (2019) research on improving system's coverage by using heuristics in indoor positioning dataset, however, it should be noted that in future the gateways should be placed more densely to ensure the satisfying coverage so that heuristics would not be needed.

However, the study contributes to knowledge that the share of VA level inside of workers' uninterrupted presences can be numerically quantified, bridging more clear connection between VA assessment and presence time analysis in construction. In future, if such dataset can be enlarged to establish this correlation despite task differences, the uninterrupted presence with higher THs can then be used to predict more accurate the VA level of workers without scanning through camera videos relying on manual efforts. In addition, this could be used to determine poor productivity levels when occurring on-site and based on this, the extent to which measures to increase productivity are effective.

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UNCOVERING AND VISUALIZING WORK PROCESS INTERRUPTIONS THROUGH QUANTITATIVE WORKFLOW ANALYSIS

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ABSTRACT

Continuous improvement requires visualizing process constraints which interrupt workflows. Production control from a management perspective often operates at lower levels of information granularity than required at operational levels to perform work without interruptions. If not controlled in detail, causes and effects of workflow interruptions remain unclear in environments of high complexity and non-standardized work.

Workflow efficiency has been studied through work sampling or time-motion studies, estimating shares of direct work. However, few studies exist that show how to create digital representations of workflows and analyse them for interruptions, contributing to smoother workflows. The paper examines workflows of plumbing work from video footage. This video data is classified and analysed for frequency, causes, and effects of work interruptions.

Results indicate that value-supporting activities caused the largest proportion of interruptions. Moreover, the proportion of non-value-adding activities increases when durations of interruptions rise. Based on the results, the paper contributes to further understanding of workflow interruptions in plumbing work. Finally, it provides suggestions on how to close gaps of information granularity between management and operational levels, through the development of simulation models and the application of automated data collection, contributing to developing digital twins of construction processes.

KEYWORDS

continuous improvement/kaizen, production control, job-sequencing, time-motion study, workflow.

INTRODUCTION

On-site production in the construction industry comprises individual but interdependent units with different requirements, workflows and equipment that together create a product

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over time (Chua et al. 2010). In such a dynamic, complex, and uncertain environment, adapting to unforeseen circumstances is key to ensuring coordinated and smooth operations. Deviations from schedules and standard processes cannot be completely prevented, although countermeasures are often taken at the management level and improvisation at the operational level (Hamzehet al. 2019).

Production control approaches like the Location-Based Management System and the Last Planner System aim to reduce waste, decrease variability, and increase productivity. Both are used to track completed tasks by comparing actual start and finish dates with planned milestones and adjusting accordingly through a technical or social process at trade and project levels (Kenley & Seppänen, 2010). At trade levels, the detail of information required to perform daily or task-related work is of higher granularity than at a project level as in LPS and LBMS (Görschet al. 2020; Grau et al. 2020). Task orders at operational levels should include start and end dates as well as information on the products to be built, locations, materials, equipment, method, etc. (Song, Fischer, & Theis, 2017). Production control, operating at a lower level of information, can be seen as a black box where the cause and effect of constraints remain unclear. However, to reduce variability and increase productivity, process inefficiencies in the form of waste must be made visible and eliminated accordingly (Koskela, 2000). Time-motion studies enable collecting workflow information of individual workers in detail (Demirksen et al. 2020) and reveal ineffeciencies in the supporting environment.

The paper aims to analyse the revealed gap in information granularity (black box) by collecting workflow data from a time-motion study and analysing causes and effects of workflow interruptions. The study focuses on plumbing work, which is often considered complex. The paper aims to answer the research questions: 1) How can workflow interruptions in plumbing work be analysed and explained? 2) How can an analysis of workflow interruptions help to close the information granularity gap? Answering research question two leads to a discussion on how such a quantitative approach can be utilized in the future by a digital twin model to improve individual workflows and decision-making continuously in real-time (Sacks et al. 2020).

LITERATURE REVIEW

Workflows and their efficiency have often been studied (Kalsaas 2010; Neve et al. 2020; Thomas et al. 1984) using work sampling methods observing on-site activities of workers either qualitatively (Grosskopf et al. 2013) or quantitatively (Kalsaas et al. 2014)) Observations are often conducted over extended periods of time, but lack in considering long-term causes and effects Collected data points represent situational perceptions (snapshots taken at random or regular intervals) rather than ongoing work processes (Jenkins & Orth, 2004).

Alternatively, video-based work sampling allows the application of time-motion studies. Time-motion studies are recognized as the combination of an industrial efficiency technique (time study) by Taylor (1911) and a labour process analysis technique (motion study) by Gilbreth and Gilbreth (1922). Activities needed to execute a task are continuously and directly observed, by tracking their time durations (Thomas et al. 1991). Such studies are widely used for determining time needed to carry out tasks, finding most economical ways of executing work, smoothing workflows, standardization of methods, and work training (Barnes 1949; Meyers and Stewart 2002). Time-motion studies can examine workflows, including their share of direct work (Demirkesen, Sadikoglu, & Jayamanne, 2020), and analyse causes of interruptions. Time-motion data can be seen as a quantitative and digital representation of an installers individual workflow based on real-time data. The analysis requires a high manual effort and is not done in real time. However, such a workflow representation allows comparisons between the as-designed, as-planned, as-built, and as-performed states of a construction project, which can be seen as a digital twin of a construction processes (Sacks et al. 2020). This lean approach of a digital workflow visualization based on real-time data facilitates visualizing process inefficiencies and helps in selecting appropriate control for flow. This also allows production teams to prioritize their work to ensure a continuous subsequent flow of work (Sacks et al. 2009).

METHOD

To observe an installer´s activities, a time-motion study was conducted. A video-based work sampling approach has been chosen to examine such a workflow in detail and study the causes of interruptions over the course of an entire workday. Before commencing research, the study was evaluated by the university's ethical committee and discussed with employee and employer unions. The concerns raised by labour unions and ethical committee led to muting audio tracks of all video material. Furthermore, face-blurring software was applied to anonymize personal data captured by cameras, such as faces, and car license plates. We conducted the study using helmet mounted cameras with attached safety equipment and power banks as shown in Figure 1.

Figure 1: Used camera and helmet equipment

The participant´s activities were filmed from an installer's point of view, covering an angle of about 180°. This gave the opportunity to continuously follow the worker's workflow. At the beginning of the data collection, the participant was sceptical about the approach, which clearly changed into a proactive attitude during the week. Due to the weight of the attached camera and power bank, the installer reported some discomfort at the beginning but dissipated over time. In addition, daily set up times for the camera was required, which accounted for 1,8 % of his total working time.

After recording on-site, the video footage was watched and simultaneously classified by researchers in excel, quantifying durations of activities and developing an understanding of its root causes. Based on previous research (Kalsaas, 2010; Neve et al. 2020; Pasila, 2019), the video footage was classified according to 14 distinct categories. Table 1 describes these categories and shows whether the categories were considered as Value Adding (VA), Value Supporting (VS) or Non-value adding (NVA). Due to the muted video material, it was not possible to classify verbal conversations as VA, VS, or NVA. That is why "Discussions" have the value category "Unclassified" (UC). Additionally, break times and times due to research project related issues (helmet set-up, questions from participants to research assistants) have been excluded from the data set.

Table 1: Activity Classification Categories

Nr.	Category	Description	Value Category
1	Direct Work	Consist of activities, which increase the value of a building, component, or product.	VA
2	Inspection	Quality control measures that reduce the risk of recurrence.	VA
3	Work Preparation	All the preparatory work steps required to begin the work phase. Includes arrangement of tools and material on site (<= 5m from installation point). Includes a review of plans (as well as technical plans, material lists, schedules, etc.).	VS
4	Working with Material	Includes all work on material that prepares it for installation or holds it in place (e.g., cutting, joining with cable ties, etc.).	VS
5	Measurement	In addition to measurements, it includes recording measurement data in notebooks or on walls, for example. Includes small movements needed to take longer dimensions.	VS
6	Maintenance & Cleaning	Includes activities needed to continue working. For example, replacing tool batteries, repairing broken tools, cleaning during work, or cleaning after work.	VS
7	Hauling, short Distance	Transfer of material, equipment and tools, distance 5-30 meters from installation area.	VS
8	Hauling, long Distance	Transfer of material, equipment and tools, distance 30+ meters from installation area.	VS
9	Searching	Any activity looking for materials, tools, and equipment, which are not considered as work preparation (e.g., it takes a long time to find a missing tool).	NVA
10	Movement	Any activity involving movement without a clear purpose and not included in other categories. For example, aimless movement without material, equipment, or tools.	NVA
11	Re-work	Activities that need to be done again. Usually related to an error in the installer´s work, previous work steps of others, or changed plans.	NVA
12	Non-work-related Actions	All other activities, which are not included in other categories. E.g., waiting times and times spent walking to the site, but not discussions (category 13).	NVA
13	Discussions	All conversations with other people (including phone conversations). The content of the conversations cannot usually be deduced due to muted recordings.	UC
14	Unclear	Activities, which cannot be identified due to low footage quality	UC

The classified data represents a continuous flow of all activities during the participants workday, rather than individual data points taken as snapshots in specific time intervals. To build resilient processes that are protected from uncertainty, it is crucial to identify barriers to uninterrupted workflows in the form of activities that do not add value to the process (Grosskopf et al. 2013). To understand workflow interruptions in more detail we explored the data set quantitatively on the number of activities, interruptions, and their average lengths. Causes of direct work interruptions were further investigated.

The research was conducted in spring 2021 in a hotel and office construction project. To answer the research questions and test the quantitative analysis approach, we focused on one working day of one worker (equivalent to 5 hours 20 minutes and 15 seconds). Data used in this paper are a subset of the data collected within a larger research project. The analysed participant worked on plumbing tasks, installing copper pipes for warm and cold-water supplies. Overall, the construction project´s scope covered 22.000 sqm on eight floors and two underground floors. Additionally, two outside elevators were installed to reach off-site storage areas, which could impact movement on-site.

RESULTS

The footage has been analysed by classifying each activity by its category (table 1) and duration. Figure 2 shows shares of time spent on activities based on the classification scheme.

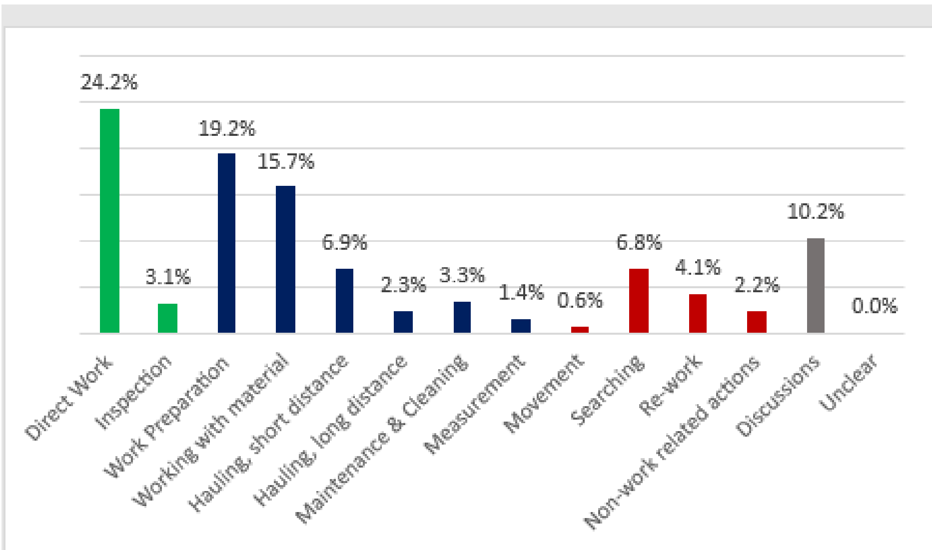

Figure 2: Share of Activities in percentage during one working day of plumbing work; Note: green bars = VA, blue bars = VS, red bars = NVA, and grey bars = UC activities

By adding up activity categories to value categories, figure 2 shows 27.3 % of time is spent on VA, 48.8 % on VS, 13.7 % on NVA, and 10.2 % on UC activities. Certain categories include wasteful activities. In this project, copper pipe work showed a high level of on-site customized solutions, resulting in high shares of “Work Preparation” (19.2 %) and “Working with Material” (15.7 %) inside the work location. Due to the high degree of customized solutions, direct work was often interrupted by workplace adjustments. These adjustments included the collection of tools, materials, and equipment relocations as well as other movement-related activities in the immediate vicinity of the installation area, even though the work area was constantly available and not occupied by other trades. In addition, 9.2 % of the installer's working time was spent on hauling activities, mostly within a radius of less than 30 metres. Although the storage areas were scheduled and accessible during working hours, there was a lot of movement due to frequent material and tool gatherings. Reasons for these frequent pickups were working with a step-by-step mentality, limited transport, and storage capacities and non-existent or insufficient work orders. Search activities (6.8 %) often arose due to the lack of material and tools during the actual task execution, as well as insufficiently organized storage areas. Other activities that reduced VA shares were “Discussions” with a 10.2 % share. Insufficient information flows were caused by e.g., outdated plans and schedules, and led to improvisation and the need of clarifications via face-to-face discussions, phone calls and instant messaging. Overall, these issues rarely prevented work, but led to improvisations and inefficient workflows.

Figure 3 visualizes the workers workflow by classified activities and their durations. From an installer´s perspective, workflow interruptions can be seen as the division of processes into individual activities that are supportive or unproductive in nature. Workflow interruptions are thought to occur when supporting processes and critical components are not managed (Ronen, 1992). As a result, they can become a complex sequence of hand-offs between preparation, search, movement, physical and mental rearrangement, waiting, and improvisation inside and outside the work location.

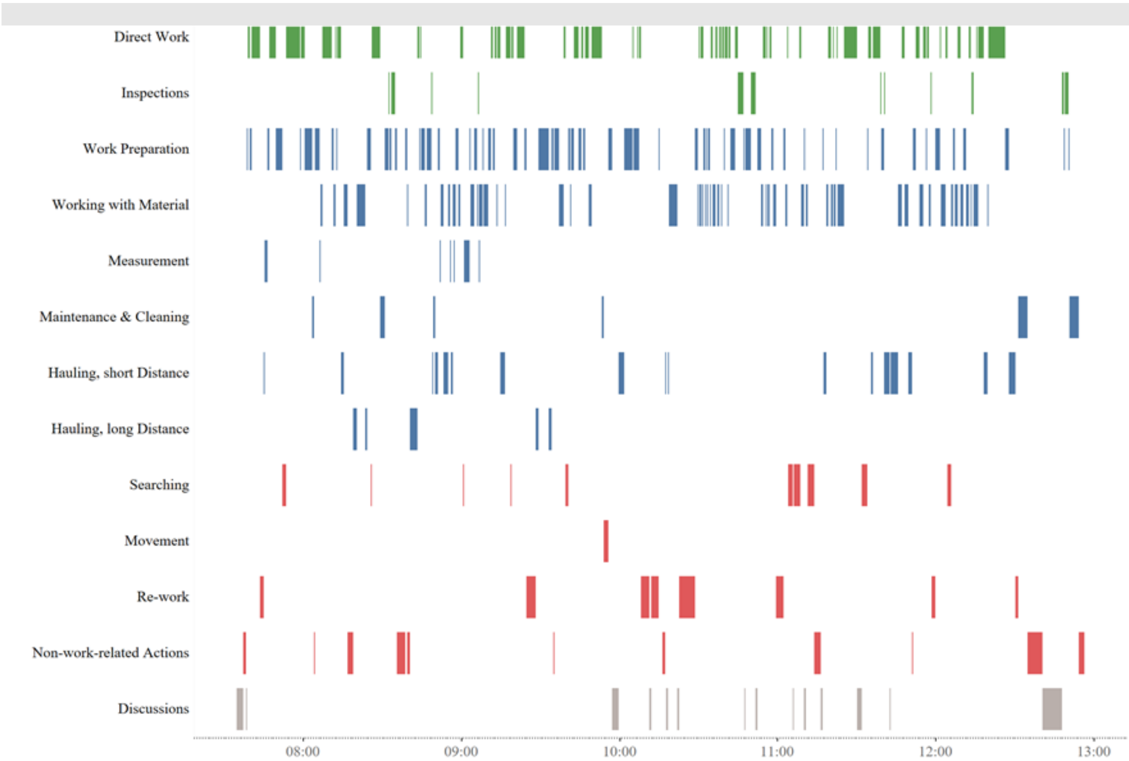

Figure 3: Classified & visualized Activities in plumbing Workflow; Note: green bars = VA, blue bars = VS, red bars = NVA, and grey bars = unclassified activities

The analysed data shown in Table 2 contains 284 activities with an average duration of 68 seconds. This represents 283 activity changes within 5 hours and 20 minutes, approximately once a minute. Here, VS activities occur the most and show the lowest average duration per activity. “Work Preparation” and “Working with Materials” were the VS activities that were carried out the most. NVA activities and discussions appear to have the longest average duration per activity, but the lowest counts in occurrence. Furthermore, the data reveals a high number of other activities must take place before getting to “Direct Work”, here in the form of VS activities, as well as discussion and movement-related activities. Such activities are part of workers daily routines but often unanticipated when work gets planned on higher hierarchical levels and later hidden in low granularity levels of information utilized within schedules and plans.

Table 2: Duration of interruptions and contained share of activities

Classification	Share of Time	Average Duration	Number of Activities
Value Adding	27.2%	01:11	74
Value Supporting	48.9%	00:58	162
Non-Value-Adding	13.7%	01:41	26
Unclassified	10.2%	01:29	22
Direct Work	24.2%	01:16	61
Inspection	3.1%	00:45	13
Work Preparation	19.2%	00:57	65
Working with material	15.7%	00:52	58
Hauling, short distance	6.9%	01:10	19
Hauling, long distance	2.3%	01:29	5
Maintenance & Cleaning	3.3%	01:20	8
Measurement	1.4%	00:39	7
Movement	0.6%	01:50	1
Searching	6.8%	02:44	8
Re-work	4.1%	01:06	12
Non-work-related Actions	2.2%	01:25	5
Discussions	10.2%	01:29	22
Unclear	0.0%	00:00	0

Direct work is interrupted 60 times during the analysed workday, most often caused by VS activities in the form of "Work Preparation" (27 times) and "Working with Materials" (23 times) as its successor. Interrupting direct work 61 times also mean starting it 61 times. Here, VS activities "Work Preparation" (27 times) and "Working with Materials" (34 times) were the most common predecessors to direct work, indicating the high degree of on-site customized solutions. The pipe fitting process ("Direct Work" and "Working with Material") included bending, cutting, drilling, screwing, levelling, welding. Due to the detailed level of customized work needed, the installers´ working position had to be constantly adapted in a tight working environment ensuring having all materials and tools constantly close by ("Work Preparation"). These supporting activities were managed by the worker himself and critical components had to be customized in-place, causing frequent workflow interruptions. Additionally, the coordination within the workspace was carried out by the installer. This coordination process often seemed unorganized and causing further interruptions, although work and storage locations were planned on higher hierarchical in advance.

A closer look at different interruption sequences (table 3), defined as a chain of activities between "Direct Work", revealed an average time of 3:29 min between "Direct Work" activities. A total of 59 sequences were observed and analysed. These sequences were clustered according to their duration (D) of interruptions in minutes (<1, >1, <5, <10 min), considering the proportion of activities they contained. There were 23 (accountable for 19.4 % of total interruption time) sequences shorter than a duration of one minute, 24 with a duration between one and five minutes (23.5 %), 4 between five and ten minutes (12.4 %), and 8 longer than ten minutes (44.7 %).

Table 3: Duration of interruptions and contained share of activities

	D< 1 min	1min< D <5min	5min< D <10min	D> 10min
Inspection	0.04	0.02	0.14	0.02
Work Preparation	0.16	0.30	0.35	0.24
Working with material	0.14	0.32	0.15	0.20
Hauling, short distance	0.07	0.09	0.15	0.09
Hauling, long distance	0.00	0.00	0.00	0.07
Maintenance & Cleaning	0.15	0.00	0.03	0.03
Measurement	0.00	0.02	0.01	0.03
Movement	0.00	0.00	0.00	0.02
Searching	0.03	0.05	0.09	0.14
Re-work	0.01	0.16	0.00	0.03
Non-work-related Actions	0.04	0.01	0.00	0.04
Discussions	0.37	0.04	0.07	0.10

Within short interruptions (< 1min), the share of discussions is the highest. While working on the task the installer was constantly in discussions with another installer, on the other side of the corridor. Since recordings are muted, the content of these conversations is unknown, although activities and gestures while discussing suggest a high proportion of work-related issues. These activities indicate the need for on-site communication building understanding due to insufficient plans, directives, and schedules. Furthermore, the short interruption cluster is characterized by activities happening in the direct vicinity of the installation area. Here, VS activities "work preparation", "working with materials" and "maintenance and cleaning" have higher proportions than others, as the high degree of customized work on-site often requires rapid material and location adjustments. These aspects account for approx. 15 % of interruptions times, which is left to the installer´s individual workspace and process coordination.

The highest shares in medium-long interruptions (between 1 and 5 min & between 5 and 10 min) are "Work Preparation" and "Working with Material". The various aspects of both activities (see table 1) require shorter and longer time periods for their execution. That is why both are represented with high proportions in all clusters. Noticeable here the proportion of "rework" is extraordinarily high, which appears coincidentally due to the small size of the data set. Additionally, "Hauling, short distance" activities reach their peak with a share of 15 percent in the "5min< D <10min" cluster. An activity correlated to "Hauling, short distance" seems to be "Searching," since its share starts rising within the same cluster. The installer needed often more supplies since he was often running short while on a task. Although his storage area was assigned close to his installation area, supply shortages led to more movement, especially because components had to be searched within the unorganized storage area. From this perspective, data indicates that these two activities are interdependent and happen often sequentially. Another activity peaking in the same cluster is “Inspection,” caused by the need to build more understanding of site and installation conditions, which is not made transparent by plans and schedules.

The long interruption cluster shows lower shares in “Work Preparation” and “Working with Material” activities than in the medium-long clusters. Noteworthy here is the peak in “Searching" activities at 15 percent, as well as the first and only occurrence of "Hauling, long-distance" activities. Overall, the longest interruptions sequences included the most NVA activities, which partly goes back to the longest average duration of NVA activities. The inclusion of high shares of "Hauling, long-distance" in combination with the highest shares of NVA activities, indicates that NVA activities happen more likely outside the installation area. Additionally, it initiates more “Discussions” since its share rises here again in comparison to the middle long clusters.

DISCUSSION

Answering research question one, most frequent workflow interruptions have been caused by VS activities, ensuring the continuation of direct work. Although such activities seem to be logical and needed, the amount of them should be questioned and further analysed for improvement strategies. A higher degree of prefabricated components and increased logistical support of workers on site can be seen as approaches for improvement.

Currently, VS activities are often informally squeezed into the installer’s schedule, although he is hired for simply installation work. This “informal squeezing” can be interpreted as the unawareness of needed process steps carrying out installation work from a management perspective. Such unawareness seems to lead to constraint analyses operating on lower levels of granularity than what is needed to carry tasks out without interruptions. This lack of awareness is at conflict with Lean principles, which calls for continuous validation and verification (Dehlin & Olofsson, 2008).

The analysed and tested data includes one working day of one worker in one certain construction project, which limits the meaningfulness of these results and explanations. However, the purpose of the paper was to present ways of analysing workflows quantitatively and explaining them, rather than drawing conclusions on different hierarchical levels, due to the limited size of the tested data.

Future research can build on these analytical data structures and explanations. The analysed data can construct a foundation for answering research question two. For example, utilizing an agent-based simulation approach based on probability functions from all classified activities can depict workers behaviour. To utilize such an approach, it needs to be enriched with robust real-time data from field observations. Such data expansion could then answer questions of validity and reliability at trade, project, or industry level. In turn, it would raise questions of data handling, which currently relies on capturing real-time data (video material) without classifying and analysing data in real-time. Thus, the utilization of information and communications technology systems to preform continuous time-motion analysis for workers and other resources need to be investigated.

Due to high portions of movement-related activities, increasing shares of VS and NVA activities, it seems reasonable to track movement patterns on-site to enrich an agent-based simulation approach with location data. This enrichment can support automized data collection and the possibility of real-time data analysis. Location data can be seen as a digital representation of up-to-date workflow information, which in combination with probability functions can be used as a feedback cycle to reflect the specificity of each construction site. Ultimately, enriching the simulation approach with additional resources e.g., location data, can contribute to observe current states of sites, predict next states, and hypothetical forecast future performance and states by altering some sets of parameters using “what if” scenarios. Such a proactive concept of analysing and optimizing construction planning is referred to as the digital twin of construction (Rafael Sacks, 2020).

CONCLUSION

This study shows ways of analysing a quantitative plumbing workflow representation from video recordings by conducting a time-motion study, observing, and classifying an installer´s activities. Workflow interruptions are explained as time spent on other activities than direct work and can be analysed based on classified activities during an installer´s working day. Due to the quantification of time spent on certain activities it is possible to analyse durations and causes of workflow interruptions. Results indicate the nature of on-site workflow patterns, frequencies of workflow interruptions in plumbing work (most often VS activities), and how certain inefficiencies affect the span of these interruptions. Due to the utilization of the developed data structure and the application of simulation approaches including up-to-date and reliable field data, “what-if” scenario evaluations can be extracted and the information granularity gap can be closed by opening the black box, which keeps cause and effects often undetected. Future research should extend the data sample, which could then be used to construct a foundation for a digital twin of workers' behavioural algorithms per construction site and reduce the amount of waste in the form of workflow interruptions.

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HYBRID LEAN DECISION-MAKING FRAMEWORK INTEGRATING VALUE STREAM MAPPING AND SIMULATION: A MANUFACTURING CASE STUDY

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ABSTRACT

Lean value stream mapping has been applied extensively in manufacturing settings to benefit the industrial sector by boosting productivity, improving product quality, and decreasing capital costs, in turn leading to customer satisfaction and manufacturer profitability. Notwithstanding the benefits, lean value stream mapping can be enhanced to dynamically reflect the statistical productivity and economic improvements to enhance the process efficiency of production lines. Findings reported in the literature points to the benefits of integrating simulation-based tools with traditional lean value stream mapping in a hybrid framework to validate the feasibility of a given improvement. The main criteria are to reduce lean waste, increase productivity, and dynamically optimize manufacturing trade-offs for push–pull and just-in-time production systems by enhancing the efficacy of lean value stream mapping using a simulation-based approach. In this context, the proposed framework leverages value stream mapping to visualize the production system's current state. It then integrates the discrete-event simulation model in order to assess the various lean improvement scenarios proposed that to transform the system to its future state. The framework is implemented in a window manufacturing production stream to test and validate its feasibility in a mass customization environment. The case study results demonstrate the value of the framework in assisting decisions-makers to evaluate different scenarios and visualize their impact for better transformation.

KEYWORDS

Lean value stream mapping, simulation-based, push–pull, just-in-time, mass customization

INTRODUCTION

Lean management was introduced to the manufacturing industry by Toyota Production System, TPS at the beginning of 1930s as an innovative approach to competing with other world-leading car manufacturers. Lean management concepts focus primarily on achieving a continuous flow of value within the production system and on reducing waste

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by analyzing the activities in a production system to distinguish between value-added activities and non-value-added activities (Sundar et al., 2014). Value stream mapping (VSM) is a lean tool that helps to define, measure, and analyze the flow of the operation or process being transformed. VSM can be used to identify problems and propose countermeasures in plain, descriptive, and enthralling ways that often cause previously dubious team members to become supportive of the proposed changes. Moreover, it engenders a holistic, interconnected, "bird's-eye" perspective within a collaborative team environment to direct the team to the "True North". However, as Abdulmalek and Rajgopal (2007) have argued, VSM alone may be insufficient to convince decision-makers to adopt lean management. They go on to suggest that while VSM can predict the future state of production with modest success, it falls short of accurately predicting some aspects of production, such as dynamic productivity.

This paper aims to develop a hybrid framework to aid management teams in identifying deficiencies in complex production systems and facilitate creating solutions by overcoming the limitations of LVSM. This tool would help decision makers to evaluate different scenarios and visualize their impact accurately by adopting trade-off analysis. Thus, helping management to implement lean concepts with a high degree of confidence of their impact on the production line. In this context. Discrete-event lean simulation (DELS) is a promising tool to complement VSM in assessing the future state of production. Moreover, economic feasibility studies must be conducted to evaluate the feasibility of implementing the proposed improvement measures identified using lean tools., and a trade-off analysis must be performed.

LITERATURE REVIEW

Lean principles were first developed by a Japanese car manufacturer, Toyota. When Toyota developed lean principles, they were striving to achieve a flow of activities with no waste in between (Sami Abdelhamid et al., 2008). Lean as a concept was first introduced to the west by "The Machine that Changed the World" book (Womacket al., 1990). The book successfully illustrated the differences between lean thinking and mass production (Melton, 2005). After the successful implementation of Lean principles, it grew in popularity and was adopted by many companies across various industries (Sami Abdelhamid et al., 2008). Lean success was mainly dependent on its focus on creating an uninterrupted flow of value-added activities and reducing waste. Producing high-quality products at the pace of customers' demands with little to no waste (Larteb et al., 2015). Lean tools are tools that were developed to achieve this endeavor; however, the literature shows no consensus on what is considered a lean tool or not (Larteb et al., 2015). Nonetheless, some of the most known techniques and tools in lean management are just-in-time, continuous improvement, pull-flow, 5S, 5 why's, last planner system, and lean value stream mapping.

LVSM was developed by the lean production movement as a tool to analyze the production system as a means to reorganize it with a lean vision (Lasa et al., 2008). First, LVSM is used to inspect the current state of the production system to develop a visual representation of the current plan. This visual representation mimics the current flow of materials and information to produce the product from its conception till its delivery to the customer (Belokar et., 2012). Showing cycle times, uptimes, etc as well. By then, analyzing the current state map, proposed solutions are developed to enhance the production system. Then, takt time is calculated and an LVSM of the future state is drawn. Subsequently, value is identified and lean techniques such as Kanban are applied to remove non-value-adding activities and bottlenecks to transfer the production system from the current state to the future state. Ensuring a seamless flow for the product through value-creating steps (Lummus et al., 2006).

However, despite the various advantages of LVSM, the literature showed multiple drawbacks. Schmidtke et al. (2014) stated in their paper that the most frequent drawbacks mentioned in the literature are mainly due to the static and low-detailed nature of the tool. For example, LVSM cannot handle describing multiple lines converging together (Braglia et al., 2009). Another prominent drawback is the difficulty of collecting relevant data in a complex production system (Forno et al., 2014). This is apparent when the data to be collected are not deterministic values (Braglia et al., 2009). The latter illustrated that this resulted in making LVSM an incompetent tool to analyze what-if scenarios. Last known problem is that LVSM does not give a clear indication about the feasibility of the proposed solutions. Hence, complementary tools shall be used to fill in the gaps where LVSM is not competent enough.

After a thorough investigation and examination of the literature, there was a clear trend encouraging the use of discrete event simulation (DES) in support of the LSVM. For instance, Grimard et al. (2005) stated that DES is essential for validating the output of multiple cells of manufacturing. According to the latter, this helps reduce the required time for such cells to reach their desired productivity. Also, illustrated in their work the promising capabilities of simulation in capturing complex production systems with variable data (Schmidtke et al., 2014). Lastly, for the cost-effectiveness of the proposed solutions, a feasibility study must be conducted to ensure the proposed solutions satisfy the customers' demands (Schmidtke et al., 2014). They also explained that the solutions sometimes require changes that might affect the quality and time of the production system, hence, a time-cost tradeoff analysis must be performed. Applying lean techniques such as push-to-pull, and just-in-time requires substantial changes to the production system. These changes seldom require continuous improvement and investment. Moreover, these changes might affect the quality of the products and the benefits are reaped later in time. Hence, trade-off analysis is essential for management teams to decide if the proposed changes justify the time, cost, and quality changes.

In researching the difference between LVSM and DELS, it can be concluded that LVSM can be utilized to assist the decision-maker in implementing the desired and feasible improvements by visualizing the production flow, identifying the bottlenecks and potential waste sources, creating the communication link that supports the information and material flow, and assessing multiple improvements scenarios. However, LVSM also has its shortcomings and limitations since it provides a stagnant representation of the process with limited view on the shop floor at a specific timeframe. Also, it becomes a time-consuming activity when dealing with complex manufacturing processes and different product families. In addition, LVSM main focus is on internal process analysis for a company, including scheduling, re-work, in-service quality, and material flow. Finally, the future state extracted from an LVSM exercise can be based on many inclusive and exclusive assumptions that can solve a secondary problem in isolation of the primary concern.

To overcome the limitations of the LVSM, DELS is utilized as an extension and alternative by providing the decision-maker with a dynamic representation and a digitized simulated process of the manufacturing process combing different product families. Also, it focuses on the external analysis merged with the internal one to include supply chain and logistics, market conditions and competitors, and customer demands.

METHODOLOGY

The methodology described in Figure 1 was developed to fulfill the research objectives and then implemented in a dedicated window production line. A high-demand product category within this plant was investigated and analyzed to improve overall throughput productivity without affecting the economic trade-off of the product and the overall business. First, the inputs to the framework were collected using a conventional time study in which the value-added and non-value-added activities were recorded. In addition, the resource allocation, sequence of operations, and production line settings were monitored, and data collected in a systematic manner. Next, information on daily orders, including product specifications and planned working schedule, was extracted from the company's Enterprise Resource Planning (ERP) database.

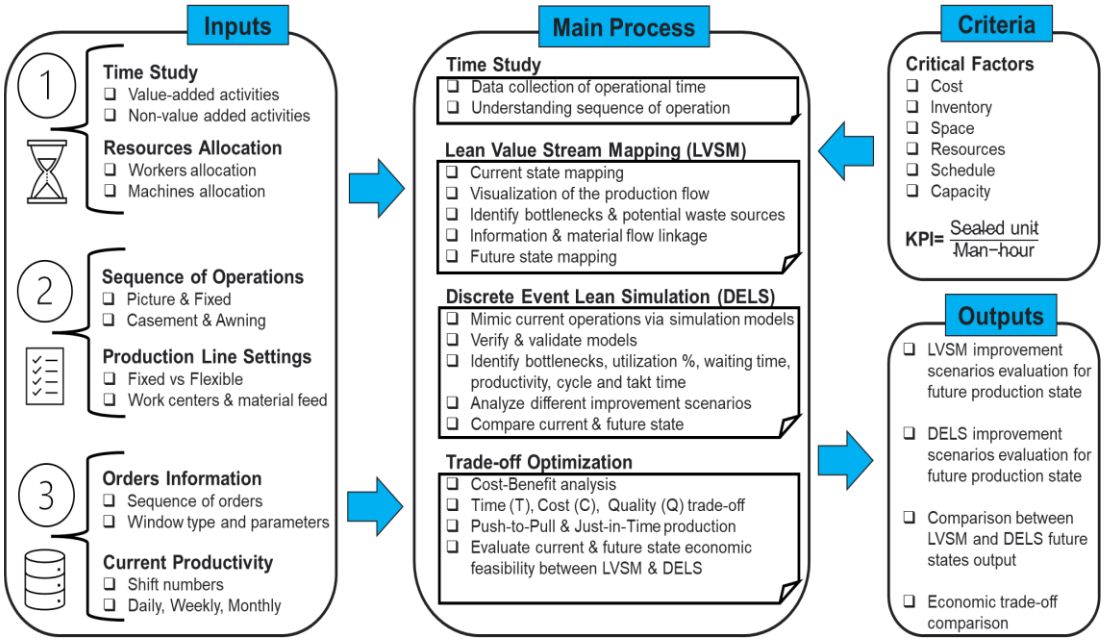

Figure 1: Overview of Methodology

Using LVSM, the current state of the production line was simulated in order to identify and visualize the eight forms of process waste identified in lean theory within the window production line. By deploying lean manufacturing methods to transform the production process from the current state to the future state, low-risk and high-risk process bottlenecks were identified, cycle and takt times were recorded, inventory and capacity limitations were flagged, and customer demand was linked with system information and material flow. It is worth noting in this regard that, in many value stream mapping cases, the desired future state can be reached by using the manual method explained in Rother & Shook (1999). This method helps the decision-maker to achieve a feasible future state that can be quickly integrated with the current production line.

However, using LVSM to define the future state can be overwhelming, time-consuming, and complicated in some instances. For example, predicting resource utilization and current and future stock demand during the production process is not achievable with such static models. To overcome these obstacles, a DELS model was built to mimic the current state of the windows production line. The simulation model was developed using Simphony, a simulation software developed at the University of Alberta as a dynamic modeling tool to emulate the manufacturing process (AbouRizk et al., 2016). The simulation model helped to visualize the desired dynamic features of the future state prior to implementation, thereby assisting decision-makers in accurately estimating the impact of the proposed changes on the production line. Before the implementation phase, the simulation model was verified and validated using statistical methods, current ERP data, and productivity analysis. The current and future process states were then compared based on six different scenarios.

It should be noted that simulation models are not used for economic optimization purposes. Thus, trade-off economic optimization was added to the framework to validate the scenarios from a cost-benefit perspective and using the time(T), quality(Q), and cost(C) trade-off technique for push-pull systems in addition to JIT production. Trade-off optimization, it should be noted, is a powerful tool for assessing proposed improvements before transformation takes place. Although this research focused on one particular window production line in a manufacturing setting, the proposed methodology can be modified and applied to other manufacturing cases as a generic hybrid framework, as illustrated in Figure 2.

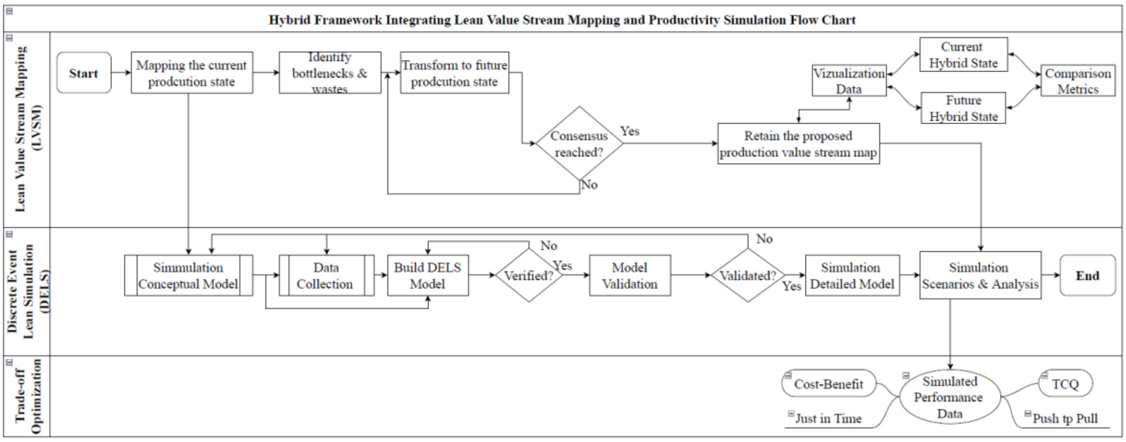

Figure 2: Hybrid Framework Flowchart

A WINDOW PRODUCTION CASE STUDY

A qualitative case study involving a window and door manufacturing company (referred to herein as "ABC plant") was selected to test and validate the proposed hybrid framework. The main criteria governing this case study were to reduce lean waste, increase productivity, and dynamically optimize manufacturing trade-offs for push-pull and JIT production systems by enhancing the effectiveness of LVSM using a dynamic model created using a simulation-based approach. At the time of the case study, this ABC plant was under increasing pressure due to internal and external factors to ramp up production and throughput of Sealed Units (SUs) to meet customer demand. Accordingly, ABC plant's desired future state and productivity expectations included the following:

- Production of 45 SUs/day, based on current and future market needs (baseline production throughput is 28 SU/day).
- Order-to-manufacturing lead time of 10 days (baseline lead time is 13.57 days).

The proposed hybrid framework was implemented to measure and record the LVSM, DELS, and trade-off optimization outputs compared to the current baseline metrics based on the desired future state. The non-value-added activities, eight wastes, and bottlenecks were determined using the conventional VSM analysis tool. In ABC plant's current state, windows are fabricated through several workstations, as described in Figure 3, where a combination of machines and workers are allocated in a hybrid push-to-pull and JIT production system. Each window undergoes a set of operations, including cutting, welding, cleaning, hardware installation, final assembly, glazing, quality check, and packaging before being shipped to the customer.

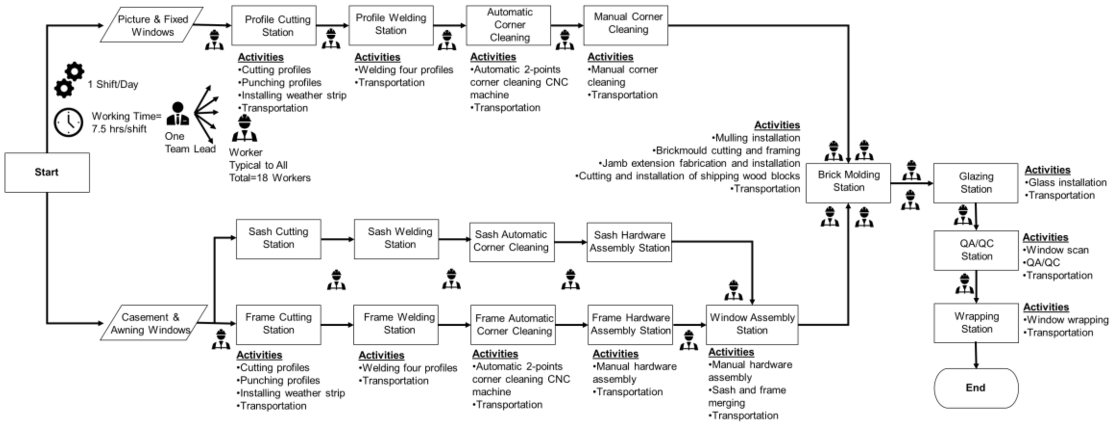

Figure 3: Sequence of Operations

LEAN VALUE STREAM MAPPING (LVSM)

Manufacturing systems do not usually operate in a linear manner because the number of workers varies from one day to another, predictability and performance deviate from the baseline, and unplanned breakdowns disrupt the process. The first activity in mapping a current process state is to select the product and its customizability options. Then, the typical process operations are mapped using LVSM to fully support better understanding of the overall process and to flag potential bottlenecks and sources of waste. Mapping the current state is an important step toward realizing the desired future state as a result of implementing appropriate process improvement measures identified in reference to the current-state map. In the present case, the inputs for this activity were imported from the company's ERP and Material Requirements Planning (MRP) systems.

The current-state map for the selected window manufacturing line using VSM notation (Rother and Shook, 2003) is shown in Figure 4. The calculations carried out in preparing the current-state map revealed that the value-added time of the process is 449.96 min while the production lead time is 13.57 working days. The process efficiency ratio was found to be 0.07 (or 7%), giving a clear indication that the selected window manufacturing process contains a variety of non-value-added activities. Next, the takt time was calculated using Equation 1, which assume a 7.5 hr (450 min) workday (excluding scheduled breaks) and that daily customer demand is 40 SUs/day

$$Takt\ Time = \frac{Total\ Daily\ Operating\ Time}{Total\ Daily\ Customer\ Demand} \quad (1)$$

The takt time was found to be 11.25 min/SU. The current-state map, it should be noted, represents a push-pull system combined with JIT production. The analysis revealed that operations such as profile cutting, profile welding, and automatic corner cleaning yielded cycle times lower than the takt time, while other operations yielded cycle times higher than the takt time as illustrated in Figure 4.

After visualizing and analyzing the current-state map and consulting with the management team, six different scenarios were proposed. The productivity improvement scenarios summarized in Table 1, were implemented in the simulation model with team consensus using pre-determined metrics to derive the future-state map.

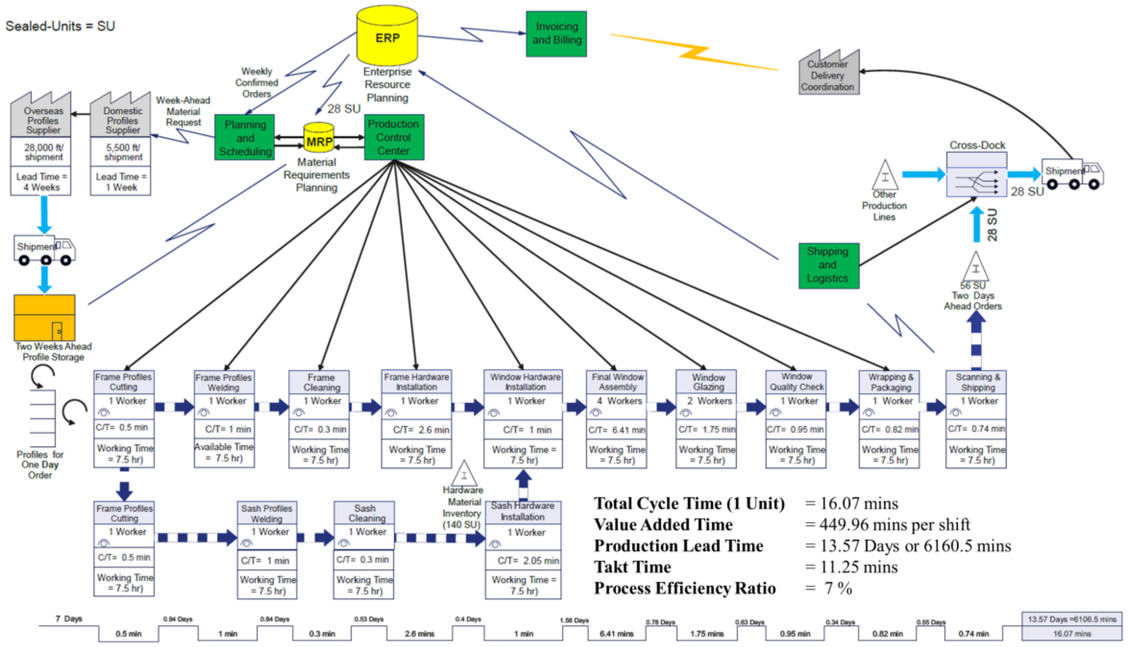

Figure 4: Lean Value Stream Map (Current State)

Table 1: Proposed Improvement Scenarios

Scenario #	Scenario Description
1	Implement 1D linear hardware installation process by changing the current production flow
2	Reduce window hardware search time by installing advanced hardware storage lighting bins
3	Improve the final assembly by installing semi-automated workstations
4	Reduce glazing search time by using smart glass organizing carts
5	Combination of Scenarios 1,2,3, and 4
6 A/B	Scenario 5 combined with a line balancing measure (i.e., adding/reallocating two workers

Discrete-Event Lean Simulation (DELS) Model

The initial step in designing and developing a simulation model is to reflect the process's built and current state. In the present case, LVSM was the primary input in developing the simulation model. After visualizing the current state of the production line and analyzing its sequence of operation, allocated resources, cycle and takt times, bottlenecks, and waste sources, and setting out assumptions, the simulation model was built using the data collected from the ERP and MRP systems. A database for the simulation model containing all the relevant information was created using Microsoft Access and this database was then linked with Simphony.NET. The case study involved some inherent complexity due to mass customization and variations in operations leading to cycle time fluctuations, in turn, to different attributes being simulated.

The case study target was set to five days of production, June 5, 6, 7, 8 and 09, 2021. The simulation running time was 7.5 working hours, representing one working shift per day. The designed model was tested, verified, and validated using various methods and approaches to track the total number of SUs produced per day. All the tests indicated that the simulated model is close to reality and represents the current state with an average variance of just 6%, lower than the established simulation model threshold of 10%. After validating the simulation model, the six scenarios were simulated, and their results were compared to the baseline productivity rates as shown in Table 2.

Table 2: Scenarios Productivity Comparison

Productivity (SU/Hr)	LVSM			DELS			LVSM & DELS
Scenarios	Current	Future	Diff. (%)	Current	Future	Diff. (%)	Diff. (%)
Baseline	3.51	-	-	3.73	-	-	6%
1	-	3.77	8%	-	3.96	6%	5%
2	-	3.75	7%	-	3.81	2%	2%
3	-	3.96	13%	-	4.18	12%	6%
4	-	3.78	8%	-	3.86	4%	2%
5	-	3.88	11%	-	4.61	24%	19%
6A	-	4.29	22%	-	5.76	51%	34%
6B	-	3.24	-8%	-	3.46	-7%	-1%

TRADE-OFF OPTIMIZATION

Multi-objective optimization problems typically deal with conflicting target key performance indicators (KPIs) wherein an increase or decrease in one KPI will affect another KPI. Trade-off optimizations, meanwhile, is an essential tool that measures the change in KPI objectives relative to changes in others and then optimizes the values to provide the decision-maker with the best fit improvement by which to move from the current state to the future state. In this research, the economic trade-offs of the various improvement scenarios were calculated in order to validate the best fit scenario in terms of its capacity after LVSM and DELS were used.

Return on Investment (ROI)

In this research, ROI was implemented as an indicative analysis tool to decrease the uncertainty in selecting the best proposed productivity improvement scenarios from a financial perspective. Equation 2 is used to calculate the scenarios ROI.

$$ROI = \frac{V_I - C_I}{C_I} \tag{2}$$

where V_I = current value of the improvement in dollars, and C_I = cost of the improvement in dollars.

Cost-Benefit Analysis (CBA)

The Cost-Benefit Ratio expressed as Aggregated Cost-Benefit Ratio (ACBR), which quantitatively analyzes the comprehensive performance of the proposed improvement scenario, reveals the monetary value for the purpose of evaluating the comprehensive improvement performance of a given scenario, as illustrated in Equation 3.

$$\text{Aggregated Cost Benefit Ratio (ACBR)} = \frac{\sum EB}{\sum AC}\ x\ \sum_{i=1}^{n} \frac{C_F}{(1+r)^i},\ 0\ \leq\ \text{ACBR}\ \leq\ 1 \qquad (3)$$

where ∑EB represents the expected benefits, ∑AC represents the associated costs, C_F is the cash flow in dollars, r is the discount rate between 0 and 1, and i is the time of cash flow between 0 and 1.

Time-Cost-Quality (TCQ)

Researchers have introduced a variety of mathematical models for time-cost-quality (TCQ) trade-off analysis to tackle optimization under uncertainty. Equation 6 shows that if TCQ is a positive value, the improvement scenario will result in a higher concurrent trade-off that improves quality after implementation, while, if TCQ is a negative value, then the improvement scenario will result in a lower concurrent trade-off that improves quality after implementation.

$$TCQ\ Trade - Off\ Ratio = \frac{T_S}{T_B} x \frac{C_S}{C_o} x \frac{Q_I}{Q_B} \qquad (6)$$

where TCQ ranges between 0 and 1, T_S = time saved in minutes, T_B = baseline time in minutes, C_S = cost saved in dollars, C_B = baseline cost in dollars, Q_I and Q_B = improvement and baseline quality, respectively, between 0 and 1.

RESULTS AND DISCUSSION

The goal for this scenario productivity analysis is to find the bottleneck of the production line and determine the proper solutions to eliminate it. However, it should be noted that by performing changes in one station, another station may become a potential bottleneck. Therefore, this research takes into consideration this possibility and provides feasible solutions given the current manufacturing capacity while also not creating any new bottlenecks. After running and validating the simulation, bottlenecks are identified and some future-state scenarios are tested with the goal to reduce or eliminate their impact on the manufacturing line, always aiming for productivity improvement and line balancing. By comparing the production line's current state (using LVSM) with the future state (using DELS), the productivity rate for each improvement scenario was calculated. The comparison between scenarios is presented in Figure 5.

Given the case study constraints, limitations, and assumptions, Scenario 6A was found to be the best fit in terms of overall metrics with 63% productivity improvement. The company's current daily demand at the time of the study was 28 SUs/day, and, according to our analysis, the company could increase its throughput by an additional 15 SUs/day by implementing Scenario 6A. However, this improvement would come with a cost burden for implementation that would, in terms of ROI, entail a three-month payback period. Next, all improvement scenarios were compared to the LVSM and the DELS baseline. It was found that, by combining scenarios 1, 2, 3, and 4 (i.e., Scenario 5), ABC plant would boost its productivity from 3.73 SUs/day to 4.61 SUs/day resulting in seven additional SUs compared to the baseline productivity rate. However, this scenario would have a higher ROI compared to scenario 6A.

Meanwhile, it was found that removing two workers from the production line (i.e., Scenario 6B) would decrease daily productivity and increase the economic trade-off. The highest ACBR was that of Scenario 6A at 0.406. Although this scenario has a higher initial cost than the other scenarios, the financial benefit ultimately attainted is also considerably higher, with the total annual estimated savings of approximately $422,000.

As with ACBR, the highest is that of Scenario 6A at 0.254, meaning that this scenario entails more labor resources and a higher degree of automation, but also higher quality.

Table 3. Trade-off Optimization Results

Scenarios	**1**	**2**	**3**	**4**	**5**	**6-A**	**6-B**
Estimated cost ($)	$26,000	$8,000	$55,000	$6,000	$95,000	$115,000	$75,000
Current time (Mins) LVSM	3.60	1.00	6.41	0.75	11.76	9.41	15.68
Proposed time (Mins) DELS	1.58	0.20	4.41	0.35	6.54	5.23	8.72
Total time saving (Mins)	2.02	0.80	2.00	0.40	5.22	4.18	6.96
Total time saving (%)	56%	80%	31%	53%	44%	44%	44%
Productivity Rate (SU/Hr)	3.957	3.808	4.181	3.864	4.610	5.763	3.458
Difference from Baseline Productivity (3.733 SU/Hr)	0.22	0.07	0.45	0.13	0.88	2.03	-0.28
SU per day on 7.5 hrs shift (Baseline = 28 SU/day)	29.68	28.56	31.36	28.98	34.58	43.22	25.93
Average times a worker perform the activity /day (Ea.)	28	28	28	28	28	28	28
Average time workers spend on the activity (mins/day)	100.80	28.00	179.48	21.00	329.28	263.42	439.04
Savings in time (mins/day)	56.56	22.40	56.00	11.20	146.16	182.70	109.62
Current No. of Workers (Ea.)	1	1	4	2	8	10	6
Worker full burden rate ($/hr)	$38.00	$38.00	$38.00	$38.00	$38.00	$38.00	$38.00
Savings ($/day)	$36	$14	$142	$14	$740	$1,157	$416
Savings ($/year)	$13,074	$5,178	$51,781	$5,178	$270,298	$422,341	$152,042
ROI	1.989	1.545	1.062	1.159	0.351	0.272	0.493
ACBR (Months)	≈ 24	≈ 19	≈ 13	≈ 14	≈ 4	≈ 3	≈ 6
TCQ	0.126	0.050	0.124	0.025	0.325	0.406	0.244

CONCLUSION

This research investigated two productivity improvement tools for assisting decision-makers in evaluating productivity improvement scenarios prior to implementation: traditional lean value stream mapping and discrete-event lean simulation. The two tools were integrated into a hybrid decision-making framework to reduce lean manufacturing waste, increase throughput and productivity, and dynamically optimize economic trade-offs for push-pull and JIT production systems. The proposed framework was found to overcome the constraints and limitations of traditional lean value stream mapping by incorporating simulation. The robust hybrid framework was implemented in a case study to test its applicability and feasibility in the context of mass customization systems to demonstrate how simulation-based analysis can facilitate the transformation of the production system from the current state to the future state. Various productivity improvement scenarios were applied to a window production line. The results demonstrated the framework’s validity in simulating and visualizing the impact of the different improvement scenarios on overall productivity, and therefore its value in assisting decision-makers in evaluating alternatives prior to implementation as part of a continuous transformation program.

Trade-off optimizations were then applied in order to assess each scenario from an economic perspective, demonstrating the utility of the framework supporting decision-makers in identifying the best fit improvement scenario. The framework was designed as a generative decision-making tool and was applied to different product streams under certain limitations and assumptions. Future work will include the development of a genetic algorithm to assess the trade-off optimization and Pareto analysis to evaluate competing objectives and measure their impact before implementation.

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SITUATIONAL AWARENESS IN CONSTRUCTION PROJECTS USING TAKT PRODUCTION

Heikki P. I. Halttula[1] and Olli Seppänen[2]

ABSTRACT

The construction industry is improving its processes targeting to increase productivity. Lean construction has been in use for decades, and now lean is expanding in the form of takt production. Takt production gives clear steps to apply lean in daily construction projects. Takt production transfers the improving flow from the manufacturing industry's conveyor belts to construction sites.

Digital situational awareness systems are good examples of new digital solutions in construction. They provide possibilities to construction stakeholders to better control and improve their processes by visualizing waste and helping find the root causes of problems to be fixed.

This paper aims to study how digital awareness systems support takt production in construction projects. This study is a qualitative case study based on a project implementing a digital situational awareness system and relies on project staff interviews and the data available on the project. The project team has successfully improved takt production with digital awareness systems for revealing and fixing waste. They have successfully improved the productivity of tasks. Digital situational awareness systems can play an important role in the continuous improvement of processes in the construction industry.

KEYWORDS

Productivity, lean construction, situational awareness, takt production, waste.

INTRODUCTION

Takt production has been proposed as a lean production planning and control method, resulting in several benefits, such as shorter cycle times and better transparency (Lehtovaara et al., 2021). Previous studies have investigated the link between takt production and prefabrication (Chauhan et al., 2018) and industrial logistics and takt production (Tetik et al. 2019). Still, few studies have discussed the digital tools required to support takt. Takt production requires problems to be solved within takt time (Frandson et al., 2015). Therefore, there is a need to see in close to real time how the actual construction is proceeding, how materials are being delivered, and get information of all

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the obstacles that prevent resources from working continuously according to takt production plan. New technologies related to digital situational awareness (SA) are being developed (Lappalainen et al., 2021) and becoming more real-time and they could play an important role in revealing waste as it occurs. There are technologies that pass-on the site status information digitally online without human interpretation. These systems are based on positioning sensors, cameras, drones, and 360-videos. There are so far no studies on how digitalized SA could support takt production and enable continuous learning, especially related to automatic waste detection and eliminating waste inside the takts during construction. This article aims to investigate the connection between digital SA and takt production in a single case where both were implemented in the same project and see how they can support each other. The study is exploratory research which is insightful to illuminate the understanding of a topic that is new or not studied earlier entirely (Saunders et al., 2009).

LITERATURE REVIEW

SITUATIONAL AWARENESS

SA concept was originally developed to improve safety in air traffic by giving better awareness of the situation to air traffic controllers and pilots (Harrald and Jefferson, 2007). Several industries like construction have adopted the idea of integrating the knowledge of repeated situation assessments to a coherent picture (Sarter and Woods, 1991). Situation assessments are complex and are limited by cognitive limitations of working memory and attentional capacity (Endsley, 1995). SA intends to help decision-making in a dynamic environment where data processing is limited by human cognition. Endsley's (1995) three-level SA model is the most widely used. It consists of three categories:

1. Observation of the current situation
2. Understanding of the current situation
3. Predictions of the future

Digitalized management increases in the Construction industry (CI) when digital platforms are used for production control and reporting purposes (Dong et al., 2006). Transparent and data-centric SA is based on applications and digital platforms. These digital solutions can be in the key role to solve the traditional problems related to CI projects (Aasland and Blankenburg, 2012). Although the SA concept was initially developed for other industries, there has been increasing interest in utilizing the concept in construction (Lappalainen et al., 2021).

Numerous papers have been written concerning SA and its sub-solutions for CI. The focus of these papers has been, on the utilization of work machines and equipment, occupational safety, and the role of BIM (Building information modeling) in SA (e.g., Lonsdale, 2004) and construction logistics management (e.g., Ghanem et al., 2018). Research has also focused on establishing a more holistic picture of the situation (O'Reilly et al., 2005) and integrating decentralized information in the CI (Kärkkäinen et al., 2019). Typical SA solutions evaluate the status of the environment, analyze the current status and create forecasts and alerts for decision making. So far, most attention has been given to analyzing the current status and most SA systems in construction are not yet good at projection (Lappalainen et al., 2021).

The new concept of Digital Twin Construction (DTC) proposed by Sacks et al. (2020) could fill these gaps in current solutions. Digital Twin Construction aims specifically at a closed loop system, where data about the actual process is collected during production, analyzed using AI methods and used to simulate and forecast future actions. Ultimately DTC aims to use information of production to help plan and design future projects. Sacks et al. (2020) indicate that while a lot of data is already being collected, positioning there are gaps in integration of multiple data sources. They list a lot of different data collection methods, of which tag identification systems, smart sensors and computer vision systems are used as part of the SA system described in this study. We explore the research gap indicated by Sacks et al. (2020) by manually integrating these data sources which can hopefully guide the future development of DTC systems.

TAKT PRODUCTION

Takt production has recently received a lot of attention in the lean construction community. The number of takt time related articles only in the five latest IGLC conferences is 29. Two alternative methods, Takt Planning and Takt Control (TPTC) and Takt time planning (TTP) have been proposed. TPTC approaches takt by defining functional areas and defining repeatable Standard Space Units (SSU) for each different function (such as an office). Then work packages are defined and quantities are calculated to determine the amount of work for each work package. Takt areas are combinations of SSUs (Binninger et al. 2017). In contrast, TTP (Frandson et al. 2013) approaches takt with a more bottom-up approach, emphasizing involving the trades who determine how they would like to work. Although collaboration can also be used as part of TPTC, TTP uses collaboratively defined work densities to determine appropriate takt areas. Both systems have a similar approaches to level production, including shifting scope, chancing manpower, or taking actions to decrease on-site work. In both systems capacity buffers are preferred, rather than time buffers typically favored by other location-based planning methods, such as the Location-Based Management system (Frandson et al., 2015).

However, although papers have documented several benefits, such as decreased project durations (Frandson et al. 2013), improved productivity (Heinonen & Seppänen 2016) and increased construction flow (Lehtovaara et al. 2021), very few cases have been reported with systematically collected empirical data. The only attempt to combine digital SA to takt production was reported by Alhava et al. (2019). The outcome of their study was that digital SA saved a takt production -project that could not follow takt production due to quality defects. The digital methods found a lot of waste in the project. Although the project was successful, and achieved a 30% cycle time reduction, the progress captured by digital systems was messy and revealed a lot of waste. In Alhava et al., (2019) study, the analysis was done after the fact. Our aim is to use digital SA to continuously analyze takt production to improve the process.

Continuous analysis of wasted effort in takt areas could play an important role in improving takt production. There are some previous studies in the literature where waste has been evaluated automatically based on indoor positioning. Zhao et al. (2019) proposed the concept of uninterrupted presence of workers in work locations which they claimed correlated with value-adding time. They later expanded the concept to task level (Zhao et al., 2021) and defined presence index as the share of uninterrupted presence during task duration. These metrics are used to identify opportunities for improvement in this research.

METHOD

This study is a qualitative exploratory case study with an inductive research approach. An exploratory study is insightful to brighten the understanding of an issue that is new or not studied earlier thoroughly (Saunders et al., 2009). Data collection methods are semi structured interviews, site observations and studying the project data produced by a SA-system. The research question driving this research was:

How can digital SA improve the use of takt production?

The studied project is a renovation project. The renovated real estate is an eighty-year-old former headquarters office building that consists of six and eight-story buildings. The A-building has already been renovated into a hotel, and the B-building renovation as office space is still active. All data in this study is from the B- building renovation project. The project is in a city center. The project delivery type was a modified version of a management contract. The management contractor has only management personnel, and all construction work has been procured from contractors. They all had a clause in their contracts that agreed to use the takt production system. The client and owner of the building is an investment fund.

The authors collected evidence by organizing interviews with the site superintendent and the productivity engineer (PE) who the digital SA provider employed. Interviews were supplemented by studying the digital SA data and making observations on site. The authors had access to all the data available in the system, including the PE's weekly reports. PE’s information on the construction process was based on structured observations and participant observation. The structure of information PE collected was agreed upon with the customer before the project start and was secondary data for the authors.

In the semi-structured interview, the interviewee was given the discussion topics, and the interviewee answered openly. The topics were: general information about the project, takt production details, the SA system features and experiences, cooperation with the contractors, and improvement needs. The interviewer also asked some refining questions. The authors organized a site visit to supplement the interview findings.

The SA system was composed of indoor working area cameras, 360 videos, and the location information of resources using an indoor positioning system. There were altogether 11 indoor cameras whose location was determined by the contractors. The goal was to cover as large an area as possible with one camera and ensure that the cameras do not interfere with the work. One camera was directed to the inside yard to monitor logistics deliveries. At the beginning of the project, the management contractor took two 360 videos a week from each floor, but later one 360 video a week. The technology positioning the resources was based on low-energy Bluetooth (BLE). The location anchors were installed as a grid on each floor, and location beacons were installed on each worker’s helmet. The location information was saved if the presence of the resource was at least two minutes. The presence was considered uninterrupted (Zhao et al., 2019) if the presence was at least ten minutes in a work location without breaks. The presumption is, that workers can only add value when their presence is uninterrupted at least 10 min on the planned area (Zhao et al. 2019). Around 60 Gb of data was collected each week. The data was managed in the data hub using a cloud service. SA system was supplemented with software for takt planning and software for logistics management. The project personnel used these three applications to understand takt planning, supply chain activities, and the locations of resources with comprehensive pictures of the status on site and documented activities for past weeks' work. This is the use of SA on category 2 in Endsley's (1995) three-level SA model. The indoor cameras covered two takt areas at the same time.

The project used a commercial solution for situational awareness. The system pseudonymized personal data by blurring images and not including the names of people in the tracking results. Researchers collected personal data for semi-structured interviews. Because the authors did not collect or handle sensitive personal data, an ethical review was not required.

RESULTS

SEMI STRUCTURED INTERVIEW AND THE SITE VISIT

The authors interviewed the site superintendent and the productivity engineer (PE). The author's site visit was organized at the later phase of the project. The site visit helped to understand the challenges with an old, renovation building in the city center. Logistics planning has an essential role in a successful project.

The case study project

The contractor's construction process was based on takt production. Each floor was divided into five takt production areas. There also were backlog areas where the takt production was not in use. In the first hotel renovation building, the contractor used a four-hour takt time per hotel room, but the takt time was selected to be eight hours (one working day) in the office building. There were masons, plumbers, drywall men, ventilation and pipe shafts masonry, plate wall work, soffits, plasterwork and painting, ventilation, pipelines, electricity, automation, and space surfaces resources in the indoor working phase teams. Then kitchens with glass walls, ceilings immediately after electricity, floor surfaces, listings, and door installations. The first resource plans were done based on the standard production planning database and then finetuned together with contractors. The production was planned using specific software for takt planning.

Experiences and improvement need

Camera information was used for general supervision. 360-videos were used for quality control. The 360 videos are helpful because it is possible to turn the view to specific locations in the room accurately. The superintendent could follow if the resources were in the right location and following the schedule.

The camera view and recordings were used during meetings to facilitate discussions of work done and the planning of future work. An indoor positioning system could show the actual location of resources. If the resources were not in the planned area, it was studied why the work could not be done according to the plan. The PE used camera and presence information and site visits to investigate waste. PE improved productivity by giving feedback twice a week in site meetings with the superintendent and contractors. PE also wrote weekly reports of the observed wastes and suggestions on how to fix them.

The system helped improve supply chain reliability and reduced schedule risks. The PE's weekly reports highlighted the deviations in the logistics. At the beginning of the project, the number of logistical variations that stopped the work was fifteen each week. PE could follow the logistic deliveries using the specific application. PE reported the logistics deviations and started the discussions with the contractor to improve the deliveries matching better to the actual need on site. The use of the system reduced the number of fatal logistical deviations to five deviations per week.

Uninterrupted presence in work locations helped to identify wasted effort and with PE investigation, several wastes were identified and fixed. For example, on weeks 40…42, PE reported a constantly low presence index of floor rebar contractors and several short visits to other floors, and several work interruptions. PE reported on week 41 that the materials should be moved to the work area and reschedule the use of resources so that work is uninterrupted by increasing assistant work resources. As a result of the feedback, on week 43, PE reported that the active presence had risen from 20 % to 70 %.

The site superintendent's feedback on the SA system was positive, and he was keen to use the system in the following projects. He also pointed out that the cameras do not replace human supervision on site. Construction is teamwork, and human contact is necessary. The interviewees stated that the plumbing resources had more difficulties following the takt plan than the electricians. The location information (figure 3) confirmed that the electricians could better follow the takt plan.

However, several improvement areas were also noticed. In this case, the agreement between management contractor and their contractors did not include clauses about the utilization of resource positioning. This led to difficult discussions when workers needed to be convinced to carry a positioning beacon. However, the project team convinced all the important contractors to participate in positioning. Going forward, there should be a description and requirement in project agreements explicitly describing the SA system and the use of people tracking on the project. The preliminary information and training of the contractors' workers are essential.

The technology of resource positioning was prone to the fact that sometimes the positioning anchors were moved from their location, e.g., before painting. Sometimes there were not enough electricity plugs, which caused the electricity source of anchors' to be used for construction equipment. Sometimes the workers had just forgotten to take the positioning beacon with them. The site superintendent suggested that the system provider implement the positioning beacon in the same sticker as the information of passed security training, which the workers must use.

DATA OF THE CASE PROJECT

PE documented the observations of the location of resources, duration of tasks, logistical deviations, and other waste observations weekly. The SA software stores the data in the data hub in cloud. Figures 1 & 2 are screenshots of the SA-application. In figure 1, there is a view of one electrician's presence in second floor takt areas 1…5 on 15 minutes levels. It can be seen that the electrician was moving between several takt areas and spent most of the time on areas 4 and 1 on the second floor. According to the takt plan, the electricians should work on first floor area 2. In figure 2, there are the actual locations marked as red dots concerning area 1. It is then possible to drill in and identify on the floor plan how

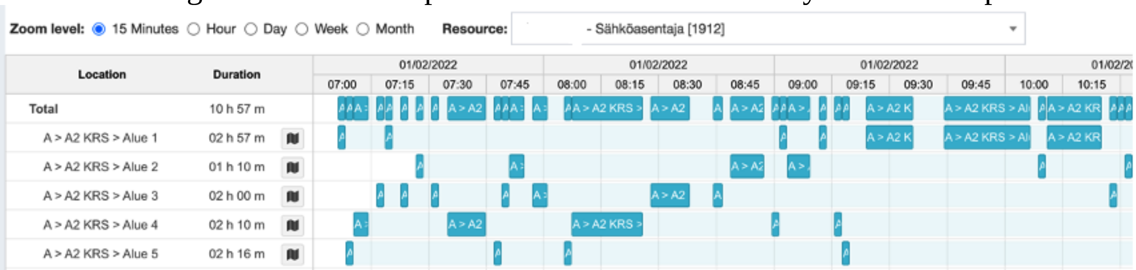

Figure 1. The figure shows an Electrician's presence on the second floor takt areas during a working day.

much time was spent on planned areas and how much time on storage areas and other areas that does not add value. Analysis of waste on task level made it possible to fix the problems rapidly, which was a requirement due to the short takt time of 8 hours.

Figure 2. The figure shows an electrician's presence indicated as red dots on the second floor takt area 1 (Alue1) during a working day.

Figure 3 shows an overview of presence during several weeks. The time flows vertically (week numbers) and takt areas are shown on the horizontal axis. This picture gives an instant view of how well the resources follow the takt production plan (thicker cells). The plumbing resource (upper table) has high deviations in task locations, which is a sign of disturbances. The percentage in each cell should be 20% if one week's plan includes five days. Electricians were able to follow the takt plan with fewer deviations. The presence

Week	A > A1 KRS > Alue 1	A > A2 KRS > Alue 1	A > A2 KRS > Alue 2	A > A2 KRS > Alue 3	A > A2 KRS > Alue 4	A > A2 KRS > Alue 5	A > A2 KRS > Rappu	A > A3 KRS > Alue 1	A > A3 KRS > Alue 2	A > A3 KRS > Alue 3	A > A3 KRS > Alue 4	A > A3 KRS > Alue 5	A > A3 KRS > Rappu	A > A4 KRS > Alue 1	A > A4 KRS > Alue 2	A > A4 KRS > Alue 3	A > A4 KRS > Alue 4	A > A4 KRS > Alue 5	A > A4 KRS > Rappu
46	2 %	4 %	0 %	1 %	1 %	0 %	0 %	0 %	1 %	1 %	1 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %
47	1 %	1 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
48	5 %	3 %	0 %	2 %	2 %	1 %	0 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %
49	4 %	3 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	2 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
50	7 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	1 %	0 %
51	4 %	2 %	0 %	3 %	0 %	10 %	0 %	2 %	2 %	12 %	0 %	2 %	0 %	8 %	3 %	12 %	7 %	5 %	0 %
52	6 %	5 %	0 %	3 %	0 %	0 %	0 %	0 %	1 %	7 %	0 %	0 %	0 %	7 %	6 %	11 %	6 %	2 %	0 %
1	1 %	1 %	1 %	6 %	0 %	1 %	0 %	11 %	11 %	34 %	13 %	9 %	0 %	1 %	3 %	1 %	0 %	0 %	0 %
2	4 %	26 %	0 %	0 %	0 %	1 %	0 %	2 %	6 %	24 %	15 %	18 %	0 %	1 %	1 %	0 %	0 %	0 %	0 %
3	23 %	53 %	0 %	1 %	2 %	2 %	0 %	3 %	0 %	3 %	1 %	1 %	0 %	1 %	0 %	0 %	0 %	1 %	0 %
4	30 %	10 %	7 %	12 %	8 %	13 %	1 %	0 %	1 %	0 %	1 %	1 %	0 %	0 %	1 %	1 %	1 %	1 %	0 %
5	16 %	3 %	0 %	0 %	0 %	2 %	1 %	1 %	1 %	3 %	1 %	4 %	2 %	2 %	1 %	1 %	2 %	3 %	1 %
6	6 %	2 %	0 %	0 %	1 %	3 %	1 %	0 %	0 %	1 %	3 %	16 %	2 %	3 %	2 %	0 %	1 %	1 %	1 %

Week	A > A5 KRS > Alue 1	A > A5 KRS > Alue 2	A > A5 KRS > Alue 3	A > A5 KRS > Alue 4	A > A5 KRS > Alue 5	A > A5 KRS > Rappu	A > A6 KRS > Alue 1	A > A6 KRS > Alue 2	A > A6 KRS > Alue 3	A > A6 KRS > Alue 4	A > A6 KRS > Alue 5	A > A6 KRS > Rappu	A > A7 KRS > Alue 1	A > A7 KRS > Alue 2	A > A7 KRS > Alue 3	A > A7 KRS > Alue 4	A > A7 KRS > Alue 5	A > A7 KRS > Rappu	A > A8 KRS > Alue 1	A > A8 KRS > Alue 2	A > A8 KRS > Alue 3	A > A8 KRS > Alue 4	A > A8 KRS > Alue 5	Total huors
46	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	87 %	0 %	0 %	0 %	0 %	04:33
47	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	1 %	1 %	1 %	0 %	93 %	0 %	0 %	0 %	0 %	19:16
48	0 %	0 %	0 %	0 %	1 %	0 %	1 %	0 %	4 %	0 %	1 %	0 %	24 %	11 %	17 %	4 %	9 %	0 %	13 %	0 %	0 %	0 %	0 %	13:02
49	0 %	0 %	15 %	0 %	0 %	0 %	1 %	0 %	66 %	1 %	0 %	0 %	3 %	0 %	2 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	09:06
50	7 %	13 %	14 %	11 %	15 %	0 %	2 %	2 %	6 %	2 %	3 %	0 %	0 %	0 %	1 %	0 %	1 %	0 %	9 %	0 %	0 %	0 %	0 %	73:25
51	0 %	0 %	2 %	0 %	1 %	0 %	4 %	2 %	3 %	1 %	2 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	4 %	3 %	0 %	1 %	3 %	61:01
52	3 %	5 %	2 %	2 %	1 %	0 %	1 %	1 %	1 %	2 %	3 %	0 %	3 %	6 %	2 %	4 %	6 %	0 %	0 %	0 %	0 %	0 %	1 %	82:12
1	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	60:08
2	0 %	0 %	0 %	2 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	05:27
3	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	3 %	0 %	0 %	0 %	0 %	0 %	2 %	74:27
4	0 %	2 %	0 %	1 %	1 %	0 %	0 %	0 %	0 %	0 %	2 %	0 %	0 %	1 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	76:02
5	5 %	3 %	1 %	2 %	4 %	0 %	1 %	0 %	1 %	2 %	1 %	2 %	6 %	5 %	4 %	15 %	3 %	0 %	0 %	0 %	0 %	0 %	0 %	61:09
6	0 %	0 %	2 %	2 %	4 %	1 %	20 %	3 %	5 %	11 %	3 %	1 %	0 %	0 %	1 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	29:26

Week	A > A1 KRS > Alue 1	A > A2 KRS > Alue 1	A > A2 KRS > Alue 2	A > A2 KRS > Alue 3	A > A2 KRS > Alue 4	A > A2 KRS > Alue 5	A > A2 KRS > Rappu	A > A3 KRS > Alue 1	A > A3 KRS > Alue 2	A > A3 KRS > Alue 3	A > A3 KRS > Alue 4	A > A3 KRS > Alue 5	A > A3 KRS > Rappu	A > A4 KRS > Alue 1	A > A4 KRS > Alue 2	A > A4 KRS > Alue 3	A > A4 KRS > Alue 4	A > A4 KRS > Alue 5	A > A4 KRS > Rappu
1	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	3 %	0 %	2 %	0 %	2 %	0 %
2	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	32 %	11 %	12 %	6 %	1 %	0 %
3	0 %	0 %	0 %	0 %	0 %	1 %	0 %	19 %	7 %	9 %	9 %	26 %	0 %	1 %	0 %	3 %	2 %	8 %	0 %
4	1 %	20 %	4 %	8 %	13 %	14 %	1 %	7 %	3 %	6 %	5 %	11 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
5	1 %	35 %	8 %	10 %	9 %	19 %	1 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %
6	1 %	33 %	1 %	1 %	2 %	3 %	0 %	0 %	0 %	0 %	1 %	3 %	0 %	0 %	0 %	0 %	0 %	3 %	0 %

Week	A > A5 KRS > Alue 1	A > A5 KRS > Alue 2	A > A5 KRS > Alue 3	A > A5 KRS > Alue 4	A > A5 KRS > Alue 5	A > A5 KRS > Rappu	A > A6 KRS > Alue 1	A > A6 KRS > Alue 2	A > A6 KRS > Alue 3	A > A6 KRS > Alue 4	A > A6 KRS > Alue 5	A > A6 KRS > Rappu	A > A7 KRS > Alue 1	A > A7 KRS > Alue 2	A > A7 KRS > Alue 3	A > A7 KRS > Alue 4	A > A7 KRS > Alue 5	A > A7 KRS > Rappu	A > A8 KRS > Alue 1	A > A8 KRS > Alue 2	A > A8 KRS > Alue 3	A > A8 KRS > Alue 4	A > A8 KRS > Alue 5	Total huors
1	18 %	17 %	18 %	15 %	21 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	27:07
2	2 %	2 %	2 %	1 %	3 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	2 %	1 %	1 %	19 %	2 %	07:10
3	1 %	1 %	0 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	2 %	2 %	6 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	69:36
4	1 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	1 %	0 %	0 %	1 %	2 %	1 %	1 %	0 %	1 %	0 %	0 %	0 %	0 %	0 %	0 %	66:05
5	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	0 %	3 %	0 %	0 %	1 %	0 %	7 %	1 %	0 %	0 %	0 %	0 %	0 %	62:53
6	0 %	0 %	0 %	0 %	0 %	1 %	1 %	0 %	0 %	0 %	8 %	8 %	20 %	0 %	1 %	0 %	13 %	1 %	0 %	0 %	0 %	0 %	0 %	43:49

Figure 3. Weekly summary of the plumbing (upper table) and electrical (lower table) resources' uninterrupted presence. Thicker cell borders indicate the planned tasks, and green cells are the actual locations that follow the plan. Red cells are locations outside planned areas. Rows are a weekly (five working days) summary of all resources' activities (13 plumbers and 9 electricians had the positioning beacon) in the takt areas.

in the planned takt areas is relatively small, indicating that there is still much room for improvement. If waste can be eliminated and presence indices increased, the risk of delays lowers and the takt times could be planned shorter in the future.

The SA system may also include condition sensors with max and min alerts which can be used to evaluate whether external conditions are available to start work. PE's task is to follow all this digital information and report the site management regularly deviations.

DISCUSSION

A SA system has three levels (Endsley, 1995). The study results show that the digital SA system provides level 1 and 2 information that improves the use of takt production. The digital SA system provides observations of the takt production status. Different camera and video information and outputs like individual workers' location at 15 minutes intervals (figure 1) are examples of the observations. The schedule where the actual workers' presence is combined with the planned takt production tasks (figure 3) helps to understand the outcomes of waste. The current system still needs PE to point out the critical observations and support the superintendent in understanding the meaning of observations. The observations show the waste like low presence index, which root cause can be deviations on material delivery or in work arrangements on site. Level 3 predictions of the future are still on PE's and superintendent's responsibility. In the future, AI may detect waste and its root causes and predict the delays and other challenges based on on-site observations.

The digital SA provider's PE gave the site manager and contractors weekly reports. In practice, PE finds waste, which was made visual by using site cameras, 360-videos, and resources location tracking. Some of the findings were valuable. The fatal deviation of material deliveries was managed to drop from 15 to 5 per week. The positioning system of resources gave the accurate location of resources and the time of presence. It was possible to calculate the real presences percent on the takt area. The project team was able to improve the presence index from twenty to seventy percent in some cases.

The system had significant benefits, and it helped the site superintendent detect waste and then find the root cause and fix it. The system produces reliably the actual schedule (figure 3) based on the real resource actions on site. There are things to improve as well. The use of a digital SA system should be mentioned in the project agreement. The project staff should be informed and explain why the digital SA system has been implemented and the benefits for each stakeholder group. The positioning grid's installation had challenges when the tags were removed during painting. The location sensor should be attached to each worker's helmet at the beginning of the project and not allow workers to keep the sensors in pockets, where they quickly forget.

It is good to point out that the waste found was concerning individual processes in takt. The improvements did not shorten the planned whole construction duration because it is hard to change the whole takt train if some operation can be improved. However, decreasing waste is directly beneficial to the participating contractors, who can then consistently hit their takt times and it also reduces the schedule risk of the main contractor. The largest opportunities arise if the use of digital SA systems is continuous and used in all projects. The data should be collected more systematically to evaluate how much buffer there is in task durations and capture lessons learned to future takt projects. In this project, tasks had a different variance in their durations. When the variance lowers due to continuous development, it gives the site management possibilities to decrease the takt times and thus the total duration in the next project. All this data of the actual resource positions during several projects helps the resource planning in the following projects. The actual information of resource locations in projects can later be used for artificial intelligence (AI) solutions to predict project delivery success versus planned turnover and project costs. AI can later detect waste and suggest how to fix it.

This study was based on the data of one construction project. Therefore, there are limitations on how to apply the results. The variance of the observations was also high. This study gives good reasons to make new studies using digital SA systems and takt production together. The combination could decrease the risk of schedule overruns, uncovers production problems, and makes it possible in the long run to continuously improve takt production and achieve shorter takt times which ultimately can shorten construction durations without sacrificing quality and cost.

CONCLUSIONS

According to Sauders et al. (2009), the exploratory case study method can be used if an issue is new or not studied earlier thoroughly. The SA technology is new, and the experience of using it to improve takt production is also new. The best advantage the digital SA provides to takt production projects is that it gives online information on how the project proceeds. The data is reliable because it has been produced automatically without human interpretation. Project staff can react to the information found and fix the issues before turning them into loss, delays, or other waste. Many other systems (Alhava et al., 2019) give the information afterward, and the information is based on the workers' interpretation.

In this case, it was easy to recognize the recurring structures of the SA system. Status of the environment and observations were simple to authenticate from site cameras, 360 videos, and location data of resources. It helps to understand the current situation. Since the observations were real-time, the waste could be detected and could be easily improved by analyzing the process. This helped in the production of future takt areas. The location reports of resources showed the status of takt production and were a basis for the future status prognosis. Real time views produced by SA system and PE's reports were the basis for decision-making. SA system and PE make the waste visual, and site management makes the decisions based on these facts.

The goal in the case project was to use digital SA to continuously analyze takt production to improve the process. The digital SA system made the waste visual. PE's report highlighted the findings to the site manager responsible for finding the root cause and fixing the issues. As a result of this study, the SA system gives tools to construction sites to analyze production on time and react to found issues. SA systems produced valuable data on the construction project. It would be feasible to collect data continuously on the takt production project and individual resources performance. This data can be a basis for continuous improvement on construction sites. The data was manually analyzed in this study. When the analysis becomes automatic through AI methods, we are one step closer to achieving the vision of Digital Twin Construction (Sacks 2020).

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SCRUM COMPLEMENTING LAST PLANNER SYSTEM – A CASE STUDY

William Power[1], Dr Derek Sinnott[2], and Dr Patrick Lynch[3]

ABSTRACT

Scrum emerged from the software sector and has been identified as a novel methodology that is radically different from traditional project management teaching. However, there is a paucity of data from real life case studies that affirm Scrum can benefit construction execution.

This paper reports on a 20-week Scrum implementation across seven teams on a construction project that must achieve a critical building weathertight milestone. The study adopted a mixed-methods approach utilising case study design and data collected from a literature review, project documentation review, direct observation, purposeful semi-structured interviews, and a focus group workshop.

Scrum complements Last Planner® System (LPS) implementations and brings specific benefits at point of work execution by reducing weekly missed tasks resulting in increased and more reliable Planned Percent Complete (PPC). An 11 percent increase in average PPC accrued from utilising Scrum to complement LPS by reducing reasons for non-completion (RNC) of work tasks at crew level work interfaces. Additional softer benefits in the form of enhanced inter-trade communications and collaboration, as well as greater involvement of the entire crew in striving to achieve task execution. Further in-practice and academic research is required in aligning construction processes and methodologies with the concepts and definitions found in Scrum.

KEYWORDS

Lean construction, agile, scrum, last planner system, collaboration.

INTRODUCTION AND LITERATURE REVIEW

The basis of Lean thinking is the understanding and design of production processes (Koskela 1992, 2000) and Rooke (2020) asserts these processes depend on people to make them happen. While early Lean literature may have overly focused on the 'hard' tools and techniques at the expense of the 'softer' behavioural aspects (Hines et al. 2020), LC brings a balanced view of both people and production process into construction (Rooke 2020).

The LC community has consistently sought learnings from other business sectors with a view towards enhancing construction's performance. As early as 2002 Koskela and Howell expanded their earlier work on the theoretical foundations of project management

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and referred to two innovative methodologies that were a radical change from the existing teaching of project management. These were LPS and Scrum (Koskela and Howell, 2002a, p.2). LPS was developed as a collection of functions that assist practitioners coordinate production operations on construction projects (Ballard and Howell 2003; Hamzeh et al. 2016; Power et al. 2021). LPS has since become a dedicated and foundational tool of LC and applies the fundamentals of Lean thinking to construction planning and execution (Ballard and Tommelein, 2020). Meanwhile, at the same time (early 1990's) Jeff Sutherland and Ken Schwaber were creating Scrum '…as a faster, more reliable, and more effective way to create software in the tech industry' (Sutherland, 2014, p. vii). Koskela and Howell (2002a) identified Scrum as being a comprehensive management method that skipped over conventional project management doctrine and suggested the success of Scrum and LPS theories offered substantial improvement on the traditional theory of project management as espoused in PMBOK.

Case studies have established that Scrum can enhance design coordination (Kalsaas et al. 2014; Lia et al. 2014; Demir and Theis 2016), collaboration in planning (Daniel et al. 2020), and management of construction projects in a multi-project environment (Hamerski et al. 2019). While LPS has also thrived in design, management, and support functions there is a paucity of tangible data to demonstrate the benefits Scrum can bring to construction execution. This paper examines the use of Scrum in construction and offers findings and recommendations from a case study conducted on a construction project.

SCRUM

The Scrum Guide (2020) describes Scrum as: '…a lightweight framework that helps people, teams and organisations generate value through adaptive solutions for complex problems.' 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 tasks (Sutherland 2014; Layton et al. 2020; Engineer-Manriquez 2021). Scrum requires a Scrum Master (SM) to create a working environment where a Product Owner (PO) organises the work to be completed into a Product Backlog; the Scrum Team works on prioritised tasks converting them into increments of value during a Sprint; and the Team and its stakeholders inspect the results and adjust (continuously improve) for the next Sprint (Sutherland, 2014). Scrum relies on the deep tacit knowledge of its team members to rapidly address work batches and continuously release increments of value to the next customers in line (Owen et al. 2006). The Scrum framework is purposefully incomplete and is a radical change from the traditional prescriptive management methodologies; rather than provide people with detailed instructions, the rules of Scrum guide persons relationships and interactions (Schwaber and Beedle 2002; Scrum Guide 2020).

SCRUM THEORY – RELEVANCE IN CONSTRUCTION

Agile processes are based on an empirical control method – a process of making decisions based on the realities observed on the project (Layton et al. 2020). Action follows from each situation created by prior action. This is labelled 'management-as-organising' by Koskela and Howell (2002a, p.8), but in a 'lightweight manner' as described by Owen et al. (2006, p.54). Table 1 summarises Koskela and Howell's (2002a) work on interpreting the theory underpinning Scrum.

Table 1: Underlying Scrum theory (from Koskela and Howell 2002a)

Theory	Explanation
Planning	Management-as-Planning: High level to develop Backlog of Value to be delivered; Sprint planning cycle & Daily review cycle. Management-as-Organising: Pre-determined work cycles and conversation routines. Action created from prior action & coordinated within the Team. Management is addressing the structuring of the setting of action, in terms of predetermined work cycles and associated, routinised conversations.
Execution	Pull from Backlog; self-assign tasks; deliver regular Value in Sprints; Team self-inspects and adapts; the whole Team is the customer of the task.
Control	Three levels of control exist: 1. Highlight & escalate impediments / blockers for resolution (based on scientific experimentation model – focuses on learning & knowledge creation). 2. Completed Sprint offered to Customer & Management (based on scientific experimentation model – focuses on learning & knowledge creation). 3. Refine and readjust Product Backlog prior to next Sprint (based on thermostat model – manages time & cost issues).

Critically, Scrum is different from traditional project management teaching as it does not have a Work Breakdown Structure (WBS) and task dispatching decisions are decentralised from management to the team (Koskela and Howell 2002a). The Customer and management determine the value and features required by creating a Product Backlog and Scrums planning theory allows the Team to self-organise work in sequential Sprints. Scrum's execution theory pulls from a Product Backlog of customer requirements. Self-organising teams of three to nine persons self-assign tasks that are sized to deliver value at a regular cadence called Sprints. Scrum uses frequent and first-hand inspection of the work where teams can make immediate adjustments coordinated by its members as opposed to the traditional management methodology of centralised management (Chen et al. 2007; Sutherland 2014; Layton et al. 2020). Control theory in Scrum exists at three levels according to Koskela and Howell (2002a). At the lowest level each team member highlights impediments to task execution and escalates these to higher levels for resolution. At the next level the team presents its completed Sprint achievements to both management and customer, exhibiting both value and functionality offered to the project. Feedback and continuous improvement are incorporated into the next Sprint. The highest control level in Scrum concerns the entire project where the Product Backlog is refined and overall project control relating to cost, scope and schedule is revised and reimagined as required (Koskela and Howell 2002a; Sutherland 2014; Layton et al. 2020). The key concept of agile thinking and the Scrum framework is the constant focus on value identification, value generation, and value delivery (Sutherland 2014; Layton et al. 2020; Engineer-Manriquez 2021). Agile theory and the Scrum framework closely align with the primary lean aim of providing value throughout the delivery process as opposed to traditional construction and project management which, from the start, focuses on clearly defined value outcomes defined as project deliverables (Owen et al. 2006).

SCRUM IN CONSTRUCTION

Since the potential of Scrum for construction was first highlighted by Koskela and Howell (2002a), there is a lack of published studies relating to Scrum application in the construction sector. Owen et al. (2006) suggested agile project management can relate to construction but highlighted several obstacles to its adoption. Numerous authors admit Scrum is more easily applicable to design (Owen and Koskela 2006; Chen et al. 2007; Kalsaas et al. 2014; Demir and Theis, 2016) and others (Bertelsen, 2002; Bertelsen and Koskela 2003) add that constructions rigid assembly sequence plus its complexity, means change and reworks are difficult to accommodate in construction. Conceptually, design in construction and software development are similar in their iterative character as regular increments of work (value) can elicit feedback until client satisfaction is achieved (Kalsaas et al. 2014; Demir and Theis 2016). These feedback loops and the ability to inspect and frequently adapt to feedback and change are core to the Scrum framework (Sutherland 2014). Some implementations have complemented LPS in design with Scrum sprints enhancing the execution phase (Lia et al. 2014; Kalsaas et al. 2014).

The current approach to planning in traditional construction project management is mostly limited to the transformation of inputs to outputs (Sacks et al. 2016; Daniel et al. 2020); numerous authors agree this cannot enable the collaboration and social network structure required for effective and timely task execution (Demir and Theis 2016; Power and Taylor 2019; Ballard et al. 2020). However, according to Daniel et al. (2020), the 'flow' and 'value' views offered by LPS and Scrum can provide the resources required for smooth running of a collaborative construction production system. Additionally, the structure and process of both LPS (short term planning, execution and control – Koskela and Howell, 2002a, p.6) and Scrum (focusing on Minimum Viable Product through Sprints – Layton et al. 2020, p.438) completes the 'transformation' of inputs to value outcomes.

SCRUM AND LPS COMMONALITIES

Researchers and practitioners should recognise that LPS was specifically designed as a system for planning and controlling production on projects and extended to '…both production (i.e., striving for targets) and project planning and control (i.e., setting targets) in the 2020 Current Process Benchmark (Ballard and Tommelein 2021). Scrum is a subset of Agile, has its roots in lean and in Deming's PDCA (Sutherland, 2014), and according to Poudel et al. (2020) LPS and Scrum share several principles relating to team collaboration in both work organisation and enhancing customer value. Suggested commonalties from Poudel et al. (2020) and Engineer-Manriquez (2021) are: a) both are frameworks designed to increase value delivered to the customer by pulling increments of value adding work into progress while also protecting team capacity by limiting work in progress, b) both use different planning levels to break down and coordinate activities, c) both emphasise systematic learning and continuous improvement, d) LPS master and phase schedules are similar to the Scrum Product Backlog, the constraints concept is common to both, and LPS weekly work plan is equivalent to the Scrum Sprint Backlog, e) both require consistent team collaboration to refine planning and daily coordination and this is managed with scheduled events, f) both use metrics to track progress and performance.

METHODOLOGY

CASE PROJECT

The case project is in Ireland and is an extension to a distribution warehouse for an international manufacturer. The building is 12,000 m^2 in floor area, is 15m high, and has

28 dock leveller truck loading bays on opposing elevations. The building is steel portal frame on concrete pad foundations with elevation and roof cladding panels. A major ground works enabling project plus substantial works at the 100m interface with the existing facility adds to the overall complexity of the project. The initial key objective is to achieve a handover milestone date for the finished floor space to enable the racking installation provider to gain early access. The project was 26 weeks in progress, had 20 weeks remaining until the key interim handover milestone, and was already three weeks late due adverse weather affecting the soil stabilisation works. The schedule was re-baselined with a commitment to recover the three weeks slippage and retain the original interim milestone date. Therefore, the problem to be addressed was to steer the project towards achieving agreed Conditions of Satisfaction (CoS) relating to the early-access milestone. Additionally, the Project Director was concerned of over-runs in the remaining schedule duration as there were substantial financial penalties for not achieving the milestone.

RESEARCH DESIGN

The paper reports on a case study of Main Contractor implementing Scrum to achieve a critical milestone on a construction project which was running three weeks behind programme. The team had been using LPS but were still experiencing problems at crew level relating to coordination and workface organisation. This study utilises a mixed-methods approach with case study design in accordance with Yin (2009). Case study is a widely used research design and according to Yin (2013) is best placed to answer ‘how’ and ‘why’ questions. Principles of action research and learning were also applied as the researcher was coaching the project team during a critical phase of the project. Figure 1 presents the layout of the Scrum framework utilised on the project.

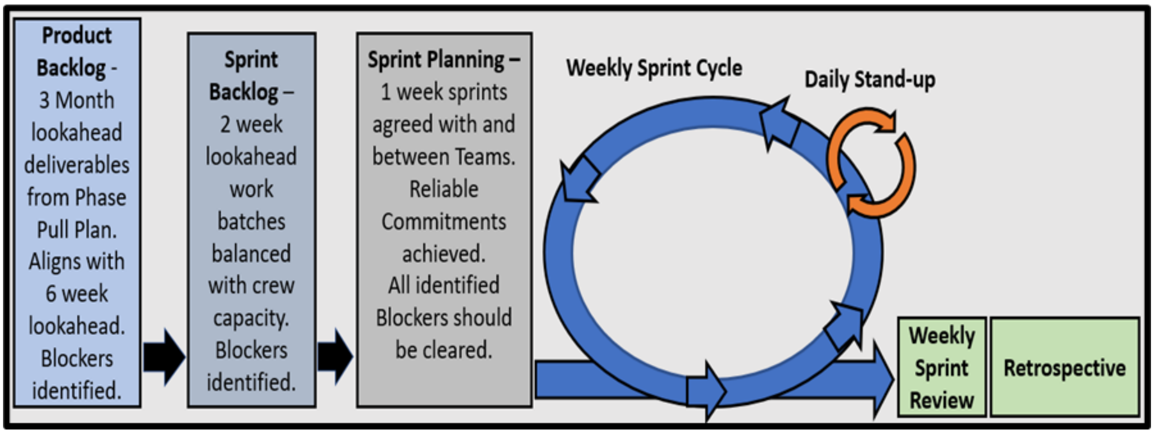

Figure 1: Scrum framework implemented on the case project.

The framework presented in figure 1 aligns with the conceptual model presented by the founders of Scrum, and as described by Sutherland (2014), Layton et al. (2020) and Engineer-Manriquez (2021). A key input is the LPS functions of Pull Planning, Lookahead Planning, including early constraints identification (called blockers on this project), to prepare the prioritised Backlog of tasks for the work crews to plan from.

Purposefully selected interviewees were familiar with construction and participated on the project. An external Agile coach/Certified Scrum practitioner was invited to observe the implementation and his feedback was also included in the research data. In accordance with Braun and Clarke (2006) the transcribed interviews were thematically analysed; triangulation was ensured when conclusions reached from emerging themes were compared with workspace board outcomes and the literature review findings to check their reliability and integrity. In accordance with Eden and Huxham (1996) an action research approach was utilised to monitor and measure the effectiveness of interventions. An integrative literature appraisal examined existing Lean, Agile, Scrum, and LC literature. Seven virtual workspace planner boards from the contractors critical to achieving the milestone (Roofing, Cladding, Precast, Dock Enclosures, Groundworks, Flooring, Core Team and Blocker) were examined for level of task detail and alignment with milestone targets.

On achievement of the milestone, a focus group workshop was conducted with the site management team and key contractor supervisors. Purposeful semi-structured interviews were conducted with six senior figures on the project. LPS Pull Plans, Weekly Work Plans, and PPC data was also available to the researchers. Table 1 presents the data sources for the research.

Table 1: Research Data Source

Source	Participants
Integrative Literature Review	Lean, Agile, Scrum, LC Literature & particular focus on past IGLC contributions
Project Documentation	Project schedules, “S” curves, Weekly reports, Seven virtual workspace planner boards, LPS PPC & RNC data.
Direct Observation	Action Research Diary
Purposeful Interviews	Interviews with Contractor Director, Project Manager, Client Representative, Roofing Contracts Manager, Precast Installation Director, External Agile coach / Scrum practitioner. (n=6)
Focus Group Workshop	A facilitated focus group workshop was conducted with team members and key sub-contractors (Roofing, Cladding, Precast, Groundworks, Dock Enclosures, Flooring) on achievement of the milestone.

Limitations exist around the single case example, the small sample size, and the limited sample profile.

FINDINGS & DISCUSSION

LPS data

The team had been using LPS and PPC was averaging 72 percent for the first 26 weeks of the project. This included four weeks of persistent rainfall which caused three weeks slippage in the schedule. The impact of the exceptional rainfall caused a 4 percent drop in average PPC; excepting these outlier 4 weeks gives an average 76 percent PPC over the first 26 weeks. In addition to weather impact, examination of the RNC data pointed to tasks over-running due to inter-trade communication and coordination issues at point of work interfaces.

Defining the problem

Root cause analysis investigation found crew leaders were attending LPS morning huddles, but communications were not relayed to all team members, especially relating to handovers to other trades. Preparing for the flooring contractors’ arrival to site would involve critical interface coordination. Therefore, a more detailed communication strategy that involved crew members from all teams focusing on priority handoffs would be required.

Conditions of Satisfaction

Understanding exactly what was required to satisfy the key milestone needed to be understood by all stakeholders in the process. The racking installer provider required a clear floor area available as they had multiple installation crews assembling different racking systems simultaneously. The building also needed to be weather tight. The flooring contractor required 4 weeks installation duration, requested 50% of the floor area to be available, and needed the space to be wind and rain-proof. A process mapping exercise reduced this request to 33% of the floor area. However, detailed daily coordination of the key contractors would be required to seal the building envelope to align with the partial handovers for the flooring contractor.

Why Scrum?

Scrum had been used in the design phase of the project and management noted the daily huddles involving the workers in the teams as opposed to just the team leaders. An After-Action-Review (AAR) post-design phase identified the connectivity created at team level as a key advantage of Scrum over the crew supervisor-level engagement of LPS. Additionally, examination of the RNC on the weekly LPS implementation illustrated a trend of missed tasks accruing from incomplete or late handoffs and poor interface coordination at crew level. Chen et al. (2007) figure 1b, had proposed '…small, interactive multi-disciplinary teams… absolutely self-managing' (p.63), illustrating a model which assured communication saturation amongst Teams. For these reasons the Project Director requested Scrum concepts be implemented in conjunction with the LPS implementation.

Team level communication

Individual teams communicated directly with each other and any issue unresolvable at site crew level was immediately escalated by the SMs to the Core Team / Blocker Board. A key finding was the amount of rapid decision-making enabled on the site thus minimising escalation to management and subsequent waiting for responses. The SMs played a critical role in ensuring the path ahead was always clear to allow the team to achieve steady flow and consistent production outputs. The Product Owner (PO) of the onsite teams was the Project Manager (PM) and the Project Director was PO for the Core Team / Blocker Resolution Board. Each team was assigned a SM with junior PM #1 supporting and serving Cladding, Roofing, and Precast teams. Junior PM #2 supported and served the Ground Works, Floor Install, and Dock Enclosures as SM. The lead author served the Core Team / Blocker Board as SM. All POs and SMs received Scrum training and certification. Effectively, the SMs became facilitators of conversations within and between the site teams ensuring daily and weekly planning interfaces were constantly to the forefront. All Team members received introductory Scrum training explaining their roles and the objectives of the implementation.

Daily routine

Critical also to success was the importance of routine; figure 2 illustrates the weekly Scrum cycle noting the demand on the work crews is only 10 minutes for the daily stand up at the same time each day.

Scrum Weekly Cycle				
Mon	**Tue**	**Wed**	**Thur**	**Fri**
Team Daily Stand-up (Pre-0900)	Team Daily Stand-up (Pre-0900)	Team Daily Stand-up (Pre-0900)	Team Daily Stand-up (Pre-0900)	Team Daily Stand-up (Pre-0900)
Scrum Masters & Project Manager Stand up (1020-1030)	Scrum Masters & Project Manager Stand up (1020-1030)	Scrum Masters & Project Manager Stand up (1020-1030)	Scrum Masters & Project Manager Stand up (1020-1030)	Scrum Masters & Project Manager Stand up (1020-1030)
Core Team / Blocker Board Touchpoint (1335-1345)	Core Team / Blocker Board Touchpoint (1335-1345)	Core Team / Blocker Board Touchpoint (1335-1345)	Core Team / Blocker Board Touchpoint (1335-1345)	Core Team / Blocker Board Touchpoint (1335-1345)
		Sprint Planning (1630-1700)	Sprint Planning (1630-1700)	Sprints Review (1500-1515)

Figure 2: Scrum implementation weekly cycle

The importance of routine and a rapid blocker escalation and resolution process were critical to the success of the implementation. Each crew's stand up would take place at the same time daily. On the case project, each SM had to support three teams so they would schedule the individual stand-ups at 0745, 0815, and 0845. The key point was each stand up was conducted before 0900. The SMs and the PO had their stand up at 1020, just after their morning break. This ensured communication saturation early in the day – the site management team were aware of any issues or concerns that may affect performance.

Complementing LPS

In LPS it is generally the crew leader who attends the morning huddle however, in the Scrum stand-ups on the case project every crew member had a voice, and this was a critical aspect in empowering everyone to contribute. Simple issues like diminishing supply of screw fixings, anticipated specialist equipment requirements, or advance notice of a member needing a day off were communicated. Figure 3 presents PPC figures for 26 weeks with LPS and for the following 20 weeks with Scrum complementing the LPS functions. PPC over the first 26 weeks shows the impact of excessive rainfall on the soil stabilisation and foundation installation activities with sub-60 percent figures for three consecutive weeks (6 to 10). However, PPC was still struggling to consistently achieve reliable 80 percent weekly. Scrum complemented the LPS at crew level daily interfaces and average PPC from week 27 to week 46 was 87 percent; this was an 11 percent PPC increase from the first 26 weeks adjusted average PPC. Comparison of RNC from post-week 27 data (Scrum) with pre-week 27 data (without Scrum) points to a reduction in scheduling and coordination issues at interface handoffs between crews. Table 3 points to tangible PPC improvement from the introduction of Scrum and suggests PPC may have remained below 80% weekly if Scrum had not been introduced.

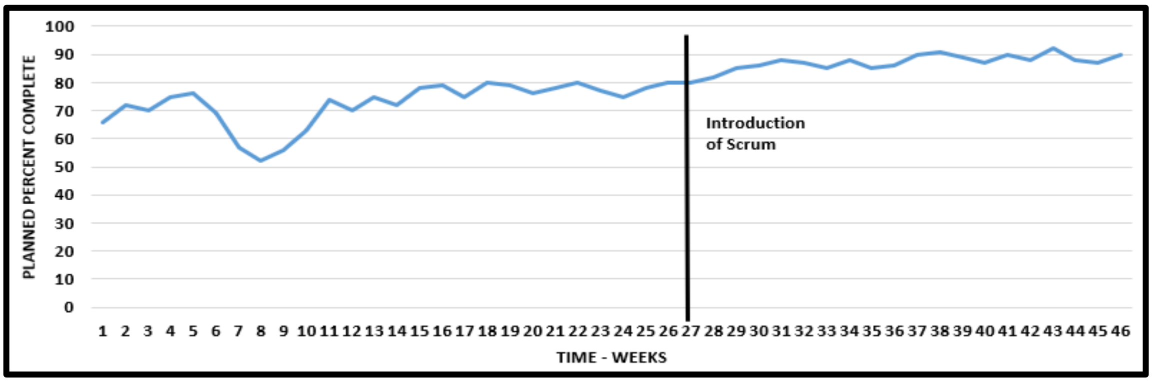

Figure 3: Impact of Scrum on PPC

It is important to note that the functions of LPS were essential towards establishing the Pull Plan, identifying constraints at multiple levels, consistently preparing for flow, stabilising the lookahead, and aligning the Product Backlog, Sprint Backlog, and Sprint Planning with the lead-in to preparing a weekly work plan. Site management and crew supervisors still attended the LPS huddles and planning sessions and PPC was recorded weekly.

Scrum Master role

With everyone involved there is less waste relaying communications and less chance of misunderstanding. Notably, the SM, even though a member of the site management team, was equal in status to all other team members in the Scrum teams. SMs must work as both coaches and facilitators (Layton et al. 2020) and this was a critical role for the SMs on the case project. SMs shielding the Team from external distractions or demands as well as maintaining focus on the Sprint was of immense benefit according to the interviewees. A summary of the interview themes and findings are summarised in table 2.

Table 2: Interview findings

Theme	Comment
Communication	Entire crew involved in daily stand up. Communications channelled to SM & PO stand up & to Core Team / Blocker Board Touch point & rapidly back to Team at next stand up. Better site interactions, communications & knowledge sharing.
Team autonomy	Team felt they were not being directed by management with constantly changing objectives & deadlines. Once a Sprint was set, the Team was free to deliver in the best way they decided.
Consistency in planning	Routine brought by the process brought consistency to the week and month.
Team Spirit	Limitation of work in progress, allied to external impediment removal protected the Team from unnecessary stresses. SMs shielding the Team from external distractions or demands as well as maintaining focus on the Sprint protected Team capacity and focused on the goal. This fostered a collaborative, innovative, and proactive culture making the project a 'happier' place to work.
Continuous improvement	Due to the small-sized teams (largest Team had eight members) there was continual and focused interest & motivation in improving the process.

Blocker identification and removal

The focus group workshop findings suggest more detailed interface planning effort at site level, particularly coordination by the SMs, ensured smoother workflow and less reactionary planning at the workfaces. When issues arose, there was a process in place to ensure rapid escalation and resolution of the issues. The findings from this facilitated focus group workshop are presented in table 3.

Table 3: Focus group workshop findings

Theme	Summary
Weekly planning	Clarification of priorities & alignment with other trades ensured clear focus for the upcoming week.
Short cycles	Breaking the work into smaller batches ensured more frequent hand-offs of value to the next trade in line.
Removing blockers	SMs helping identify blockers & then taking the blocker for resolution took stress off the Team
Engagement & involvement	Entire Team involvement in the Stand-up huddles generated more information and assisted with focus & alignment.
Ensuring next work area is available	With SMs interacting between Teams there was greater reliability in ensuring the next areas and handoffs were available.
Completion of work & quality	SMs encouraged completion of increments that delivered value handoffs to next trades in line. No multi-tasking. Focus on the quality handoff.

After time, a climate of greater inter-trade agreement and alignment on achieving schedule dates emerged. Teams became more pro-active in foreseeing potential blockers and took positive action for the betterment of the project and other trades progress. A tangible benefit of the implementation was the improved quality of the completed work elements to the next trades. Trades working closer together created relationships and with that a responsibility not to pass on defective work. Work being broken into smaller batches resulted in shorter turnover cycles and resultingly brought improvement to the schedule duration as there was less work in progress and less waiting time.

Clarity and agreement of the definition of 'Done' ensured greater alignment between Teams. Where Chen et al. (2007) suggested some lean and agile applications increase project complexity, this study asserts effective Scrum implementations utilising small, autonomous, self-performing teams, served, and facilitated by focused SMs can enhance interface management and simplify daily and weekly production.

CONCLUSION & RECOMMENDATIONS

The schedule early access milestone was achieved however, the authors do not claim this was solely due to the Scrum implementation. The study illustrates how Scrum could be implemented on a construction project and presents examples of the benefits that accrued from this specific implementation. The fact that the Main Contractor and sub-contractors decided to continue the Scrum framework into the next stages of the project suggests advantages have accrued to all parties. While acknowledging that a mature LPS implementation would possibly have achieved similar results, the authors question if LPS would have reached the required level of maturity as quickly as the Scrum process. Additionally, we posit an issue for current LPS implementations is the dissemination of information from crew leaders to crew members; on many large projects it is usually only crew leaders attend huddles and planning sessions. Within the Scrum framework everyone is involved in planning and execution thus extending LPS to every individual as opposed to just every crew leader. We suggest introducing Scrum was easier as the implementation involved individual Teams; this would have been closer to the traditional siloed models inherent in construction and not such a culture shock as some of the instantaneous collaboration demanded by LPS. Therefore, the cultural change demanded was not huge and, in fact Scrum satisfies Team members intrinsic desire for involvement. Critically, adding the services of the SMs as a facilitator, coach, roadblock remover, coordinator, planner, liaison with other contractors, and servant leader brought extra support to individual Teams and to the overall site coordination and was a key enabler of improvement and success. Additionally, the Main Contractor's management process became smoother as the two SMs were embedded within the production teams and then liaising cyclically with the PM and the Project Director. Working with smaller increments ensured greater quality control and visibility of the true status of project progress. The authors acknowledge this was a simple and straight forward implementation on the structure and envelope of a project superstructure. Next steps would be to carry the process through services installation and commissioning.

Finally, further practical, and academic research is required in aligning construction processes and methodologies with the concepts and definitions found in Scrum.

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LOCATION-BASED WORK SAMPLING

Cristina T. Pérez [1], Stephanie Salling [2], and Søren Wandahl [3]

ABSTRACT

Previous studies have applied the Work Sampling (WS) technique in different job sites to determine how workers employ their time in relation to a taxonomy of various work activities. However, no other significant contribution has been discussed for including location information of the work activities. This study added a geographic location to each random WS observation for a more comprehensive work efficiency analysis. In this paper, an implementation analysis was presented based on the findings from a case study. The research process followed four steps: (1) clarifying the categories of the activities; (2) deciding the confidence interval; (3) collecting and extracting data; and (4) analyzing the data. For adding location data to the technique, the authors used the geographic coordinates provided by smartwatches used by the research team connected to two Global Navigations Satellite Systems (GNSS), and the coordinates obtained from photos taken for each observation. Each observation made contained the following information: (1) photo; (2) timestamp; (3) trade observed; (4) work category; and (5) geographic coordinates, consequently, workspace category. This paper presents as the main contribution an adaption of the WS technique, named Location-based Work Sampling (LBWS), which can provide a better understanding of the ongoing activities' behavior.

KEYWORDS

Location-based Management (LBM), Visual Management, Waste, Work Sampling, Geographic location observations.

INTRODUCTION

The time study technique popularized under the name of Work Sampling (WS), which is deployed to determine how workers spend their time on different work activities, became popular, among other reasons, due to its easy and straightforward application. The theory of WS is based on the laws of probability, which indicate that observations made at repeated random times will have the same distribution. Thus, random observations can be translated into percentages of time spent in activity categories (Barnes, 1968).

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Over the years, the technique has been employed by Lean practitioners and researchers for several different purposes: (a) to provide insight for comparing the average productive workforce utilization to respective work processes in various projects (Picard, 2002); (b) to measure labor efficiency and inefficiency (Neve et al., 2021; Ramaswamy, 2009); (c) to measure and conceptualize flow and workflow (Kalsaas, 2011; Wernicke et al., 2017); (d) to identify the share of time spent on a single activity of the same construction process on different job sites, e.g., transportation (Pérez et al., 2015); (e) to set up a baseline measure for improvement and to serve as a challenge to management and the workers (Neve & Wandahl, 2018); (f) to understand the evolution of share of time spent in different work categories along the years (Wandahl et al., 2021), among others.

In most cases, the researchers and practitioners focused on understanding the share of time spent in the different work categories without explicit attention to the location where those consuming time activities were being conducted; and when identifying the observation locations, the observers generally divided the site into observation zones. An example of this was presented in the study of Wernicke et al. (2017). The authors categorized the observation made on an off-site production system regarding the following work areas: floor line, assembly line, and safety line. However, the difficulty arises because of the fundamental difference between the work zones of a manufacturing plant, as opposed to a construction site; the work activities do not change through the locations.

Hence, previous studies provide little insight about causative factors about the distribution of the share of time through the job site locations. Thus, this research aims to fill the knowledge gap regarding how to use the WS technique to provide information for identifying where the work activities identified were observed. This research supports the idea that the adaptation of the WS technique combined with among other Location-Based Management Systems (LBMS) can be considered decision support systems. Hence, this exploratory case study was driven by the following question:

- Which opportunities can merging geographic location data with Work Sampling data bring for construction management?

An exploratory case study of a building renovation project was deployed to address this question. This paper differs from others WS studies in its practical focus: this is a study using actual data for understanding the utility of geographically located observations (geo-located observations for short) collected during the WS application to improve project control and site efficiency. This is an ongoing research project, so the utility of this new WS adaptation was not yet fully evaluated. Therefore, the discussion of the results is mainly descriptive.

RESEARCH METHODOLOGY

This research deployed a case study (Yin, 2003) as a primary research strategy, as case studies offer flexibility for explorative and theory-building research in real-life contexts. During the case study, the research scope can be re-addressed and complementary data sources can be acquired, while the method also serves several types of research objectives (Beach et al., 2001). Among the number of options in carrying out case research, the authors characterize this study as an exploratory case study.

This case study is part of a research project aiming to improve productivity in the Danish construction sector by adopting Lean tools, techniques, and methods. The main actors of the research project are: (1) a consultant firm; (2) a research team represented by the authors of this paper, and (3) three Danish medium and large-sized contractors (named in this research as Organization A, B, and C). The consultant firm is responsible for the Lean implementation. The research team aims to establish the construction project efficiency baseline before and after the Lean adoption. For that, the authors gathered data using several sources of information and techniques. This paper focuses on the data collected through the WS application in a job site of Organization A. The construction company provided access to project-related documents, observation of routine activities, and interaction with team members to learn about the processes on site.

The case organization of the present paper (Organization A) is one of the main contractors in the building sector in Denmark. The case study was conducted on a building renovation project in Roskilde during weeks 45 and 46 of 2021. The construction project consists of renovating 24 five-story housing buildings. The project presented several milestone phases. Four buildings of phase 1 were under renovation during the period of this case study, named Building A1, B1, C1, and B2 (see Figure 1).

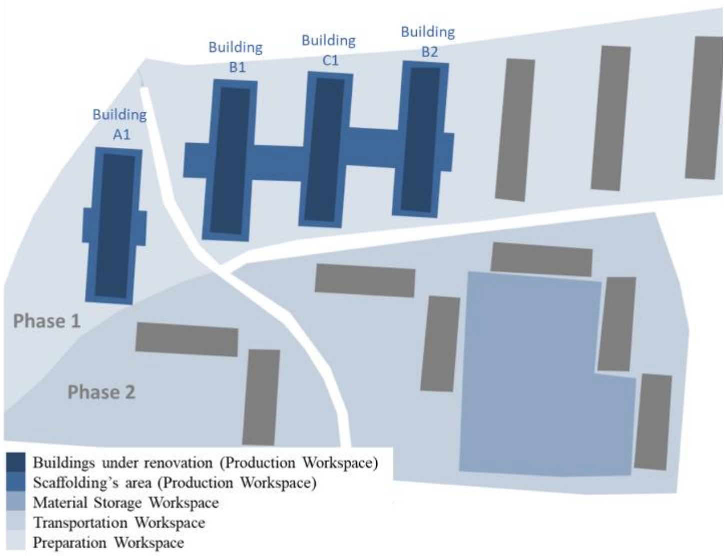

Figure 1: Job site layout.

Figure 2: Façade scaffolding and scaffolding between Buildings B1 and C1.

The main renovation tasks were applied from outside-in and related to mainly carpentry work, such as replacing windows and roofs. Installing new ventilation and electricity systems represented the only two inside renovation activities. During the execution of the renovation project, tenants are granted rehousing in the period when their apartment is being renovated, but they are living in the apartment during the remaining renovation. For this reason, most of the renovation activities were conducted outside the buildings from a façade scaffolding (Figure 2). Moreover, from the referred scaffolding, workers completed masonry and painting work.

Organization A placed modular containers within the job site for storage, administration, and changing rooms (named as Material Storage Workspace in Figure 1). The main material storage area, destined for inventory deliveries, is located next to the administrative containers. Several camp 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. Organization A rented a façade scaffolding with plastic covering the entire temporary structure for each building under renovation. The scaffolding of Buildings B1, B2, and C1 are interconnected to facilitate workers' movement among the buildings, as illustrated in

Figure 2. The scaffoldings included a cabin as the main lift solution (see the lift in Figure 2) for material transport. Moreover, a mobile crane was used for lifting windows using hooks for installation and pallet lifts for transportation.

RESEARCH DESIGN

The research process followed these steps: (1) to clarify the categories of the work activities and workspaces; (2) to decide the confidence interval and the accuracy desired; (3) to collect and extract data; and (4) to analyze the data.

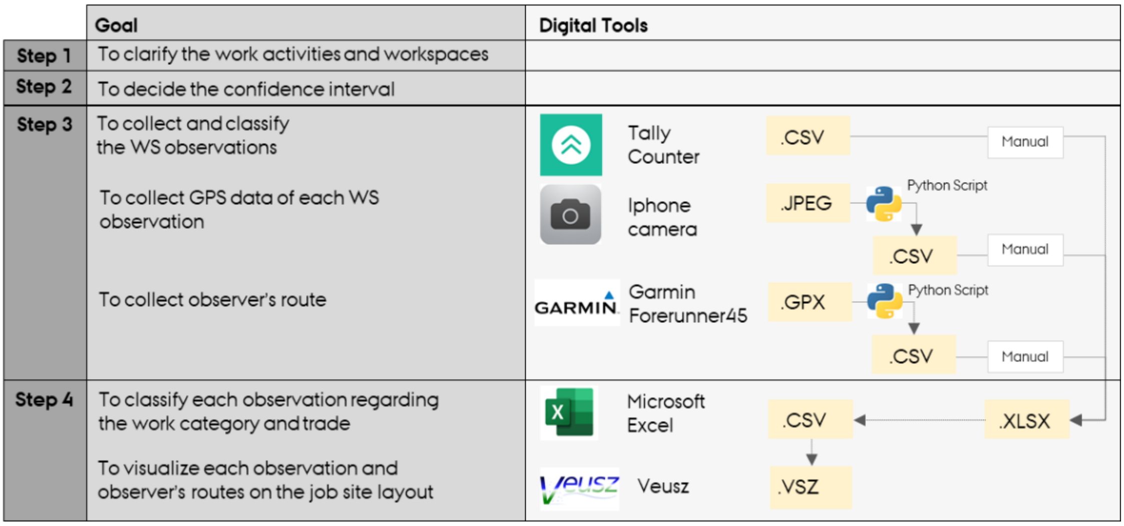

Figure 3: Research design.

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 as 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; (2) talking, e.g., discussing the installation process; (3) preparation, e.g., measuring with a ruler; (4) transportation, e.g., carrying tools; (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 of the scheduling phase 1 excluding the production workspace; (3) material storage workspace, consisting of the container's area; and (4) transportation workspace, considering the area between phase 1 and the material storage area. The job site division into workspaces is seen in Figure 1.

The scope of the observations was limited to the trades that conducted their activities outdoors during the period of visits. So, the WS technique was applied in seven trades including a total of 40 workers (representing a sample of N=40) from Day 1 to Day 7: (1) carpenters (N_1=13, representing 32.5% of the workers); (2) masons (N_2=5, 12.5%); (3) electricians (N_3=4, 10%); (4) ventilation (N_4=6, 15%); (5) scaffolders (N_5=2, 5%); (6) painters (N_6=4, 10%); and (7) demolish trade (N_7=6, 15%).

Step 2: Deciding the confidence interval and the accuracy desired

The data collection period lasted seven days (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 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. Figure 4 presents the distribution of the observations through the working hours, and Figure 5 illustrates the number of observations on each of the seven days of data collection. The blank space represents the lunch break. The random tours, conducted from Day 1 to Day 7, aimed to avoid observing patterns of behavior. Hence, the observers varied both their routes through the job site and, to increase randomness, the times for observations. According to CII (2010), the required number of observations per hour is 46 for a site with 0-50 workers. Thus, for workdays with 7.5 hours of working time, a minimum of 345 observations were required, i.e., ≈ 50 observations per day. After completing seven days of data collection, 993 geo-located samples were recorded with a 95% confidence interval of ± 2%.

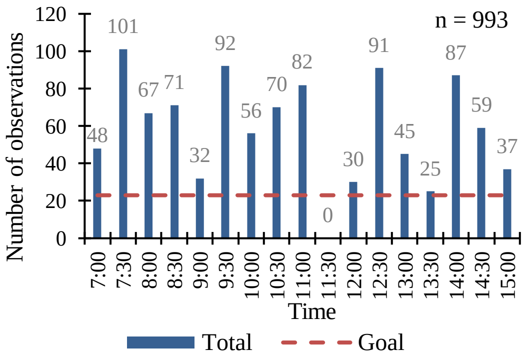

Figure 4:Total number of observations distributed along the workday.

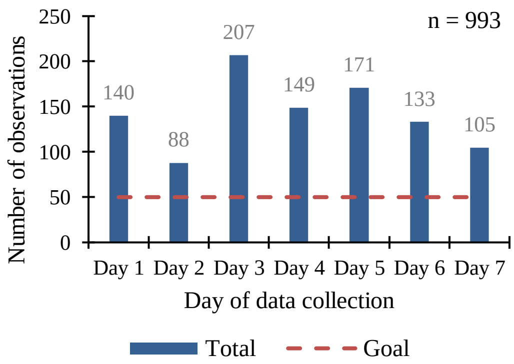

Figure 5: Total number of observations on the 7 days of data collection.

Step 3: Collecting and extracting the data

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. At no time were individuals' faces or other identifiers registered; the purpose of the photo was to collect the geographic coordinates from each observation. The authors extracted each observation's location 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.).

A smartwatch, specifically a Garmin Forerunner45, was worn for tracking the path conducted during random tours. This device allowed to identify the location where each observation was made, and the zones observed during the tours. This device provided the geographic coordinates using a combination of two Global Navigations Satellite Systems (GNSS), those being: The Global Positioning System (GPS) and the GLONASS GNSS.

The smartwatch data was synchronized to the laptop Garmin application using a USB cable. The activity saved during the 8-hour tours was exported in a GPS Exchange Format (GPX), then transformed into a CSV using phyton programming. Thus, each geo-located observation contained the following associated information: (1) photo; (2) timestamp; (3) trade observed; (4) work category; and (5) geographic coordinates, consequently, workspace category.

Step 4: Analyzing the data

The analysis aimed to resolve the research question For this, 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. Not only the observations collected were imported from the CSV files, but also the path conducted by the observes during the WS application. The authors collected the coordinates of the job site facilities and buildings using the smartwatch, and converted them to a visual layout using the RouteConverter program. RouteConverter is a free, 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.

RESULTS AND DISCUSSION

Figure 6a presents, using black dots, the location where each geo-located observation (n=993) was made during the WS application. Moreover, light grey dots represent each of the locations of the path where the observers conducted the random tours. From the images represented in Figure 6a, it can be observed that the locations of the observations are mainly distributed in Building A1, B1, B2, and C1 as expected, and, in some cases, observations were made in the material storage area.

In Figure 6b, the observations are marked with distinct colors according to the trade they represent (blue for carpenters, brown for masons, dark grey for electricians, yellow for ventilation workers, blue for scaffolders, green for painters, and red for demolition trade). In this way, it is possible to create a subdivision of each geo-located observation into trades which can provide a detailed view of where each task is being conducted.

For example, taking a closer look at Day 4 (Figure 6b), 149 observations were made on this day. 82 of these, or 55%, were of the carpenter crew (blue dots). They were mainly observed on Building A1 and B1, and in the material storage workspace and preparation workspace by the offices. Masons were observed 21 times, corresponding to 14% of the total number of observations on Day 4. The masons were mainly observed on building C1 and in the area between buildings. The electricians (dark grey dots) were only observed 2 times on this day, both in the material workspace, representing 1% of observations. The distribution for the remaining 4 trades is as follows: 10 observations of ventilation workers (yellow dots), 17 observations of the scaffolding crew (blue dots), 8 observations of painters (green dots), and 9 observations of the demolition trade (red dots), corresponding to 7%, 11%, 5%, and 6% of the total number of observations for Day 4, respectively.

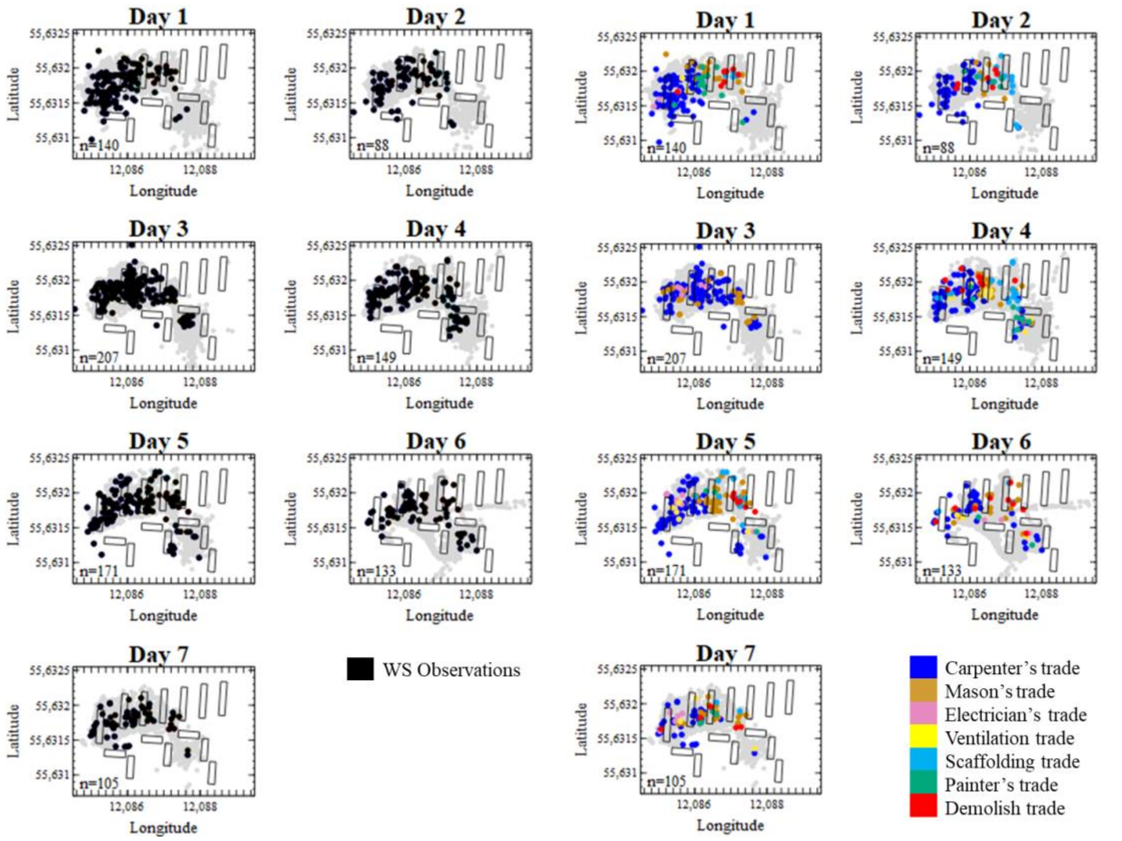

Figure 6: (a) Location of each observation; (b) Trade classification of each observation.

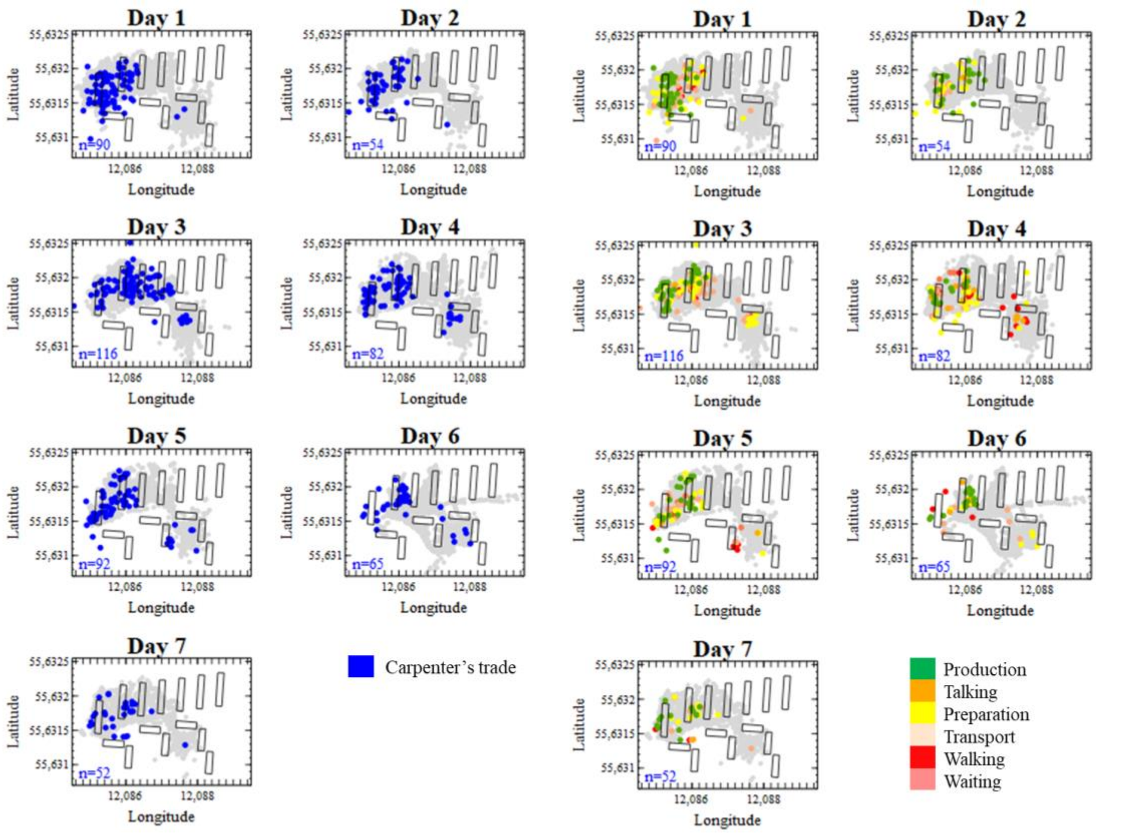

Figure 7: (a) WS on carpenters trade; (b) Position of carpenters' WS categories.

Using this 2D representation to see where on the job site construction workers are located can be used during planning meetings with contractors to see where the potential problems are, thus forming the starting point for discussion. This way, objective data presented in visual form can be a joint base for learning. By discussing the change in position during a week, each trade can explain to the others what causes position changes in their workflow, and this way, all trades obtain a greater overview of the renovation process. So, those illustrations can allow trade supervisors and managers to solve minor flow problems and coordinate details in their work schedules, thus preventing minor issues growing bigger.

The analysis of the distribution of the time of each trade can also be conducted. Figure 7 presents the distribution of the observations made on the 13 workers of the carpenter trade. In Figure 7a, all observations are shown in the same color, which gives an initial overview of the location of the observations. In Figure 7b, the observations are colored according to their work category. The total number of observations on the carpenter trade (n=574) are distributed with 28% on production, 7% on talking, 30% on preparation, 22% on transportation, 10% on walking, and 3% on waiting. Figure 7b shows that production tasks generally take place in and around buildings A1, B1, and C1. Preparatory tasks also take place here, but they are also observed in the material storage area, where a dedicated preparation workshop was set up. Waste work observations (walking and waiting categories) are scattered throughout the site.

Looking more closely at one of the data collection days, it is possible to elaborate further on the Location-Based Work Sampling (LBWS) results. An example of the Distribution of Observations (DO) collected on a single day, Day 4, can be seen in Figure 8. With these illustrations, the share of time spent in each work category and in each workspace can be analyzed from several different perspectives.

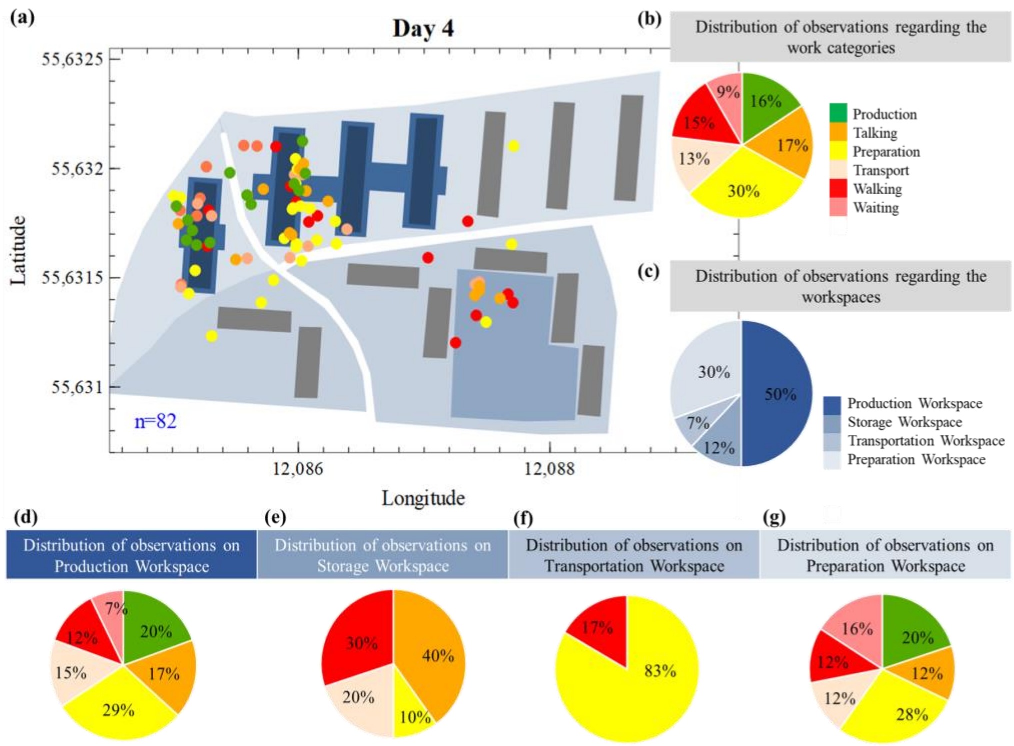

Figure 8: (a) WS on carpenter trade taken on Day 4; (b) DO regarding the WC; (c) DO on workspaces; (d) DO on Production Workspace; (e) DO on Storage Workspace; (f) DO on Transportation Workspace; and (g) DO on Preparation Workspace.

Firstly, Figure 8b gives a general insight into which work category carpenters spent most of their working time on. It can be seen that almost one-third of the carpenters' time on Day 4 was spent on preparation tasks, which is close to twice the amount of time that was spent on direct work. Secondly, the time spent by carpenters in the production workspace was the same as in the other three workspaces combined (Figure 8c). The carpenter trade had 41 samples recorded in the production workspace, equaling 50%. As this workspace is surrounding all the buildings undergoing renovation, the amount of time spent in this area represents, among other things, carpenters moving from one building to another, preparing windows, which are stored in this area, and preparing materials.

The third perspective illustrates the distribution of work categories observed in each workspace, illustrated in Figure 8d, e, f, and g. Although 50% of samples recorded on Day 4 (Figure 8c) were observed in the production workspace, only 20% of these observations showed the carpenters being productive in this area (Figure 8d). The carpenters spent most of their time in the production workspace on preparation activities, corresponding to 29% of the observations (Figure 8d). A plausible explanation of this is the nature of the roof renovation process, which involves a lot of measuring and cutting activities before the installation of roof materials can take place. The roof is a large area, and the limited number of cutting stations and dedicated material storage areas explain the relatively large share of observations made on walking and transportation in this workspace (i.e., 27%, Figure 8d).

In the storage workspace, 40% of the observations are talking, 10% are preparation, 20% are transportation, and the remaining 30% are walking (Figure 8e). There are two reasons for this distribution: firstly, this workspace is also where the changing rooms and breakrooms are placed, so it is here the carpenters start and end their workday, and where they come back to have their lunch break in the middle of the day. Naturally, this leads to much of the time in this area being spent on walking and talking. Secondly, besides the preparation workshop mentioned earlier, the storage workspace contains all the workers' tool containers. This explains the 30% of observations on preparation and transportation combined.

The transportation workspace is where the smallest number of observations were collected, only representing 7% of the total number of observations on Day 4 (Figure 8c). Here, only preparation (83%) and walking (17%) were observed (Figure 8f). This workspace is placed between the production and preparation workspaces and the storage workspace, which explains the share of walking observed here. The distribution of work categories observed in the preparation workspace is shown in

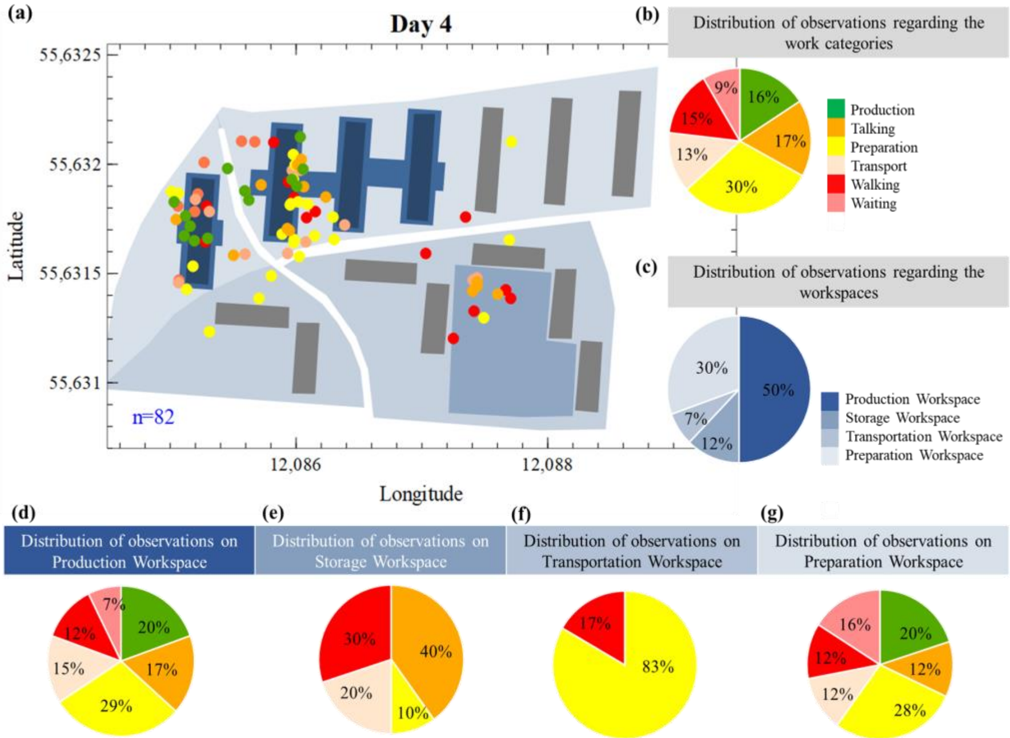

Figure 8g. As expected, most of the carpenters' time in this workspace is dedicated to preparation activities, representing 28% of the observations. The remaining 78% of observations are distributed very similarly to the distribution in the production workspace due to the diversity of tasks carried out in this area, as described in the paragraph above concerning Figure 8c.

The main contribution of this new WS adaptation is related to the implementation of some core Lean principles: (1) use visual management; and (2) process transparency. Firstly, the adoption of LBWS could enable the adoption of visual management tools to identify where the activities are conducted by using color-coding to place trades. Moreover, LBWS will support identifying where productive, preparatory, and waste activities happen. LBWS supports identifying the working areas where most waste happens as many potential problems quickly become evident.

Secondly, process transparency can be achieved through the simple representation of trade location on the job site. LBWS used for representing where activities are being conducted can enable an effective communication of the project to the stakeholders. The level of detail of the LBWS depends on the level of control of the job site manager. The division of the WS work categories into smaller tasks according to the same level as the Work Breakdown Structure (WBS) can be a useful tool to visualize and manage the project. However, decomposition into all work activities can make the WS application very intricate and time-consuming. The time it takes willbe disproportionate compared to the benefits. The same example can be used for the division of workspaces. As every project is different, the right workspace decomposition for the LBWS is the one that best fits the Location-Breakdown Structure (LBS) used by the job site manager.

Lastly, based on the presented discussion, the authors define 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.

The visual technique shows the observations made on construction trades and work categories in the foreground and job site spaces in the background.

CONCLUSION

The application of the WS technique on construction sites has, in general, been limited to the understanding of how workers spend their time regarding work categories. For a more comprehensive work analysis, this study aimed to identify which opportunities adding geographic information to the random observations made (named in this study as geo-located observations) can bring. To address this, the authors presented the implementation of a novel adaptation of the WS technique, named Location-Based Work Sampling (LBWS), based on the findings from a case study conducted on the job site of a large contractor in Denmark. LBWS was used to visualize how and where seven trades spent their time during seven days of data collection in a renovation project.

Creating a relatively simple visualization of the observations on the job site layout showed that a more comprehensive analysis of the job site activities could be conducted. Many research opportunities arise from this exploratory case study. Geographic location observations will be helpful in the implementation of the Lean principles of "use visual management" and "process transparency". The association of the geographic position of each observation with the scheduled activities can be further investigated. The new adaptation of the WS technique can provide a better understanding of the ongoing activities' behavior and contribute to the existing Location-Based Management Systems.

However, several limitations were identified for the adoption of LBWS. The main limitation relates to the use of geographic coordinates provided by the photos taken with smartphones and smartwatches, which are mainly ideal for outdoor locations. Thus, limiting the application of this technique to construction activities carried out outdoor. In future studies, the research team will test other technologies for indoor geo-location when activities are observed inside the buildings under renovation. Moreover, other kinds of tools will be tested to add location information to the WS observations. Another significant limitation is related to the data collection process on the job site. Data collection is a very time-consuming activity. To overcome this limitation, automated methods for data collection can be implemented in future steps. The present researchers will test the adoption of location-tracking sensors (e.g., GNSS) embedded into wearable devices for collecting workers' positions and activity recognition. Lastly, the results are mainly descriptive because of the small amount of data collected in one single case at this stage of the ongoing research project.

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SYNERGIES BETWEEN LEAN CONSTRUCTION AND ARTIFICIAL INTELLIGENCE: AI DRIVEN CONTINUOUS IMPROVEMENT PROCESS

Diego Cisterna[1], Svenja Lauble[2], Shervin Haghsheno[3] and Jan Wolber[4]

ABSTRACT

Both, Lean Construction (LC) techniques and Artificial Intelligence (AI) methods strive for the continuous improvement of production systems in projects and organizations. A combined implementation of both approaches is an ongoing research area. Therefore, the question arises as to whether the added value generated by implementing both approaches jointly is greater than the added value generated by implementing them independently and what is the significance of people in their combined use.

This paper explores theoretically the potential of synergies between LC and AI in the AEC sector with exemplary use cases as well as their resulting effects. Humans play a crucial role as interface between a combined use of both of them. As a result, a framework containing LC, AI and people is formed as basis for further combined developments. Therefore, change management, an area in which Lean has spent several years developing, can help both approaches gain traction. With the results, targeted applications can be developed, and practice can be supported.

KEYWORDS

Lean construction, artificial intelligence, continuous improvement, integration, cultural change

INTRODUCTION

With the industrial revolution, humans have been increasingly physically relieved in many ecosystems by machines and took the lead role of the production system. 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

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and machines. Following, humans are recentered in the focus. 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.

In contrast, with the growing available amount of data and computing power, methods of Artificial Intelligence (AI) are a newer field in the AEC industry. AI use cases in construction are for example generative design (Chase, 2005), predicting construction durations (Petruseva et al., 2013) or costs (Wilmot & Mei, 2005), detecting the construction progress (Dimitrov & Golparvar-Fard, 2014) or hazards on construction sites with image recognition processes (Seo et al., 2015). These use cases show that AI models also strive to improve existing processes towards a higher level of predictability, sustainability, or transparency. Here, humans are increasingly mentally relieved.

Lean Management techniques and AI elements are strongly linked: "*Just as the introduction of Lean Management has driven profound cultural changes in corporate culture, the introduction of AI in manufacturing processes requires its own cultural adaptation to which Lean Management must play a critical role*" (Four Principles, 2019).

By doing this, our proposition is that potential synergies can be leveraged and the role of humans in mental and physical processes focused. Few research papers so far analyze the potential synergies between both fields: Lean Construction (LC) and AI. Vickranth et al. (2019) analyze potentials of Lean techniques, AI in Construction as well as Enterprise Resource Planning to involve these fields in construction projects. Here, the authors supposed to integrate AI tools in the monitoring phase, while to implement Lean techniques in the planning phase. These detached observation of AI and LC does not show the potential synergies. Arroyo et al. (2021) describe AI use cases in construction and emphasize the crucial role of ethical and social aspects in the AI development. The authors conclude that the use cases must be well considered so that a deep process understanding is not lost by a pure outsourcing to AI models and humans are still a central aspect. They identify that there are potential synergies between both fields without a closer consideration.

Following synergies between both fields are so far not systematically elaborated and use cases involving both fields are not summarized. **Therefore, the question arises as to whether there are synergies between the two fields that result in more added value when both approaches are applied together than by applying them independently and what role people play in their combined use**.

In this paper potential synergies between Lean Construction and AI will be analyzed. Accordingly, both fields will be first described. Following, use cases involving Lean Construction techniques and AI elements are systematically explored. As a result, a framework containing both fields and the human factor will be created.

BACKGROUND

LEAN MANAGEMENT

Lean management refers to a philosophy with values, principles, methods, and tools with the aim of eliminating or reducing waste and focusing on customer needs (Bertagnolli, 2018).

Lean management has its origins in Toyota's production system. The term Lean was first mentioned in the book "The machine that changed the world" (Womack et al., 1991) and further developed as a philosophy in "Lean Thinking" (Womack & Jones, 2003).

Today, the approaches of Lean Thinking are implemented in a wide variety of industries such as construction.

Lean thinking approaches consist of five principles: identify the value to the customer, define the value stream, apply the flow and pull principle, and strive for perfection (Womack and Jones 2003).

Salem et al. (2006) compiles essential lean techniques with their principles. These techniques do not represent a conclusive summary, but rather serve as an exemplary framework for the present work. This study was selected as a LC framework because the author contrasts, in his research the techniques developed for lean construction with those developed for lean manufacturing, where IA is more widespread.

Table 1: Lean Implementation Tools (Table 1 in Salem et al., 2006, adapted)

Scope	Technique	Scope	Technique
Flow variability	Last Planner System® (LPS)	Transparency	Five S's
	Takt-planning and Takt-control		Increased visualization
Process variability	Fail safe for quality	Continuous improvement	Huddle meetings
			First run studies

LEAN CONSTRUCTION AND ITS TECHNIQUES

Lean Construction is the adaptation of Lean principles derived from the Toyota Production System into the construction sector. (Salem et al., 2006)

Last Planner System® (LPS)

The Last Planner System describes an incremental method for process planning with the inclusion of the last planners or foremen. Starting from the framework schedule, the planning is refined step by step up to a 6-week forecast. In the control system, key figures are included with the aim of the Continuous Improvement Process (CIP), such as the Percentage Plan Complete (PPC). (Ballard)

Takt-planning and Takt-control

In Takt-planning, the process plan is divided into a spatial, temporal and content dimension with the aim of stable realization and clear presentation. In the cycle control, the plan is adjusted together with the foremen and key figures for the CIP are included.

Fail safe for quality

Fail safe for quality summarizes techniques for controlling quality and safety issues. This includes Gemba walks with action lists.

Five S's

The five S's include the steps: Sort, Straighten, Standardize, Shine and Sustain. This pursues the goal of maintaining the cleanliness and a systematic workplace organization.

Increased visualization

Commitment charts, mobile signs, Kanban cards or projects milestones can be used for visualization. The goal of these is to increase attention to deviations, for example.

Huddle meetings

Huddle or stand-up meetings are short, sharp, focused, daily team meetings with foremen (see last planner) to discuss overlapping activities or challenges on the jobsite. Also, huddle meetings include daily meetings with site personnel to discuss the day's activities, items related to safety or order and cleanliness.

First run studies (PDCA cycle)

First run studies are carried out according to the four steps Plan, Do, Check, Act (PDCA). In this way, new methods, a modified process sequence or a redesign of the crew can be tested in their implementation.

Continuous Improvement Process (CIP)

Figure 1 summarizes the Continuous Improvement Process (CIP) as the principle to strive for perfection. After a first implementation of one of the mentioned Lean techniques, Key Performance Indicators (KPIs) are defined as metric to systematically measure and track the CIP. These KPIs can also be part of the project's documentation. They support the observability and transparency. As a positive result of implementing the Lean technique, waste is reduced, and the client value is enhanced. The KPIs and with it the project improves, so that more and more people begin to apply this Lean technique. Finally, as a result of this beneficial effect, additional Lean practices will be deployed, triggering another evolution in the cycle.

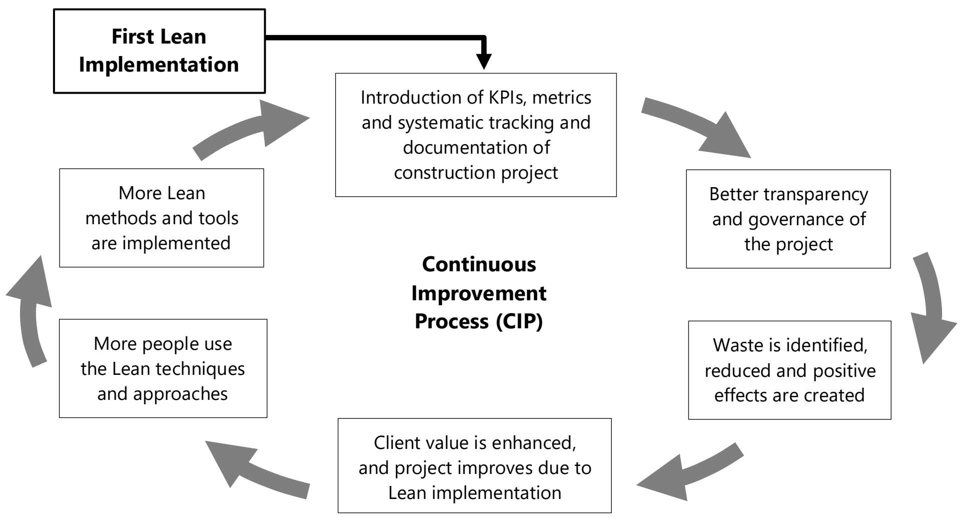

Figure 1: The Lean virtuous cycle (based on the five lean principles of Womack and Jones (2003))

ARTIFICIAL INTELLIGENCE

Artificial intelligence (AI) is a field of research within computer science that deals with the development of intelligent machines and computer programs. Since its origins in the 1960s, a multitude of technical developments have led to the fact that the results of this field of research are nowadays an integral part of our everyday life. They are used in autonomous driving, in medicine, but also in many other areas of our daily lives.

Historically, the foundations for this were laid by the British mathematician Alan Turing in 1936. In 1955, John McCarthy was one of the first to define AI as machines that behave as if they had intelligence (Ertel, 2016). In contrast, since natural intelligence includes consciousness, emotionality, and intuition in addition to complex cognitive abilities, the following definition for AI fits better: artificial intelligence "[...] gives computers the ability to learn without being explicitly programmed." (Samuel, 1959)

Over the years, two subfields within AI research have emerged as particularly promising. These are the area of Machine Learning (ML) and Deep Learning (DL). Here, ML is a subset of AI and DL is a subset of ML (Wittpahl, 2019). Common to both subsets are the idea of learning patterns from data and thus generating knowledge from experience. In this way, a system can subsequently apply the self-acquired knowledge representation to process unknown tasks of the same type (Döbel et al., 2018).

Within these categories that comprise AI frameworks are designed to handle specific challenges. There are several frameworks for identifying unknown patterns in various forms of data. These include Computer Vision, which recognizes objects in images, Natural Language Processing (NLP), which recognizes words in text and in audio, and Data Analytics, which analyses massive amounts of data. For instance, there are frameworks for developing “Expert Systems” that are based on decision trees. There are also other frameworks that use a combination of the above mentioned to be applied in Robotics or in the Creation of Virtual assistants such as “Chatbots”.

Guo (2017) defines seven steps for the application of AI:

1. Data collection: The first step significantly influences the outcome of the learning process, depending on the quality and quantity of the data collected (Guo, 2017). Formally, a sample is taken here from a population, which should therefore be as representative as possible.

2. Data preparation: After the desired data has been collected, it must be prepared and organized in different ways depending on the algorithm used. Data preparation often takes up most of the time in the machine learning process (Webb, 2010). To test the model after learning, the existing data is divided into training data and testing data (Ertel, 2016). A typical example of this step is the labelling of photos to train computer vision models.

3. Framework/Model selection: With the target to learn with the data thus prepared, a choice of model must now be made. This is partly dictated by the framework of the problem, the type of input and output data or the number of features. Last but not least, it also depends on the experience and intuition of the programmer. A newer research area in AI is explainable AI (XAI) to solve some ethical and social aspects within a growing complexity. ‘Human in the Loop’ contains the integration of humans in the above-mentioned steps such with an appropriate design and KPIs. Also, Schia et al. (2019) states that “the human-AI trust will be the most decisive factor for a successful implementation.”

4. Training: After the steps of the preparation now the actual successive learning process of the model begins. Based on the data provided, an approximation is sought by gradually adapting the model to the data using the feedback signal (Chollet, 2018).

5. Evaluation: After training the model, the learning success must be verified using the generalization capability with performance indicators such as the MAE (Mean Absolute Error).

6. Parameter optimization: In this step, hyperparameters that are fixed at the beginning of the models are adjusted (VanderPlas, 2016). Adjusting the parameters can substantially improve the learning outcome, if necessary.

7. Deployment: Once all adjustments to the model have been made, it is ready for deployment. Here, the human factor becomes relevant as employees and the management must be involved and convinced to carry out a successful change management.

Continuous Improvement of AI

Figure 2 shows the cycle how AI models can continuously be improved. With the deployment of an AI model in construction supporting the people in their work, the project improves. As more people utilize the AI model, more data is generated. This extra data enables more accurate predictions, and the model improves as result.

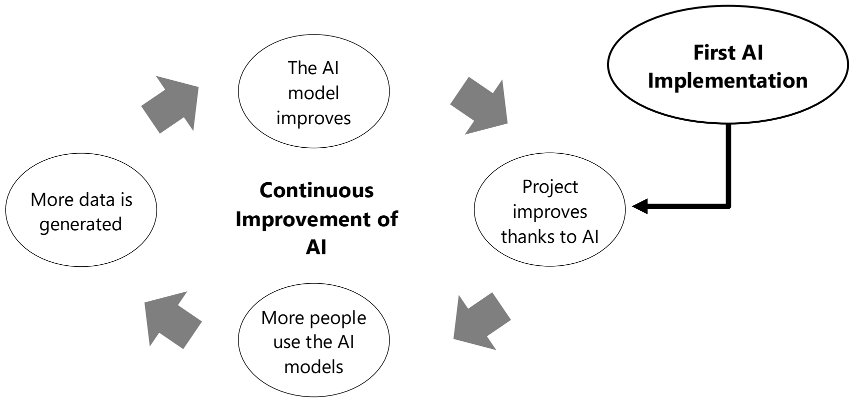

Figure 2: The AI virtuous cycle (Figure 9.9 in Mauro and Valigi (2020), adapted)

METHODOLOGY

To be able to profit from potential synergies between the two topics of Artificial Intelligence (AI) and Lean Construction (LC), there must be a motivation for the people involved. Synergy is understood to be when "[...] through the interaction or combination of factors, a different, e.g., greater effect is achieved than corresponds to the sum of the separate, independent individual effects" (Ebert, 1998). The following procedure according to Ehrensberger (1993) is used to systematically determine synergies. This consists of four steps:

1. The **problem area** of the jointly used concepts is to be identified.
2. **Synergy processes** are to be identified. In these synergy processes, the basic concepts are to be identified as in step 3 and 4 described.
3. In them, the **basic effects** and their **subsequent effects** resulting from the synergies are to be classified in the following five dimensions: **Quality**, **Time**, **Quantity**, **Type** and **Space** dimension and to be evaluated.
4. The synergies are to be classified in an **interaction-oriented framework** to further define the context of consideration. These consist of **Strategic**, **Organizational**, **Cultural** and **Community** dimensions.

The identification of the synergies and the classification of their effects and type of interaction in their different dimensions is carried out jointly in brainstorming workshops with experts in AI and LC from the German research project “Smart Design and Construction” (SDaC). This project which integrates AI approaches into the AEC industry, consists of more than 40 partners from the construction sector, IT industry, and research organizations.

At the end, the results are synthesized in a framework for the interplay between LC and AI.

RESULTS

Step 1: Identification of the problem area: The goal is to identify the synergies of both topics AI and LC in their mutual application. In both topics the continuous improvement process (CIP) of the existing production system is a core element. Thus, the goal is not to analyze a specific method or technique from one of the two topics in more detail. The target is to examine the synergies of the CIP with both topics.

Step 2: Identification of synergy processes: On the one hand, the LC techniques according to Salem et al. (2006) and the (sub)processes required for this are analyzed. On the other hand, data collection and data preparation are particularly time-consuming when applying AI methods. These two steps are therefore also the focus of the synergy analysis.

Step 3 and 4: Identification of effects and interaction-oriented framework: Following Ehrensberger's procedure, it was found that the interplay between LC and AI revealed both effects and interaction-oriented dimensions. As a result, it became possible to find synergies between LC and AI in all Lean techniques defined by Salem et al. (2006) and in steps 1, 2, 5 and 7 of the seven steps for implementing AI defined by Guo (2017).

Table 2 shows the AI processes that are supported by LC techniques, while Table 3 shows the LC techniques that are supported by AI models. Both Tables list examples of synergies between AI and LC that can be deployed at the process and technology domains of a project (see Figure 3). The classifications were generated based on the expertise of AI and LC specialists and the results of prototyping nine AI applications in AEC environments between 2020 and 2022 as part of the SDaC project.

Table 2: Synergic interactions in which Lean supports AI Processes

AI Process	Synergy with LC techniques	Effect(s)	Interaction-oriented dimensions
Data collection	**Data to train AI Models** With LC techniques, metrics and KPIs (e.g., PPC) are introduced. Time series are recorded by a systematic tracking and documentation of the construction project	**Quantity** (More data is generated through people)	**Community** (People generate the data)
Data preparation	**Structured data & KPIs** 5S can be used not only to organize physical assets, but also data. It can be applied in data preparation, as it allows to classify (sorting) data, standardizing data categories, filtering out (shine) data outliers and sustain the data structures	**Quality** (Structured data & KPIs)	**Organizational** (Structure of data)
Evaluation	**Validation of AI model** Model performance validation and setting a basis for model optimization can be compared to PDCA's “Check” and “Act” steps. Visualization and interpretation support model validation (e.g., Mean absolute error (MAE), Shapely Framework). Further on, with the “5 Whys” method the evaluation result can be challenged.	**Quality** (Better observability and governance of the project)	**Strategic** (Definition and evaluation of objectives for the AI)
Deployment	**Change management** With Lean techniques concerns are tracked, people and management involved in the implementation process: e.g., PDCA support tracking the implementation, in huddle meetings the deployment can be discussed	**Quantity** (More people using the AI-model)	**Cultural** (Change Management)

Table 3: Synergic interactions in which AI supports Lean Techniques

LC Technique	Synergy with AI models	Effect(s)	Interaction-oriented dimensions
Last Planner System® (LPS)	**Better forecasts** AI might quickly simulate multiple scenarios to aid project planners in establishing project lookaheads AI could learn from historical data about frequent trade problems and issue early warnings. The vast amount of information stored in previous project documents might be utilized. Transmitting knowledge and best practices can prevent information loss between projects.	**Quality** (of project lookahead, KPIs and meetings) (Better forecasts) **Quantity** (of restrictions) **Time** (project duration)	**Organizational** (Project planning) **Cultural** (LPS commitment culture)
Takt planning and Takt control	**Better forecasts** Based on historical data and environmental parameters, AI models might estimate workload values, takt times, etc. to harmonize machine and human work cycles. AI could optimize processes and deal with complexity interdependencies between trades.	**Quality** (of process and work packages definition) **Quantity** (of work packages and takt areas automatically optimized) **Time** (project duration)	**Organizational** (Project planning)
Fail safe for quality	**Automation and assistance** Computer vision AI models could supervise the construction site identifying automatically dangerous situations and production quality losses to trigger action alerts and to document the root causes. A real-time safety and quality awareness system can be created to analyze historical data and to uncover key problems.	**Quantity** (of actions defined for improvement) **Quality** (of product)	**Strategic** (Product improvement)
Five S's	**Automation and assistance** Computer vision AI models could monitor the order and cleanliness of the workplace for maintenance and improvement.	**Quality** (of workplace) **Space** (to work)	**Cultural** (Culture of cleanliness and organization)
Increased visualization	**Automation and assistance** The AI could collect information from different sources on the project such as software, cameras, documents, sensors, etc.) to filter and display it automatically in a visual form.	**Quality** (of decision-taking process) **Quantity** (collected data and easy-to-understand KPIs) **Type** (change of information format)	**Strategic** (Decision taking)
Huddle meetings	**Automation and assistance** AI could enable huddle meetings with a computer vision or speech recognition-based attendance system. AI may examine participant calendars using NLP to determine user activity trends and offer the most convenient time slots for recurring meetings. It may find available slots in large teams faster than rule-based systems (e-mail clients), allowing instant problem-solving meetings.	**Quantity** (more communication instances) **Time** (shorter meetings) **Quality** (of communication)	**Cultural** (Efficient meetings) **Community** (Communication)
First run studies (PDCA Cycle)	**Better forecasts** In the PDCA cycle, AI can support the planning phase of a new measure by simulating various scenarios and by proposing several measure alternatives. For the check phase, AI could automate data capture and analysis for a faster and more reliable evaluation of the implemented measure.	**Quantity** (more measure alternatives) **Time** (shorter check phase) **Quality** (more reliable check phase) **Quality** (data-driven measure evaluation in the check phase)	**Strategic** **Cultural** **Organizational** **Community** (Improvement measures can be carried out in all dimensions)

THE AI -DRIVEN CIP FRAMEWORK

As previously stated, LC and AI implementations can promote virtuous cycles of CIP, and they can complement and strengthen one another.

Figure 3 depicts these cooperative ties between the two systems when they are implemented in parallel: **Lean implementation in construction projects can work as the ignition for AI adoption**. Because Lean is inherently data-driven, it generates process tracking and **project documentation that may be used to train AI systems.**

A first AI model trained with project data can offer predictions (planning suggestions, cost estimations, early detection of problems, etc.) or automate repetitive processes (detecting dangerous situations on camera footages or counting elements in construction plans). These **AI-based automation and assistance solutions will free people from repetitive or complex tasks**, giving them more time for value-adding activities. This will attract more people to use AI solutions, which will enhance data generation. Also, more people will be encouraged to continue utilizing Lean methods to track and document project progress and **generate more high-quality data, as it will be structured and pre-processed in the form of KPIs.**

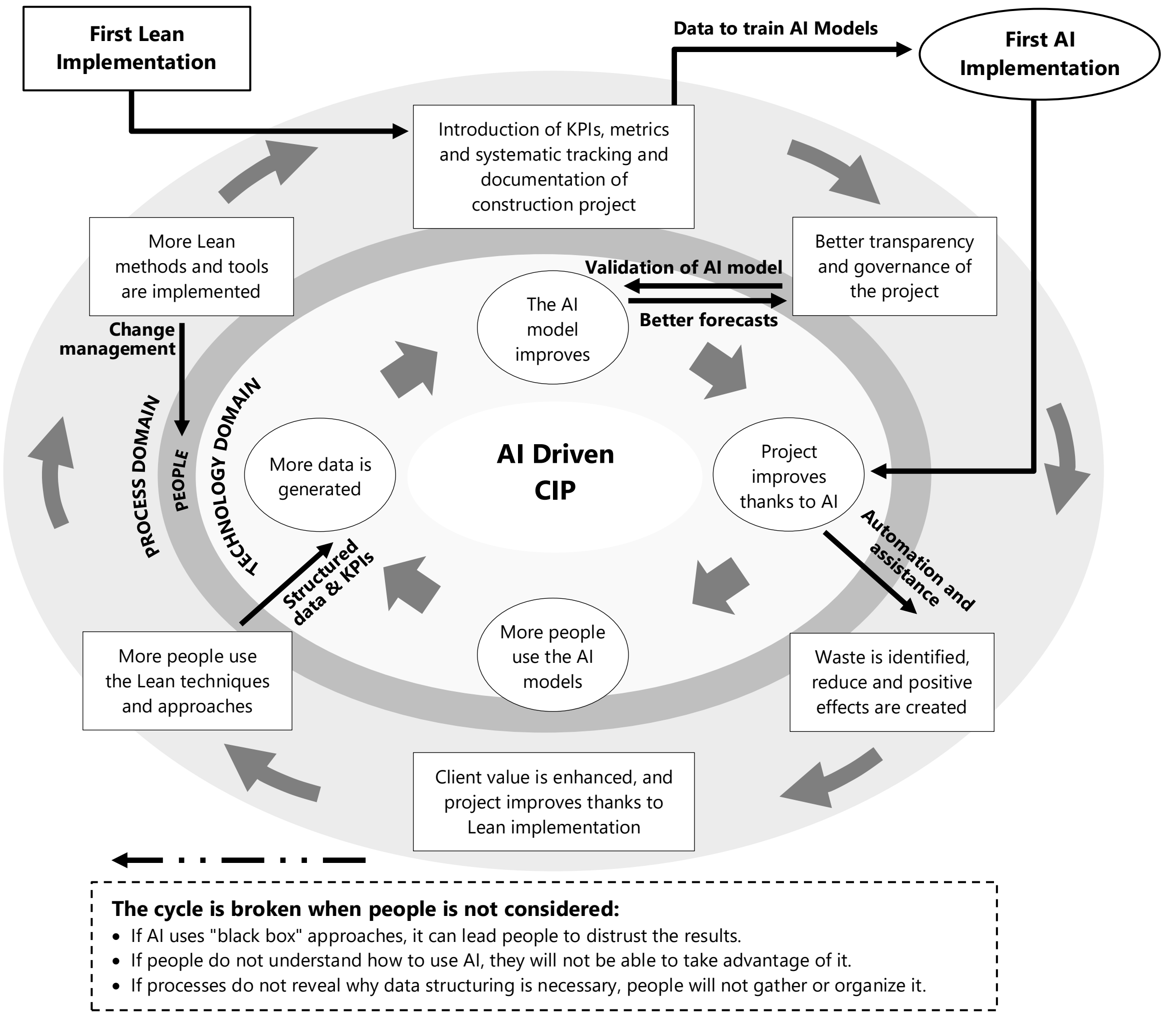

Figure 3: The AI -Driven CIP Framework

Additional and better data will improve the AI model. This will lead to **more accurate forecasts** and outcomes for AI services, which will further enhance the implemented Lean techniques for project tracking and control. Reciprocally, this increased transparency and control over the project **will enable evaluation and validation of the AI models** by correcting their parameters to further optimize their outcomes.

The integrated system's success will encourage more people to embrace Lean techniques, sparking a new virtuous cycle and causing another loop evolution. By using more Lean techniques, a holistic change management approach can be created that incorporates both LC and AI. **Change management focuses on people, who will be the fundamental pillar to keep these two circles of continuous improvement running**, as they will hold the system culturally and supply it data. **Because humans constitute system's core, this is where the cycle could collapse.** If people do not trust the outcomes of AI, do not grasp how to use AI systems, or do not understand the potential added value that may be gained by collecting data through LC techniques, the system will lack the vital support it requires to spread and grow.

CONCLUSIONS

The study was able to address the primary research questions. Firstly, numerous synergies between the two approaches have been identified that promote added value and growth in both directions. These synergies were discovered purely via the lens of the constituent elements of AI and Lean proposed by Guo (2017) and Salem et al. (2006), respectively. Additional synergies are likely to be discovered if secondary factors from both domains are investigated as well and demonstrated through case study observations. Secondly, it was concluded that the role of people plays a fundamental role in this symbiotic cooperation. When detecting synergies using the Ehrensberger model, it was discovered that human interaction was always present in the dimensions of interaction proposed by the method. Thus, when synthesizing the information gathered in the "AI Driven CIP" framework, people were elevated to a pivotal position as a unifying element between the two fields. Due to the centrality of the human factor in this hybrid system, potential threats that could interrupt virtuous circles of continuous improvement were recognized there.

Exactly in this area do AI systems require improvement. Many AI models are not human-centric (e.g., "black box" approaches often do not involve people). This, together with the lack of awareness about this new technology, has fueled the fear of many, for instance, of losing their own jobs. However, it should be noted that Lean's detractors have also expressed the same concerns as a result of its deployment. Therefore, Lean and AI have much more in common than at first glance, this shortcoming can be transformed into a virtue, as Lean has had several years of experience solving this problem by developing change management and acceptance of new ways of working in people.

Data play a key role in the proposed framework. AI needs data. As Lean generates it, the exchange of data serves as the main synergy between both systems. However, there are limitations to be weighed. A substantial quantity of high-quality data is required for AI to produce desirable outcomes. If the framework is used in only one project, AI will not be able to deliver usable results in early stages, due to a lack of training data. In contrast, if an excessive amount of data is provided, the model may be overtrained, hence diminishing its prediction potential (overfitting). If data from separate projects are utilized, there is also the possibility that the algorithms will be trained in distinct contexts, losing the consistency of the results. All these required refinements underline once more the central role that people play in the framework's operation, as only humans can prepare the correct data for AI training and validate its outcomes.

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INFLUENCE OF LAST PLANNER® SYSTEM ADOPTION LEVEL ON PROJECT MANAGEMENT AND COMMUNICATION

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ABSTRACT

Construction projects require complex management of people, resources and goals. The Last Planner® System (LPS) provides a systematic framework based on short cycles of work preparation, commitment, and control to allow implementing corrective actions. Successful LPS implementations require the combination of homogeneous mature practices and efficient horizontal collaboration. Nevertheless, partial implementations prevent liking collaboration through mid-term planning, the make-ready process and short-term work-flow stabilization. Therefore, this study aims to assess the relationship and cross-impacts of LPS adoption levels, team collaboration and project performance through an in-depth comparison of two Chilean case-study projects. LPS adoption was measured through a 50 items survey applied to 10 key actors in each project and collaboration was captured through Social Network Analysis (SNA) applied to general interaction, planning, problem-solving, feedback, learning, and leadership surveys answered by all last planners in each project. Also, each project was monitored for at least 18 weeks to capture their Percent Plan Complete (PPC), Reasons for Noncompliance (RNCs) and Schedule Performance Index (SPI). The results, consistent with previous literature, showed that mature LPS adoption significantly aids collaboration and performance.

KEYWORDS

Last Planner® System, collaboration, social network analysis, make-ready planning

INTRODUCTION

Project management requires dealing with high levels of uncertainty and variability, which, in highly interrelated networks of activities carried out by multiple stakeholders, can lead to a schedule deviation tendency (Sarhan & Fox, 2012). Traditionally, construction teams selected a Managing by Results (MBR) approach, using highly detailed initial plans and controlling them systematically using result-oriented systems such as Earned Value Method (EVM) (Kim & Ballard, 2010). Nevertheless, research has

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shown that the use of static plans, lack of stakeholder collaboration, low workforce involvement in planning, and lack of use of process-oriented indicators prevent project teams from taking advantage of continuous planning opportunities to tackle uncertainty and variability (Kim & Ballard, 2010). Thus, the Last Planner® System (LPS) was proposed to systematize planning and control, using short collaborative cycles to identify required work, schedule accordingly, prepare it and stablish execution commitments weekly monitored to determine required corrective actions (Ballard & Tommelein, 2016). Although LPS benefits are well known and widely cited (Daniel et al., 2015), researchers have found that partial implementations can limit its potential (Daniel et al., 2015). Partial adoptions, focused mainly on short-term planning despite lookahead planning and the make-ready process, are common and prevent long-term schedule accomplishment by making management reactive to RNCs rather than proactive (Lagos et al., 2017). Also, a lack of involvement of direct responsibles, called Last Planners (LPs), due to management level exclusive decision-making has been detected as a common shortcomming (Sarhan & Fox, 2012).

Previous research has shown a direct correlation between LPS maturity and performance, both in short-term stabilization and schedule accomplishment (Lagos et al., 2017). The statistically significant correlations found between the PCR, PPC, and SPI reinforce this point (Pérez et al., 2022). On the other hand, transversal studies have shown that mature LPS adoptions and proactive collaboration are mutually beneficial, since efficient communication and horizontal collaboration along the make-ready process is key to ensure short-term stabilization and sustained compliance (Castillo et al., 2018). Also, horizontal case-study research has consistently observed that, as project teams strengthen their LPS adoption, they improve horizontal communication across LPs, allowing them to proactively take continual improvement actions (Retamal et al., 2022). Thus, this study aims at gaining an improved understanding of the effects of LPS maturity on project performance, through a quantitative assessment of the effects of LPS adoption levels on collaboration and proactive management.

LITERATURE REVIEW

LPS aims at four objectives: First, Ensure close bottom-up coordination between LPs and management level, through collaborative planning and control meetings (Priven & Sacks, 2013). Second, stabilizing the workflow through the lookahead planning and the make-ready process, in which the LPs construct a four to six weeks lookahead plan to search for upcoming execution constraints and plan actions to remove them in advance, to increase the mid-term workable backlog of tasks (WB) (Hamzeh et al., 2008). Third, ensuring compliance by planning on a short-term basis, usually one week, based on commitments considering capacity, readiness and priority (Torre et al., 2021). Finally, it uses a Managing by Means (MBM) approach, where systematic process-oriented control allows teams to implement corrective actions based on compliance and take advantage of planning opportunities presented by the workable backlog (Ballard & Tommelein, 2016).

LPS process-oriented control uses four main sources of information to facilitate proactive management (Alarcón et al., 2014). The make-ready process is captured by the Percent Constraints Removed (PCR), which measures the percent of constraints removed during a short-term period from the number of constraints planned according to the LPs' commitments (Alarcón et al., 2014; Lagos et al., 2017). Short-term compliance is captured by the Percent Plan Complete (PPC), which measures the percent of execution commitments that secured a progress equal or greater than committed out of all short-term commitments made. Each unaccomplished commitment is assigned a Reason for Noncompliance (RNCs), a standardized category used to indicate the source that prevented expected progress. Finally, many implementations use the Schedule Performance Index (SPI), taken from EVM, to compare actual progress against initially planned progress at the end of each short-term period.

Multiple instruments have been proposed to measure LPS adoption, with the Planning Best Practices (PBP) index being a common standard (Viana et al., 2010). PBP studies have consistently found that mid-term scheduling practices, such as constraint identification in the make-ready process are significantly less observed than basic practices such as assessing the PPC and RNCs (Lagos et al., 2017). Nevertheless, since the PBP focuses mainly on detecting the presence of systematic practices, it does not necessarily allow to capture the links between Lean principles, LPS processes and practices to capture how collaboration impacts performance (Priven & Sacks, 2013). On the other hand, Lean maturity assessments such as the Lean Construction Maturity Model (LCMM) focus on the link between principles, processes and practices, however, LCMM captures multiple Lean tools besides LPS (Nesensohn et al., 2015).

Researchers have captured how collaboration at the different LPS processes is exherted either qualitatively through case-study observation, surveys and interviews, or quantitatively through the use of Social Network Analysis (SNA), which captures people interactions as ties between two or more network nodes and uses them to represent communication, affinity, and strength of relationships, among others (Priven & Sacks, 2013). However, SNA networks cannot isolate collaboration in a single process in other to detect how LPS practices influence collaboration (Castillo et al., 2018) , hence, using a LPS maturity instrument focused at linking processes to practices, combining the PBP and LCMM approaches could benefit the interpretation of SNA results. Previous studies have shown that LPS processes adoption positively correlates to SNA strength in planning, knowledge management, learning, and problem-solving, among others (Castillo et al., 2016). Also, similar studies have observed a positive correlation between SNA strength and performance indicators (Herrera, et al. 2018). Hence, this study aims at using SNA to better understand how more mature LPS adoptions can lead to better collaboration practices associated with proactive MBM and higher project performance.

RESEARCH METHODOLOGY

A case study approach was selected since it combines direct observation, quantitative data, and qualitative information, validated with relevant project team members through comparison and analysis, to drive conclusions (Yin, 2014). Two Chilean construction projects, characterized in Table 1, each carried out by a different company, were selected as case studies since they could be followed for a similar period since an early stage of execution, had similar scheduled scopes, belonged to companies with similar LPS experience, were carried out by teams with similar experience that received LPS training by the same consultant team and used equivalent LPS software to support it.

The research was structured in four phases. First, an extensive literature review was used to develop an instrument to evaluate a project management maturity level based on Lean Construction and Last Planner System criteria, which was validated with eight LPS professionals and academic experts and applied in both projects. Second, an online survey comprised of seven questions was applied in both project teams to obtain team communication data, which was processed using the software GEPHI to obtain SNA metrics and sociograms (Castillo et al., 2016). Third, the projects were followed for five months to capture weekly LPS metrics, and statistical analyses were carried out to allow comparison. Finally, quantitative and qualitative comparison between the projects and previous literature findings was used to drive conclusions regarding the effects of LPS adoption on project management and communication.

Table 1. Case study information

Criteria	Project A	Project B
Project type	Industrial construction	High-rise building
Initial planned schedule duration in weeks	51	49
Baseline progress prior to study	4.83%	4.41%
Execution weeks captured in the study	19	18
Baseline progress at the end of the study	52.34%	52.71%
Average number of short-term tasks	16	21
Number of project team members	49	26
Average years of team LPS experience	2.6	2.4

LPS BASED PROJECT MANAGEMENT EVALUATION

The instrument comprised five dimensions (Perez-Apaza et al., 2021; Salvatierra et al., 2015): adoption of a Lean-oriented culture; understanding of the Lean Construction philosophy; implementing known, visible, and auditable standards; following LPS processes; and applying Lean and LPS best management practices. Each dimension was assessed in ten aspects (Diekmann et al., 2003; Nesensohn et al., 2015): (1) value and waste management, (2) standardization, (3) workflow stabilization, (4) systematic planning, (5) process-oriented control, (6) knowledge management, (7) continuous improvement, (8) teamwork, (9) communication and transparency, and (10) Technology adoption to support Lean-based management. Hence, the survey was comprised of 50 questions, each evaluated in a five steps Likert Scale (Nesensohn et al., 2015): 0% – The aspect is not present or observable; 25% – The aspect is present in an unformalized manner; 50% - The aspect is generally formalized but is not known by all parties nor audited systematically; 75% - The aspect is formalized and well known but it is not audited systematically for continuous improvement; 100% – The aspect is highly formalized, well known and continuously audited.

The survey was applied to 10 key members in each team, with a 100% response rate, including at least the project manager, project leader, site engineers, technical officers, LPS facilitators, and supervisor representatives, in addition to two research observers who followed the projects for at least six weeks prior to the survey. Each answered individually and, then the mean, mode, and median of the results were presented in a workshop, where a Delphi validation process was conducted with the responders in each project and the two observators to obtain a single representative evaluation. Also, a Cronbach Alpha Coefficient test was used to assess the instrument's reliability using the 24 responses and yielded a result of 0.851, indicating that the instrument was highly reliable (Lagos et al., 2017). Finally, dimensions and aspects were characterized using the median.

SOCIAL NETWORK ANALYSIS

Interactions from the LP level upwards were captured through a survey applied to all actors involved in the LPS processes; 49 and 26 LPs in projects A and B, respectively.

The researchers held an explanation workshop in each project, give digital and printed instructions with copies of the instrument, made it available online for a two weeks period, and held presential aid instances at the worksite to facilitate response. Actors were made aware that their responses would be anonimized, only used for research purposes and that no individual response would be shared with management or third parties. Finally, management committed means to facilitate that LPs could respond the survey without the presence of third parties, management or collaborators to avoid response bias.

The instrument comprised seven questions used to capture six interaction networks. The first question served as a consistency filter to eliminate the team members with whom the responder did not exhibit frequent interaction (Herrera et al., 2020). Remaining questions captured general interaction, planning, problem-solving, feedback, learning, and leadership, as shown in Table 2. The first question filtered available options for each for the rest, except for leadership, and responders answered based on work-related interactions over the past two months. The results were converted into adjacency matrixes, where each row contained each team member's answers regarding each teammate. Each person represented a node, and each node connection represented a tie (Cisterna et al., 2018). For a valid tie to exist in general interaction, planning and problem solving, the link should be reciprocal, meaning that both teammates indicated a connection with one another (Castillo et al., 2016). A unidirectional link was considered valid in the remaining networks since it indicated that the person received feedback, learned from, or considered another team member to be a natural leader.

The matrixes were processed using the software GEPHI to construct sociograms via the Force-Atlas2 algorithm, which emulates the behavior of electrically charged particles by repulsing nodes based on size and using ties to create attraction (Jacomy et al., 2014). Four indicators were calculated in each network (Abraham et al., 2009): The average Relative Degree of the network measured the number of teammates with whom each member was directly connected, divided by the team size, to assess the percent of direct connections from an average member. The Network Density measured the percent of existing connections over the number of possible connections to assess the strength of communication among the team members. The Clustering Coefficient expressed the probability of two members being part of a completely connected group within the network. Finally, betweenness centrality measured the percent of shortest paths between any two members that passed through a specific member; thus, its average represented network homogeneity.

Table 2. Available questions in social network analysis survey

Dimension	Question	Available Options
Interaction filter	With whom have you interacted at least once during this period in a work-related matter?	List of LPs and management
General interaction	How frequently did you interact with the following teammates?	Once or twice; Approximately once a week; Multiple times during the week; Daily.
Planning interaction	How frequently do you plan collaboratively with the following teammates in a normal week?	Never; Scarcely; Commonly; Every week.
Problem-solving	How frequently have you collaborated in problem solving with the following teammates?	Never; once or twice; approximately once a week; multiple times during the week.

Feedback	What type of feedback have you received from the following teammates during this period?	None; scarce and informal; scarce but formalized; frequent and formalized.
Learning	To what degree has each of the following team members contributed to your learning?	None; little; moderately; highly.
Leadership	If a complex work-related challenge arises, who of the following team members do you think could act as natural leaders to tackle it?	Unlikely; possibly; most probably; certainly.

PROJECT PERFORMANCE MEASUREMENT

Each project was followed weekly and without intervention from the research team from earlier than 5% baseline expected progress until approximately 52% of baseline expected progress. 19 and 18 weeks of information were captured for Project A and B, respectively. In each case, the weekly PPC, RNCs, and SPI were retrieved directly from the LPS support software used by the teams. These indicators were compared among projects using the mean, standard deviation, and coefficient of variation. The average PPC, SPI, number of RNCs, and Percent of Internal RNCs (PIR) were compared among case studies using statistical mean difference analyses. First, a Shapiro-Wilk (SW) test was selected to assess normality since it is well suited for samples under 50 elements. A p-value greater than 0.05 in the SW test would indicate that the sample followed a normal distribution (Pérez et al., 2022). Then, the t-test was used to assess mean differences among normally distributed samples, and the Mann-Whitney's U test (MW) was used to compare metrics where at least one case study did not exhibit a normal distribution (Pérez et al., 2022). The null hypothesis "there is no statistically significant difference at a 95% confidence level" could be rejected if the p-value was equal or lower than 0.05 (Pérez et al., 2022).

RESULTS

LPS ADOPTION RESULTS

Although both projects exhibited at least a 50% or higher adoption in all dimensions and aspects, as presented in figure 1, project B exhibited consistent higher adoption levels. The biggest difference at the dimension level was observed in the adoption of LPS processes, where Project B exhibited formalized, known, and auditable processes in most aspects. In contrast, in Project A, some key processes such as systematic planning and process-oriented control using LPS were not known by all project participants nor audited periodically for continuous improvement. The biggest differences at the aspect level were observed in process-oriented control and technology adoption.

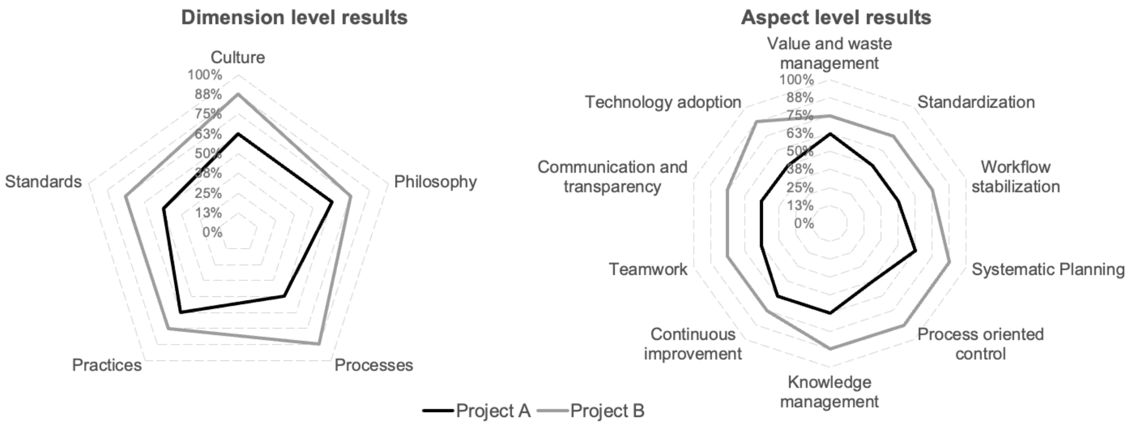

Figure 1. Comparison of LPS project management levels among case studies

SOCIAL NETWORK ANALYSIS RESULTS

As Table 3 shows, both projects exhibited similar patterns regarding the strength of the networks: Interaction and feedback were the strongest in both cases and almost equivalent to one another, planning was the third strongest network in both cases, followed by problem-solving and, finally, learning and leadership were significantly weaker than the general interaction. Also, in most cases, clustering was greater than density, indicating that not all individual interactions were direct. Although project A exhibited lower integration levels in all six networks compared to project B, it presented almost twice as many team members, which affects the results since it is less probable that a larger team has direct connections between all its members (Abraham et al., 2009). Hence, to facilitate the assessment, the results were normalized by dividing each network's metrics by the general interaction results in each project, as presented in Table 4.

Table 3. Social network analysis metrics prior to normalization

Network	Project A				Project B			
	Degree	Density	Clustering	Centrality	Degree	Density	Clustering	Centrality
Interaction	46%	47%	69%	62%	70%	73%	73%	79%
Planning	22%	23%	59%	51%	41%	43%	51%	62%
Problem solving	17%	18%	41%	45%	35%	36%	51%	56%
Feedback	45%	46%	67%	65%	70%	73%	73%	79%
Learning	11%	11%	33%	38%	28%	30%	46%	57%
Leadership	11%	11%	28%	34%	34%	35%	54%	61%

Table 4. Normalized social network analysis metrics

Network	Project A				Project B			
	Degree	Density	Clustering	Centrality	Degree	Density	Clustering	Centrality
Planning	48%	49%	86%	82%	59%	59%	70%	78%
Problem solving	37%	38%	59%	73%	50%	49%	70%	71%
Feedback	98%	98%	97%	105%	100%	100%	100%	100%
Learning	24%	23%	48%	61%	40%	41%	63%	72%
Leadership	24%	23%	41%	55%	49%	48%	74%	77%

As observed in Table 4, despite the normalization, Project B still exhibited higher integration levels regarding planning, problem-solving, learning, and leadership. Only four metrics were higher in Project A after normalization: Planning's clustering coefficient, and the betweenness centrality of planning, problem-solving, and feedback. However, these metrics were lower than Project B without the normalization. As presented in Figure 2, the administration team from Project A occupied the most central part of the planning and leadership networks while also presenting a significantly greater node degree than their teammates. In contrast, Project B presented more homogeneous planning and leadership networks, with on-site engineers occupying the center of the networks. Also, case A's planning network presents a subcontractor team excluded from the center, which was repeated in the rest of the networks.

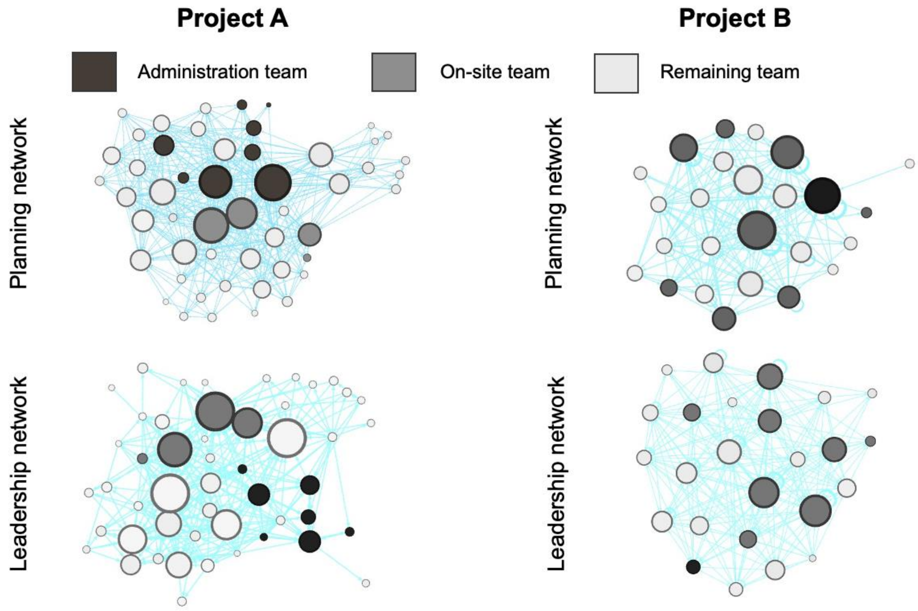

Figure 2. Case studies' planning and leadership network diagrams

PROJECT PERFORMANCE RESULTS

As Table 5 presents, Project A presented a lower SPI average, with a greater coefficient of variation compared to Project B. Project A exhibited an average tendency to decrease its SPI by a weekly rate of -1.73%, obtaining a 72.4% SPI at 52.3% expected progress, while Project B exhibited a slight tendency to increase its SPI by 0.28% weekly, obtaining an SPI of 100.4% at 52.7% expected progress. In contrast, case A presented a greater PPC average with a lower coefficient of variation and a lower number of RNCs. The differences in the SPI, PPC, and number of RNCs were statistically significant at a 95% confidence level. The percent of internal RNCs was similar in both projects and did not exhibit statistically significant differences, despite a significantly greater PIR coefficient of variation in project A. Although both projects presented a similar percent of internal RNCs, the main source of noncompletions in Project A was "overestimation of productivity and achievable progress" (32%), followed by "unforeseen requirements of information or project changes" (19%). In contrast, in Project B, their main RNC sources were "change in priorities" (41%) and "uncontrollable weather conditions" (11%).

Table 5. Project performance results

	Project A			Project B			
KPI	Mean	SD	CV	Mean	SD	CV	p-value

SPI	87.3%	14.8%	16.9%	97.0%	12.3%	12.6%	0.01
PPC	77.3%	14.9%	19.2%	58.3%	15.6%	26.8%	0.00
N° RNCs	3.27	2.14	65.5%	9.50	4.96	52.2%	0.00
PIR	61.7%	16.4%	26.5%	65.5%	3.1%	04.8%	0.07

DISCUSSION

Collaborative assessment with the teams, showed significantly different management approaches, allowing to gain understanding of the differences at adoption, collaboration and performance. First, Project A implemented a more traditional project management approach, closer to MBR, as represented by their LPS adoption levels in processes and standards, in addition to their approach of following the initial plan with minimum changes. In contrast, Project B exhibited a project management system closer to MBM, as shown by their continuous use of LPS control to drive corrective actions, captured in their LPS adoption measurement as significant differences in workflow stabilization and systematic planning, process-oriented control, and knowledge management. Therefore, the approach taken by project A was more reactive, as it focused on securing short-term compliance through corrective actions aimed at removing RNCs (Hamzeh et al., 2008); while Project B was considered systematically proactive since it focused on continuously updating the plan to ensure long-term schedule compliance (Samudio et al., 2012).

Second, Project A focused on following the initial schedule with the least variations possible and corrective actions focused on securing work conditions for tasks in the next period, aiming to improve their next PPC. On the other hand, Project B focused on continuously updating their lookahead to ensure the maximum possible progress each week, through greater attention on the workable backlog of tasks from the lookahead plan to allow flexibility even if that meant dropping certain commitments due to changes in priorities and impacted RNC composition. Although lookahead planning and work preparation metrics as the PCR were not captured in this study, the close collaborative examination of LPS adoption and performance results signaled that collaborating proactively to increase the workable backlog allowed project B to sustain higher long-term compliance, while the short-term focus of project A yielded a higher PPC but did not reflect on the long-term schedule compliance.

Third, Project A focused most management responsibilities on their administration team, as their network sociograms and metrics represented, while Project B, which shared these responsibilities with on-site engineers, supervisors, and LPs, achieved more dense and homogeneous networks, measured by degree, density, clustering, and centrality. This was also captured by the differences in teamwork and communication observed in the LPS adoption assessment. For example, Project A concentrated lookahead planning decisions at the administration level and then asked LPs to validate the plan and establish constraint removal and execution commitments. At the same time, Project B opted to ask LPs to update the lookahead plan and then validated the plan against the current state of the WB with the administration team to develop the short-term plan collaboratively. Researchers have signaled that enclosing planning, control, and decision-making mainly on high-level leadership leads to less LP participation, preventing them from proposing alternative opportunities based on the workable backlog (Mcconaughy & Shirkey, 2013). The SNA results and performance metrics are consistent with that assumption and show that while project B was able to proactively collaborate on the make-ready process to increase flexibility and protect long-term schedule accomplishment, project A was comparably more limited to reacting on RNCs to improve short-term compliance.

Fourth, even though both projects implemented LPS as their main management approach and had equivalent support systems, they significantly differed on their use of information. Project A focused mostly on following their long term plan with minimum changes, controlling short-term compliance tightly and using historical RNC information on a week to week basis to select appropriate corrective actions aimed at sustaining a high PPC.Thus, their main use of the support software and captured information was to control compliance and act accordingly. On the other hand, Project B focused mostly on securing the workable backlog, thus, using the software to assess alternative scheduling opportunities aimed at securing flexibility through collaborative planning and using theprocess-oriented information to implement lookahead planning actions and improve their make-ready process. These differences were also reflected when asking the teams "what is the main use given to the software's information on a daily basis?" where Project A answered "Tracing RNCs to detect corrective actions needed and capacity improvement opportunities aimed for the next short-term period" and Project B answered "Assessing the current state of constraints and the workable backlog to update the lookahead plan". Suppose these answers are combined with the networks' differences, it can be inferred that Project B was able to collaborate with more time to detect improvement opportunities proactively instead of reacting to RNCs based mostly on the administration team's decision-making process (Samudio et al., 2012).

CONCLUSIONS

This study assessed the relationship between LPS adoption level, team collaboration, and project performance by comparing six social networks and LPS indicators in two Chilean projects, against their LPS adoption levels, to drive conclusions using a case study approach. Both teams exhibited different approaches and results despite having similar previous LPS knowledge, experience using LPS as their main project management system, and using an equivalent LPS support system. Project A implemented an approach closer to MBR, which reflected in less connected networks, most management responsibilities enclosed in the administration team, and a lower LPS adoption level, especially in LPS processes and standards. In contrast, Project B exhibited a management approach closer to MBM with a significantly higher presence of key LPS aspects such as workflow stabilization, systematic planning, process-oriented control, teamwork, and communication, which granted higher LPs' involvement captured in the networks.

Two relevant management approach differences were identified: First, case A focused on short-term planning and opted to follow the initial plan without major changes. In contrast, project B opted to update the plan using the workable backlog systematically. Second, Project A used LPS information provided by IT support mainly to assess RNCs and implement reactive actions accordingly. In contrast, case B used it mainly to manage the workable backlog in lookahead planning proactively. The performance results showed that case A obtained a significantly greater PPC and significantly lower SPI. Hence, it was inferred that the partial LPS adoption of Project A, its short-term based reactive approach, and high-level management enclosure prevented it from achieving the LPS benefits exhibited by Project B. Therefore, even though this research did not capture make-ready process metrics, it allowed to emphasize the relevance of lookahead planning, workable backlog management, and continuous planning in close collaboration with the Last Planners to improve project performance and outcome.

ACKNOWLEDGMENTS

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BREAKDOWN WORK SAMPLING

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ABSTRACT

The Work Sampling (WS) technique has been used in the construction industry since the 1960s to understand how workers spend their time. However, the WS categories have exhibited variation throughout history due to interpretation and application discrepancies. This lack of consensus on what represents Value-Adding-Work (VAW) and Non-Value-Adding-Work (NVAW), has hindered the use of data from previous WS studies for further analysis. For this reason, this research aims to understand how the data obtained from the WS application can be analyzed to discuss value. To address this question, the authors adopted a case study as the primary research strategy. The phenomenon of the present study comprises the activities involved in the renovation process in residential buildings. The phenomenon is studied through the application of the WS technique. The authors adopted previous analyses from the existing literature and proposed new types of analyses. The discussion section presents various kinds of analysis based on a breakdown of categories into codes: (1) general analysis; (2) a category breakdown analysis; (3) one single component/material analysis; (4) recategorized activities analysis; and (5) correlation analysis. The proposal of a detailed code classification, named breakdown work sampling, represents the main novelty of this study.

KEYWORDS

Work sampling, construction site, waste time, direct work.

BACKGROUND

Work sampling (WS) is a technique first introduced in 1920s by the British industrial engineer Leonard Tippett in which work can be observed and the amount of time spent on various tasks can be determined (Barnes, 1968). WS was initially referred to as the "snap-reading method" due to its instantaneous observation nature (Tippett, 1935). The snap-reading method was executed at random time intervals using the first random table invented by Tippett (Tippett, 1935). In 1940, R. L. Morrow, who often is credited with importing the method to America, renamed the snap-reading method to the ratio-delay survey (Heiland & Richardson, 1957). In 1952, the ratio-delay survey evolved into "Work Sampling" and began to gain increased popularity during the mid-twentieth century by industrial engineers (Gouett et al., 2011).

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In the construction industry, in the 1960s, H. R. Thomas (1991) conducted one of the first WS studies. The author provided relevant insights on how a WS study could be planned and how the data could be analyzed. Currently, WS is being used by a few large construction companies to benchmark their projects so that improvements can be made and quantified. Some contractors have productivity departments that complete these studies (Gouett et al., 2011).

WS consists of a quantitative approach of intermittent, random, and instantaneous observations of work activities of multiple workers by independent observers (Barnes, 1968). The theory of WS is based on the laws of probability, which indicate that observations taken at repeated random times will have the same distribution. Hence, random observations can be translated into percentages of time spent in existing activities (Barnes, 1968).

WS can estimate the proportions of the total time spent on a task in terms of various work categories. The WS categories have exhibited variation throughout history due to interpretation and application discrepancies. Before 1985, WS studies adopted the two-category classification of direct and non-direct work. This partially reflects Ohno's (1988) understanding of work as divided into Waste Work (WW) and Value-Added Work (VAW). However, Ohno clarified that the VAW category must be further understood as consisting of Direct Work (DW) and Non-Value-Added-Work (NVAW), which does not add value but is needed under the present work conditions. The DW category is generally understood as the amount of direct, physical, and output producing work. It can be seen as the time a worker spends producing tangible output, e.g., square meters of bricks installed (Choy & Ruwanpura, 2006). In general, most WS studies agree on this definition of DW (Wandahl et al., 2021). However, for the NVAW category, a considerable inconsistency in concept and terminology appears. Some research categorizes all NVAW as WW, while other studies have a more detailed view of NVAW as several subcategories like preparatory work. Generally speaking, NVAW is in WS referred to as Indirect Work (IW), resulting in WS having three categories of time DW, IW, and WW (Wandahl et al., 2021).

The non-direct work or unproductive work category is the opposite of DW and has traditionally been quite inconsistent and included everything besides DW, such as supportive work (e.g., transporting bricks to the final destination by hand) and waiting time (e.g., waiting to receive bricks in the place of execution). The non-work definitions have fluctuated throughout the history of WS and often have been broken down into subcategories. After 1985, research generally applied the categories of DW, IW, and WW, however, with different names and subcategories, e.g., transport, travel, instruction, personal time, delay, etc. (Gong et al., 2011).

The most comprehensive version of WS in the construction sector is Activity Analysis (AA) (CII, 2010). AA differs from the conventional WS technique as it provides for a greater analysis potential due to a more consistent definition of DW, IW, and WW categories. AA groups activities of the monitored construction operation into one of seven categories. One category of DW: (1) direct work. Three categories of IW: (2) preparatory work, (3) tools/equipment, and (4) material-handling. Lastly, three categories of WW: (5) waiting, (6) travel, and (7) personal, all of which adhere to consistent definition parameters. AA is advantageous on sites that require a more detailed depiction of the construction operation without investing in the personnel for full-time direct observations (CII, 2010). Based on this idea, (Kalsaas, 2010, 2011) proposed adopting a detailed work sampling method to measure workflow efficiency.

It has been difficult to establish an accurate picture of DW, IW, and WW definitions. In general, practitioners tend to wrongly perceive IW (e.g., material handling) as value-adding, thus DW. However, this has no consistency with previous WS. Hence, it is noteworthy that it is necessary to understand work activities classification and the relationship between VAW and NVAW to better analyze previous data. Table 1 aims to summarize the main work categories used in WS literature.

Table 1: WS categories adopted by previous studies.

References	**Work Sampling categories adopted**		
	Direct Work (DW)	**Indirect Work (IW)**	**Waste Work (WW)**
Handa and Abdalla (1989)	Direct Work	Transportation; Waiting; Travel; Tool & Materials; Receiving Instructions;	Combined rates of Breaks & Personal & Late Starts; Unexplained
Oglesby et al. (1989)	Direct Work	Transport; Travel; Instruction;	Personal time; Delay
Hammarlund and Rýden (1990)	Direct work,	Transporting material and equipment; Planning	Waiting; Unused time
Thomas (1991)	Direct Work	Indirect Work	
Lee et al. (1999)	Value-added	Non-value added but necessary	Non-value added and unnecessary
Allmon et al. (2000)	Productive actions, picking up tools, measurement, holding material, inspecting, clean-up, putting on safety equipment	Supervision, planning, instruction, travel, getting materials)	Waiting, standing, sitting, non-action, personal time, late starts, early quits
Agbulos and AbouRizk (2003)	Value-adding process steps		Non-value adding process steps
Jenkins and Orth (2004)	Installation, fabrication, testing, demolition	Materials handling, design, communication, safety, positioning equipment	Waiting, personal needs, inspections, rework
Diekmann et al. (2004)	Value-adding	Non-value adding	Pure non-value adding
Thune-Holm and Johansen (2006)	Productive Time	Indirect time	Change-over time; Personal time
Strandberg and Josephson (2005)	Direct Work	Indirect work; Material Handling; Work planning;	Waiting; Moving between working spots; Unexploited time
Choy and Ruwanpura (2006)	Direct work	Preparatory; Material Handling; Tools	Travel; Personal; Waiting
Alinaitwe et al. (2006)	Building, Handling materials; Clean-up, Unloading	Supervision; Material distribution, setting out, testing	Absent; Waiting, Not working
Kalsaas (2010)	Direct Work	Personal Time; Coffee and lunch breaks; Handling material; Work planning; Waiting; Cleaning up; Reworking; Rigging; Unloading; Inspection	
Espinosa-Garza et al. (2017)	Productive	Preparation; Work supplements; Administrative; Unusual elements	Unproductive;
Sheikh et al. (2017)	Direct Work	Preparatory Work and Instructions; Travelling; Tools and Equipment; Material handling	Personal; Waiting
Neve et al. (2020)	Production	Talking; Preparation; Transportation;	Walking; Waiting

According to the terminologies identified in the WS literature, the term DW has been used in all the different classifications for WS application without exception. Some authors (Allmon et al., 2000) included activities in the DW category such as holding material, measurement, and inspections, traditionally considered IW (Ohno, 1988). The IW category represents the category that has been broken down into most subcategories. The IW subcategory that appears in most of the classifications is transport, also called material handling (Sheikh et al., 2017; Strandberg & Josephson, 2005) or material distribution (Alinaitwe et al., 2006). Some authors employed the term travel to differentiate a walking activity from a transportation activity (Oglesby et al., 1989; Sheikh et al., 2017). This term, in many cases, causes a misunderstanding, making construction academics use the term travel to include walking with and without materials. The subcategory waiting represents the category that generates more controversy among the studies. This category was initially considered an IW task (Oglesby et al., 1989); however, it has recently been considered as waste (Choy & Ruwanpura, 2006; Neve et al., 2020; Sheikh et al., 2017). This interpretation is also in line with Ohno's (1988) definition of waste.

This brief literature review revealed that the problem, also pointed out by Wandahl et al. (2021) after reviewing 474 WS studies, caused by the lack of consensus on what represents a VAW and NVAW work activity during the application of the WS technique, had hindered the use of data from previous WS studies for further analysis. Consequently, in this study, the Research Question (RQ) is represented by the following question: How can the data obtained from the WS application be analyzed to discuss value?

To address this question, the authors adopted a case study as the primary research strategy since this research strategy is helpful for answering "how" and "why" questions and where in-depth research is needed using a holistic lens (Yin, 2003). This study differs from previous AA studies or detailed WS applications due to the breakdown classification of the work categories considering all tasks conducted in one single construction process.

RESEARCH STRATEGY

A case study is an empirical inquiry that investigates a contemporary phenomenon in depth and within its real-life context, especially when the boundaries between phenomenon and context may not be clearly evident (Yin, 2003). The authors studied the phenomenon through the application of the WS techniques. In this research, the WS procedure followed the following steps: (1) selecting the construction project and the construction process; (2) clarifying the categories of the activities to be measured; (3) developing data collection forms; (4) data collection; (5) deciding the confidence interval and the accuracy desired and calculating the number of observations needed; and (6) data analysis.

STEP 1: SELECTING THE CONSTRUCTION PROJECT AND THE CONSTRUCTION PROCESS

The phenomenon of the present study comprises the activities involved in the renovation process of internal walls, ceilings, windows, and balconies in residential buildings. The phenomenon actors are the carpenter trade's 22 workers. The real-life context is represented by the construction renovation project located in the city of Odense, Denmark. This project consists of four-floor-story buildings; each floor presents two apartments, and there are a total of 587 housing units. The buildings were established around the year 1950. During the renovation work, tenants have the right to use their apartments. Hence, not all of the story buildings were undergoing renovation work at the same time. This agreement affected the construction site logistics, as the contractor had a restricted area for the construction activities. For this reason, the logistical aspects played an essential role in this project.

STEP 2: CLARIFYING THE CATEGORIES OF THE ACTIVITIES TO BE MEASURED

Two of the three authors of this paper were the observers in the study. The study lasted 10 days. During the first day of the job site visits (Day 1) the two observers developed the breakdown work codes. A total of 41 WS codes were developed within six categories (Figure 1Figure 1): (1) Production (13 codes); (2) Talking (2 codes); (3) Preparation (10 codes); (4) Transportation (10 codes); (5) Walking (3 codes); and (6) Waiting (3 codes). The six-category classification was adopted to keep consistent with previous WS studies carried out by the research team as part of a long-term research project.

Category	Code	Description
Production	C101	Installing steel profiles
	C102	Installing insulation on windows
	C103	Installing steel sill on windows
	C104	Grouting around windows
	C105	Demolishing old bricks (hammering)
	C106	Installing insulation
	C108	Installing green plastic and wall nets
	C109	Installing wood panels
	C110	Installing gypsum panels
	C111	Installing windows
	C112	Installing fire proofing plates
	C113	Installing door frames
	C114	Installing tiles on balconies
Walking	C301	Walking for having a break
	C302	Walking for materials and tools
	C303	Walking without (known) purpose
Waiting	C601	Waiting for material
	C602	Waiting for a coworker
	C603	Waiting without any (known) purpose
Talking	C501	Talking about the process
	C502	Talking without any (known) purpose
Preparation	C201	Measuring with laser
	C202	Measuring with ruler
	C203	Preparing steel profiles
	C204	Cutting insulation
	C205	Cutting gypsum panels
	C206	Cutting wood panels
	C207	Preparing the hole for the window installation
	C208	Removing temporary supports for balconies
	C209	Cleaning
	C210	Preparing tools
Transport	C401	Transporting gypsum panels
	C402	Transporting tools
	C403	Transporting support equipment
	C404	Transporting step ladder
	C405	Transporting steel profiles
	C406	Transporting window frames (plastic)
	C407	Transporting wall nets
	C408	Transporting insulation
	C409	Transporting waste
	C410	Transporting wood frames

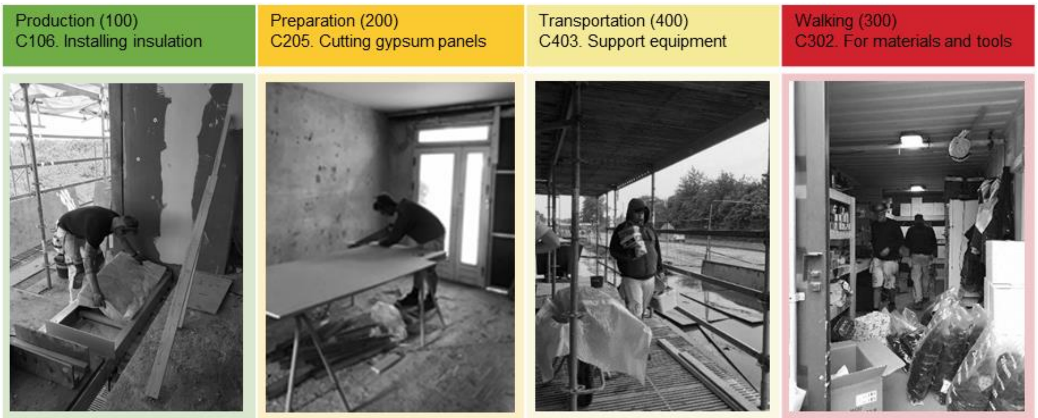


Figure 1: The 41 WS codes developed and four examples of WS codes used for carpenters' tasks.

STEP 3: DEVELOPING DATA COLLECTION FORMS

The development of the data collection form aimed to maintain control and consistency of the data to be gathered. An Excel spreadsheet was developed, which included the 41 codes. For gathering data, the authors adopted the smartphone application "Counter – Tally Counter" by Tevfik Yucek. This application allowed the researchers to digitally record each observation with an exact time stamp and to export this data in a .csv-format for further processing.

STEP 4: DATA COLLECTION

For gathering data at the construction site, the two observers conducted nine days of job site visits (8 hours/each) from Day 2 to Day 10. The data collection period was the same as the construction workers' working hours, from 06:30 to 14:30. Lunch break was from 10:30 to 11:00. Digital devices such as mobile phones and tablets were used for data collection at the construction site during random tours. These devices allowed the research team to gather data to take photos and videos of the construction processes studied.

STEP 5: DECIDING THE CONFIDENCE INTERVAL AND CALCULATING THE NUMBER OF OBSERVATIONS NEEDED

To achieve statistically significant process variables, enough random observations were conducted for the workers' crew (N=22) performing the activities under study. The formula that describes the relation between the number of observations needed and the desired accuracy is presented in Equation 1.

$$n = \frac{p * (1 - p)}{(\sigma)^2} \quad (1)$$

Where:
n = the total number of observations during the first day of data collection
p = expected percent of time required by the most important category of the study (e.g., DW)
σ = standard deviation percentage

The authors conducted nine days of WS observations on the job site (represented by the nine different blue colors used in Figure 2) within the eight working hours (horizontal axis in Figure 2). The working time was divided into hourly study periods, from 06:00-07:00 until 14:00-15:00, resulting in eight study periods per day (number of bars in Figure 2), totalizing 72 study periods, each representing a random tour around the site. The authors collected a homogeneous sample resulting in an average of 26 observations per study period (secondary vertical axis in Figure 2). A stabilization curve of the share of observations of the production codes (DW codes) was created to provide a visual check of the accuracy of the collected data (Figure 3). The curve stabilizes at 29% after around 1,200 observations, i.e., after Day 6. Upon completion of nine days of data collection, a total of 2,100 samples (n) were recorded (horizontal axis in Figure 3) with a 95% (p) confidence interval of ± 2% (σ).

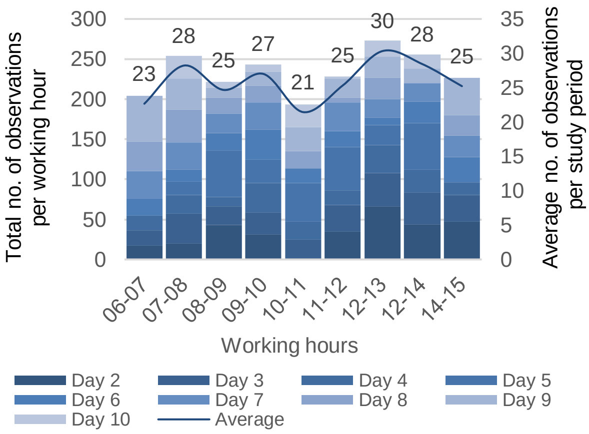


Figure 2: Frequency distribution of observations throughout the day (n=2,100).

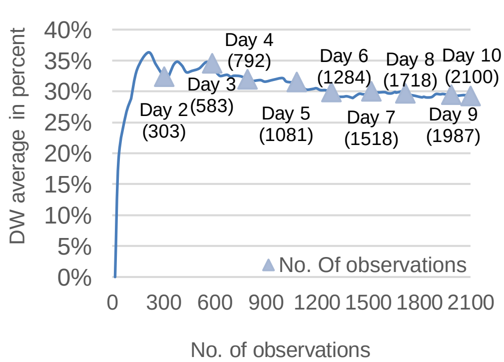


Figure 3: Stabilization curve of the DW observations (n=2,100).

STEP 6: DATA ANALYSIS

The analysis and explanation of the phenomenon of this study set out to stipulate a presumed set of causal links about it and "how" it happened. For this reason, the analysis of data collected during the case study aimed to explain how the data obtained from the WS application can be analyzed to discuss value. The authors adopted previous analyses from the existing literature and proposed new sorts of analysis, such as: (1) general analysis, to understand how the time was spent on VAW throughout the workday and the days of data collection; (2) a code category breakdown analysis, to understand which kind of activity is the most time consuming of each main category; (3) single component/material analysis, to understand the distribution of the time for a given task; (4) recategorizing activities, to be able to compare data to previous studies where observations have been categorized differently; and (5) correlation analysis, to examine the internal relationship between the different codes.

FINDINGS

GENERAL ANALYSIS

Several general analyses can be conducted looking into the results of the 6 main WS categories. Most previous research studies have focused on presenting the average percentage obtained from each WS category. These numbers can be seen in the "average" columns in Figure 4 (a) and (b). Production and preparation each account for 29% of the observations, talking for 13%, transportation for 17%, walking for 10%, and waiting for the remaining 3%. In this study, Figure 4 (a) and (b) can lead to two types of further discussion; the distribution of the time spent on VAW throughout a workday and throughout the days of data collection. The distribution among the 6 main categories changes throughout the day. This change is shown in a general way in Figure 4 (a). A different representation of the change is shown in Figure (a) and Figure (b), using two pie charts for two of the workhours. Most of the observations in the first workhour of the day are of transportation and preparation, whereas in the middle of the workday, from 11:00 to 12:00, most observations are of productive work.

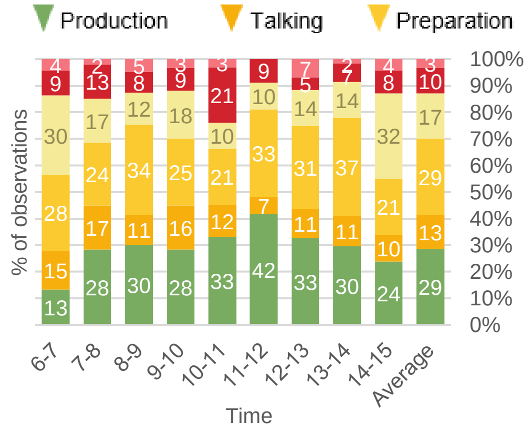


Figure 4 (a): Distribution of observations throughout the workday (n=2,100).

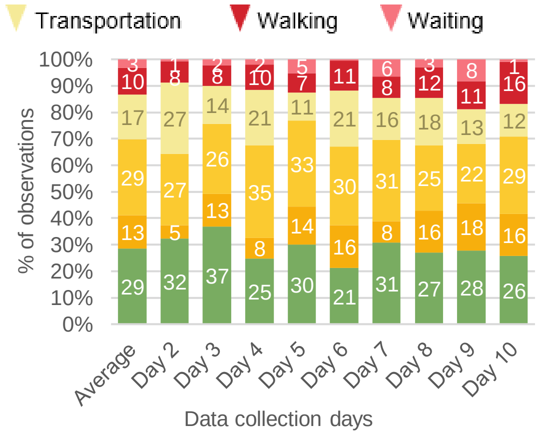


Figure 4 (b): Distribution of observations throughout the days of data collection (n=2,100).

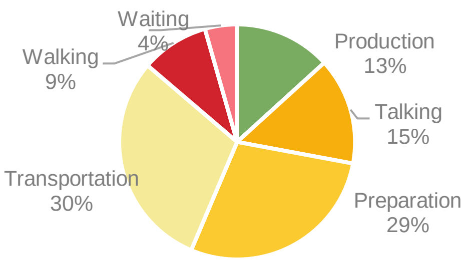


Figure 5 (a): Distribution of observations during the first working hour (n=204).

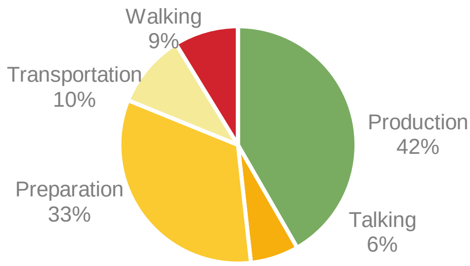


Figure 5 (b): Distribution of observations during the period of 11:00 to 12:00 (n=228).

BREAKDOWN ANALYSIS

Figure visualizes how the breakdown of the 6 main WS codes into the 41 detailed codes can be used for analysis. The Detailed Distribution of Observations (DDO) seen in Figure (a) shows that the most frequently observed productive task was C110 (installing gypsum panels) with 9% of total observations, followed by C101 (installing steel profiles) and C109 (installing wood panels), which each accounted for 4% of the total observations. Figure (b) shows that measuring with a ruler (C202) was the by far most observed task within the preparation category and also the most observed contributory task, with 10% of the total observations being of C202. C402 transporting tools were observed almost as many times asv C202 and was the task within the transportation category that was observed most times, accounting for 9% of the total observations.

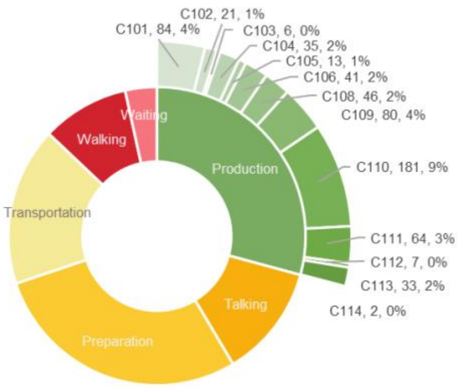


Figure 6 (a): DDO on productive tasks (n=613).

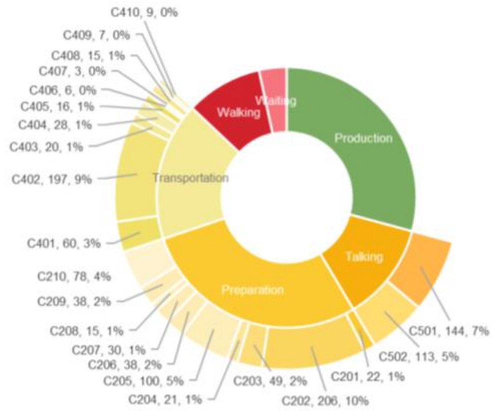
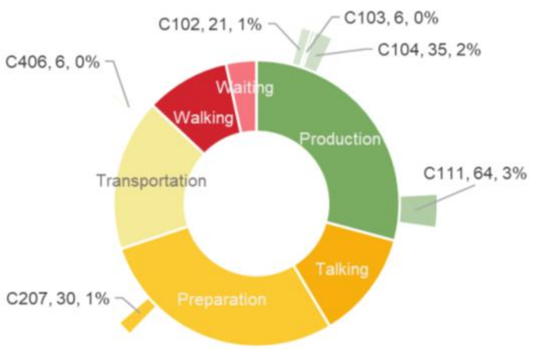


Figure 6 (b): DDO on contributory tasks (n=1,215).

ONE SINGLE MATERIAL/COMPONENT ANALYSES

The detailed taxonomy of WS codes makes way for several opportunities for data analyses. Besides breaking down the DDO within each main category, it is possible to extract information about a single component, as shown in Figure (a) and (b).



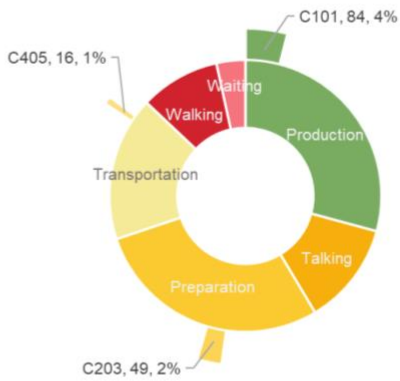


Figure 7 (a): DDO on windows (n=162). Figure 7 (b): DDO on steel profiles (n=149).

Figure (a) shows the observations of codes related to installing new windows, including C102 installing insulation around windows, C103 installing steel sill below windows, C104 grouting around windows, C111 installing windows, C207 preparing the hole for window installation, and C406 transporting temporary window frames (plastic). In the same way, codes regarding steel profiles for the drywall have been extracted in Figure (b); C101 installing steel profiles, C203 preparing steel profiles, and C405 transporting steel profiles.

RECATEGORIZING ACTIVITIES

Another possibility for analyzing the data is to move codes from one main category to another. As different interpretations between categories exist among researchers and practitioners, this represents a transparent way of manipulating the data that can be useful when comparing data to previous studies, where observations have been categorized differently. Two examples are shown in Figure (a) and (b). In Figure (a), all tasks concerning measuring and cutting are recategorized from preparation to production. Consequently, the share of observations of productive tasks raises from 29% to 50%, and preparation decreases from 29% to 8%. In Figure (b), observations of transportation of tools and support equipment are considered as preparation instead of transportation. This results in the transportation category shrinking from 17% to 6%, and the preparation category increasing from 29% to 40%. Going forward, it will be useful to break down the WS codes even further so that when extracting information on single materials or components, fractions of observations from other codes such as measuring and transporting tools can also be included.

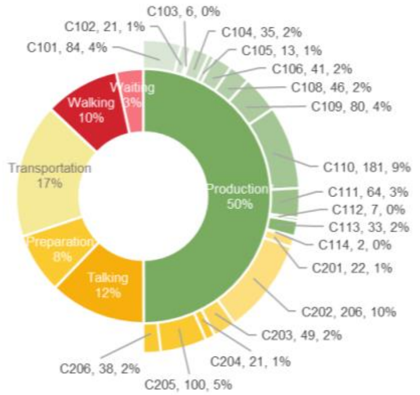


Figure 8 (a): DDO of productive tasks considering measuring and cutting tasks (n=1,049).

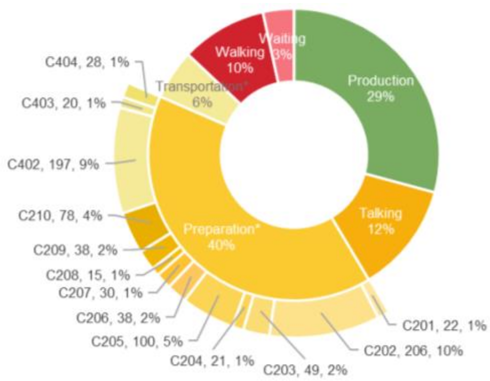


Figure 8 (b): DDO of preparatory tasks considering transporting tools and equipment (n=842).

CORRELATION ANALYSIS

To examine the internal relationship between the different observations, correlations were conducted between all of the WS codes using the total number of observations from each hour of the workday of each code. A visual representation of the correlation coefficients (R) can be seen in Figure 9. The following will discuss pairs of codes that exhibited a correlation stronger than ±0.80, and the implications of these results on the construction operation studied. There are 9 pairs of codes that have a correlation stronger than ±0.80. The strongest correlation is seen between C203 and C405, with a coefficient of 0.91. These codes represent two closely connected tasks; "preparing steel profiles" and "transporting steel profiles", thus it is not unexpected that the correlation is strong. The second strongest relationship with a coefficient of 0.90 is between C202 and C205, i.e., "measuring with ruler" and "cutting gypsum panels". This is the strongest correlation between C202 and any other code, which indicates that measuring with a ruler was applied more when preparing gypsum panels than when, e.g., preparing steel profiles or insulation.

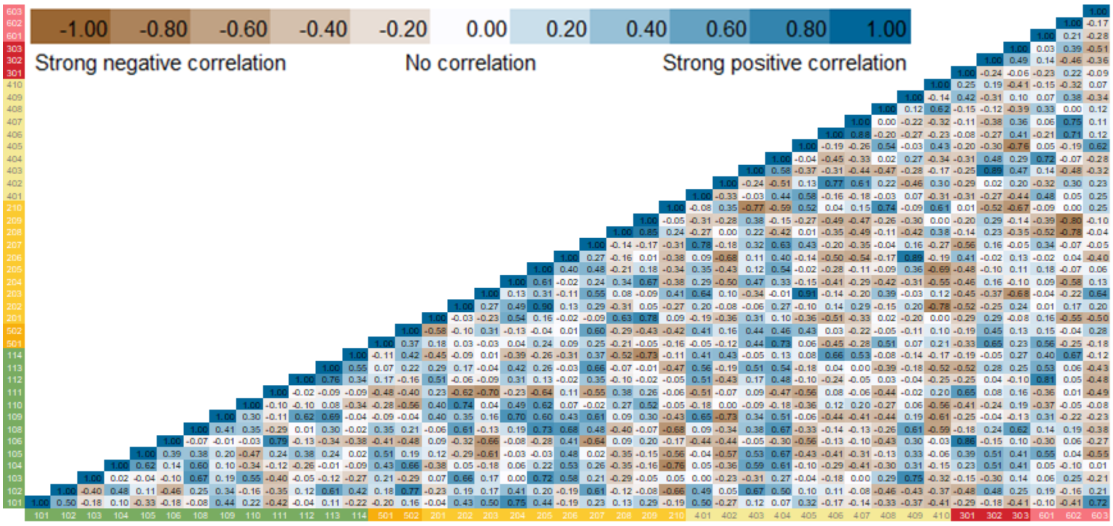


Figure 9: Correlation (R) of all WS codes.

CONCLUSIONS

This research addressed the RQ of how the data from the WS application can be analyzed to discuss value. The authors presented different possible analyses using the data gathered from a real case study. The WS was applied on the carpenter's trade on a renovation project. Carpenters spend their working hours renovating internal walls, ceilings, windows, and balconies. During the WS application, a total of 2,100 observations were made throughout ten days of job site visits through eight hours daily. This study suggests that the time spent in VAW in the renovation process studied, set of multiple operations, can easily be analyzed by performing a compilation of data divided into tasks. Whenever possible, identifying all activities or procedures will lead to a comprehensive understanding of how the workers spend their time on VAW and NVAW.

The proposal of a detailed code categorization represents the major novelty of this study as it provides for a more significant analysis potential. Adopting a breakdown classification is advantageous for field studies no matter which activities practitioners understand as a value-adding. The lack of standard terminology of VAW and NVAW would not attenuate the use of the WS data as each researcher/practitioner will be able to move codes from one main category to another. In this study, the authors developed a detailed WS form of 41 codes. In future steps, a suitable decomposition of activities fitting to the Work Breakdown Structure (WBS) of the project will be tested in a new case study. Moreover, an additional type of information, such as location, will be added to codes to provide a more comprehensive understanding of the nature of the activities.

The development of the breakdown classification for WS purposes presents some limitations that should be addressed in future research. An important limitation is related to the data collection process at construction sites during the development of the WS form. This requires a deep knowledge of the process to be studied. Moreover, this comprises a very time-consuming activity, and several workers' tasks cannot be observed during the period of the form development. Consequently, new codes will have to be added during the course of the application of the technique. Finally, statistical techniques to carry out the analyses of the WS study were not discussed in this paper.

ACKNOWLEDGMENTS

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DIGITAL TWINS AND LEAN CONSTRUCTION: CHALLENGES FOR FUTURE PRACTICAL APPLICATIONS

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ABSTRACT

The construction industry has experienced the opportunity to incorporate new technologies to solve problems in terms of information flow, collaboration, quality, costs, productivity, and predictability. Digital Twins (DT) can support solving some of these problems, mainly when associated with lean principles. However, there are still many gaps in the literature regarding the state of practice of DT for construction. This study investigates how current research on the integrated use of BIM-based DT and lean for construction projects has been positioned in front of practical challenges, aiming to identify research directions that support future applications in the construction phase. The research method adopted was a Systematic Literature Review (SLR). A total of 14 publications were identified and analyzed from the perspective of challenges for practical applications, considering seven aspects regarding DT application in other industries: cognitive and technical level of people, technology and infrastructure, support tools, standards, and specifications, cost control and management, cyber security and intellectual property rights, and insufficient development of DT. The results suggest that the challenges for DT implementation may become more complex due to the dynamic and unique nature of the construction site and that there is still a large field for further research on DT with lean. Finally, some future research directions are proposed.

KEYWORDS

Digital Twins, Lean Construction, Production Planning and Control, Integration, BIM.

INTRODUCTION

The construction industry has recently increased using technological innovations to solve existing problems. Industry 4.0 has been used over the past few years to describe the trend toward digitization, automation, and the increasing use of information and communications technology (ICT) in the manufacturing environment (Oesterreich & Teuteberg, 2016). Construction 4.0 (or digital transformation in construction) has gained

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strength in this context, inspired by the Industry 4.0 environment. Despite advances, the construction industry still faces several complex issues, including dealing with waste, inefficiencies in terms of processes, information flows and collaboration, fragmentation, conservativeness, difficulty in quality and cost control, low productivity, low predictability, and insufficient development to generate innovation technologies (Sawhney et al., 2020; Opoku et al., 2021). Digital Twins (DT) can be understood as "a model for data-driven management and control of physical systems" (Sacks et al., 2021) that have the potential to respond to such construction problems (Opoku et al., 2021).

DT are based on physical and digital world integration. Its main components (physical, virtual equivalents, and data connection) have been used in Industry 4.0 in engineering, manufacturing, operation, and maintenance (Tao et al., 2019). DT are a new phenomenon in construction, and there is still no consensus among researchers and practitioners about their role in supporting design and construction (Opoku et al., 2021; Sacks et al., 2020). Construction projects have specific aspects that must be considered. They are site-based, individual, dynamic, complex, and involve information exchange and communication between different stakeholders (Oesterreich & Teuteberg, 2016).

Construction workflows involve the interaction of a large number and diversity of physical resources (personnel, equipment, and materials), many of which are temporary. In addition, construction projects have demanded the availability of ever more detailed status information to find and remove constraints, prepare tasks, define teams, and execute services. Lean principles offer a solid base for dealing with these issues; however, its methods require a considerable flow of information and resources, which are difficult to hold without the support of information technology (Sacks et al., 2020).

Sacks et al. (2020) recently proposed the Digital Twins Construction (DTC), based on Building Information Modeling (BIM), lean construction thinking, Artificial Intelligence (AI), and wide-ranging digital site monitoring technologies to create a "data-centric mode of construction management". According to Sepasgozar et al. (2021), some of the key objectives of DT with lean integration could be reducing variability, enhancing productivity, minimizing waste, improving workflow, increasing transparency, and optimizing deliveries. DTC can provide accurate status information and optimize design and construction planning and control, making construction management increasingly proactive (Sacks et al., 2020). The synergy with lean thinking is a relevant point in DTC workflow, as is the use of BIM to contextualize related data.

Despite the benefits, according to Sacks et al. (2020), much research and development work will be needed to progress the DTC workflow and enable more future practical applications. Boje et al. (2020) and Opoku et al. (2021) also investigated the definitions, concepts, structures, limits, and requirements necessary for DT adoption in the construction industry. The authors are unanimous in suggesting that these discussions are just beginning, and there are gaps mainly regarding practical applications.

Tao et al. (2019) developed a study regarding DT application in the smart manufacturing field. They summarized the challenges for its practical application in seven aspects: (1) cognitive and technical level of people, (2) technology and infrastructure, (3) support tools, (4) standards and specifications, (5) cost control and management, (6) cyber security and intellectual property rights, and (7) insufficient development of DT. Those aspects seem general enough to resemble common challenges in the construction field. Therefore, this study investigates, from an exploratory approach, how current research on the integrated use of BIM-based DT and lean for construction projects has been positioned in front of practical challenges. The main expected contribution to the body of knowledge are some research directions supporting future applications in the construction phase.

Following this introduction, the next section presents background research, including DT definitions, technologies, and applications. Section "Research Method" outlines the methodology for selecting the articles reviewed. Section "Results" present the results of the review. Section "Discussion and Future Directions" presents some findings after the content analyses. Finally, the final considerations are summarized in the "Conclusion."

DT DEFINITION, TECHNOLOGIES, AND APPLICATIONS

The concept of DT emerged in 2003 (Grieves, 2014), but it is only now achieving more value in the industry. Currently, the first difficulty faced for the broad adoption of DT is the absence of a mutual and clear conceptual definition. As a result, researchers from different universities and institutes proposed their understanding according to their specific fields of application in the industry (Opoku et al., 2021; Tao et al., 2019).

For example, in the smart manufacturing context, DT has been understood as an emerging and pragmatic paradigm built on the concept of Cyber-Physical Systems (CPS), which aims an architecture to converge the physical and virtual spaces (Tao et al., 2019). Opoku et al. (2021) report that in more digitally advanced sectors, such as manufacturing, automotive, and aerospace, DT has been used in predictive maintenance, structural health management, shopfloor management, product life cycle management, and machinery fault diagnosis, for example. DT can be expected to experience rapid development over the next few years (Tao et al., 2019). Tao et al. (2019) summarize the value of DT for smart manufacturing in the following aspects: increasing visibility, reducing time to market, keeping optimal operation, reducing energy consumption, reducing maintenance cost, increasing user engagement, and fusing information technologies.

In the scope of this article, and considering the application to the construction stage, DT can be understood as up-to-date digital representations of a given system's physical and functional properties (Sacks et al., 2020). This system can be a physical artifact, a social construct, a biological system, or a composite system, such as a construction project, that have characteristics of physical products and social systems (Sacks et al., 2020).

DT is built on integrating various technologies and concepts of Industry 4.0. Possible integration interfaces involve data acquisition, storage and analysis, what-if scenario simulations, and visualization. Examples of related technologies and concepts are Modeling and Simulation Tools, Internet of Things (loT), Cloud Computing, Machine Learning (Tao et al., 2019), Global Positioning System (GPS), Tag Identification Systems (such as RFID or QRCode), Scanners, Camera, Big Data, Blockchain, (Opoku et al., 2021), Digital Ecosystems, Unmanned Aerial Vehicles (UAV), Virtual Reality (VR), and Augmented Reality (AR) (Sawhney et al., 2020).

In the built environment, BIM has the potential to compose the virtual counterpart of DT (Pishdad-Bozorgi et al., 2020; Sacks et al., 2020), providing significantly improved spatial context for acquired data (Gao et al., 2018) and broader situational awareness for managers (Sacks et al., 2020). However, Sacks et al. (2021) emphasize that DT is not simply an evolution from BIM or an extension of BIM tools integrated with technological solutions to sense and monitor the physical environment. A DT for construction is not limited to digitally recreating the physical system but is also connected to it automatically.

The DTC proposed by Sacks et al. (2021) is not limited to BIM capabilities. Still, it is a construction mode based on PDCA (Plan, Do, Check and Act) and lean principles, which provide reliable and timely information for management decision-making. In addition, the PDCA approach provides a cyclical and closed control mechanism that reflects the comprehension of the temporary nature of construction projects, which can and should benefit from lean practices (Sacks et al., 2020).

AI is also a central component, which can be understood as an umbrella term for applications in which machines develop human-like intelligence, dealing with learning, judgment, and problem solving (Weber-Lewerenz, 2021). Another relevant component is the data flow connection in a DT (exchange of data, information, and knowledge), which is mainly made possible by the development of IoT (Boje et al., 2020; Sacks et al., 2020). IoT infrastructure includes communication networks and protocols, software, hardware, and cloud computing platforms (Al-Fuqaha et al., 2015).

In construction sites, the possible applications of DT involve site monitoring and optimization, equipment management, asset management, supply chain management, worker-power management, and safety analysis, among others (Zhang et al., 2021). In the PDCA approach, DT can work in the following domains: (a) Plan: construction plans, (b) Do: fabrication and construction, off and onsite, (c) Check: monitoring (comparing as-built product and as-performed), and (d) Act: improve design, construction, and operation with changes to plans based on feedback received (Sacks et al., 2020).

RESEARCH METHOD

According to Kitchenham (2004), the Systematic Literature Review (SLR) approach identifies, evaluates, and interprets the relevant literature related to a specific research question, a specific field, or a phenomenon of interest. The SLR was implemented to map previous literature and meet the study's objectives. The research gap was converted into the following research question: "How has been the literature on BIM-based DT for construction and lean positioned regarding the challenges for its practical application in real contexts, mainly in the construction phase?". Fig. 1. illustrates this research process.

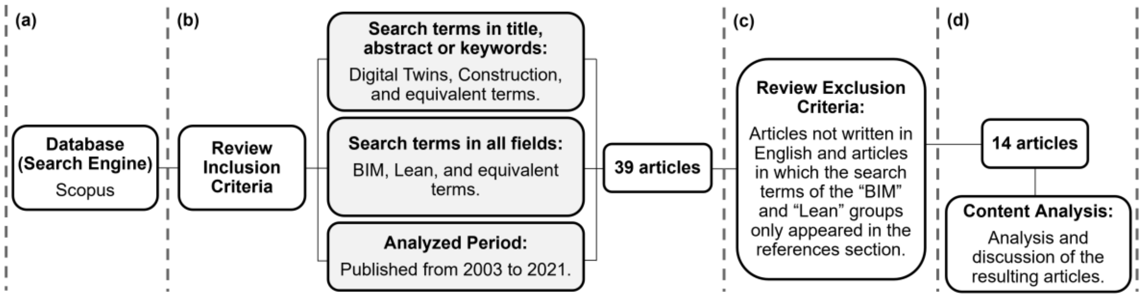

Figure 1: SLR research process.

Search strategy: the research process included the following macro steps: (a) Definition of a database; (b) Definition of review inclusion criteria and search parameters; (c) Definition of the review exclusion criteria; and (d) Content analysis. Scopus was the selected search engine due to its broad coverage of relevant academic articles.

Inclusion criteria: initially, the research groups were defined. After some scoping studies, related terms and terms considered equivalent were included in each group. Each article (Article, Conference Paper, or Review) should contain at least one search term from each group. For the "Digital Twins" and "Construction" groups, the search terms were specifically searched for in the title, abstract, or keywords of the articles in the databases. For the "BIM" and "Lean" groups, the search included all fields in the documents. The data range included articles published from 2003 (when the concept of

DT emerged) to 2021. A total of 39 articles were obtained with the inclusion criteria. The search terms used to establish the conceptual boundaries of the review are as follows:

1. Digital Twins: "digital twin"; "digital twins"; "virtual counterpart"; "digital replica"; "virtual twin".
2. Construction: "construction industry"; "construction sector"; "construction engineering"; "construction management"; "construction engineering and management"; "civil engineering"; "construction project"; "construction projects"; "construction site"; "AEC"; "AECO"; "construction 4.0".
3. BIM: "building information modeling"; "BIM"; "building information model".
4. Lean: "lean".

Exclusion criteria: the first criterion was the removal of articles not written in the English language, chosen due to its recognized universality. The second criterion was the manual removal of the articles in which the search terms of the "BIM" and "Lean" groups only appeared in the references section. This step resulted in 14 articles as the final sample.

Content analysis: the final sample was analyzed and discussed according to seven challenges for DTs practical applications defined by Tao et al. (2019) (Table 1).

Table 1: Challenges for DTs practical applications (Tao et al., 2019).

Challenges	General Description
1-Cognitive and technical level of people	It refers to the comprehensive understanding of DT and its values, the psychological and cultural boundaries that can hinder the adoption, and the technical capacity to operate DT.
2-Technology and infrastructure	It refers to technological development, the availability of related commercial products, and infrastructure aspects.
3-Support tools	It refers to clarity about available commercial support tools (software and hardware) and its current integration capacity.
4-Standards and specifications	It refers to standards specifications to ensure data exchange, integration, and fusion across models, interfaces, and protocols.
5-Cost control and management	It refers to the balance between DT costs and benefits, considering the need for time-consuming and labor-intensive, and the need for high-performance hardware and software support.
6-Cyber security and intellectual property rights	It refers to protecting confidential information to ensure security (protecting networked systems and resisting malicious attacks on sensory devices) and protecting intellectual property rights.
7-Insufficient development of DT	It refers to the clarity of concepts, availability of tools, technologies, and skilled people, and market, business, and investment strategies.

RESULTS

The sample includes 6 Articles (46,2%%), 6 Reviews (46,2%), and 2 Conference Paper (7,7%). The number of documents published per year was two documents in 2019, two in 2020, and ten in 2021. This section presents the content analysis, considering the challenges proposed by Tao et al. (2019).

1-COGNITIVE AND TECHNICAL LEVEL OF PEOPLE

Technologies are developed, designed, and used by humans, so a sustainable and ethical digital transformation in construction can only be successful if people are at the center of discussions (Weber-Lewerenz, 2021). Lean systems also adopt this point of view

(Sepasgozar et al., 2021). Weber-Lewerenz (2021) studied digital innovation in construction from a multidisciplinary perspective of Corporate Digital Responsibility (CDR). This approach can serve as a guideline for the DT operational development with ethics, morals, and sustainability. The authors pointed out that companies currently lack knowledge about the possible DT applications regarding construction workflows. Weber-Lewerenz (2021) identified an urgent need for skilled staff to implement new digital technologies in companies, representing a practical gap. There is also a need for educational strategies to help the practitioners with the multidisciplinary skills needed to deal with digitalization and its social and ethical aspects. However, digital technologies themselves can be helpful in the augment newly required skills. For example, Sepasgozar (2021) mentioned the use of VR for educational training. DT development will require multidisciplinary skills in sensing technologies, construction management, organizational sciences, data science, applied mathematics, theoretical and computational statistics, and computing science (Sacks et al., 2020). Besides that, another pointed issue is a possible cultural resistance from the skilled construction workforce to the required changes in management systems and practices (Sacks et al. 2020, Sepasgozar et al., 2021; Marocco & Garofolo, 2021). The organizational fragmentation in the construction industry can hinder the extensive process change required (Sacks et al., 2020). A first step to overcoming this boundary can be an awareness strategy for elucidating individuals concerning DT value for construction (Sepasgozar et al., 2021).

2-TECHNOLOGY AND INFRASTRUCTURE

Sacks et al. (2020) suggested the following areas for future technological DT development: data fusion to deal with the multiple data streams and derive status information; mechanisms for data storage, protocols, and algorithms for data consistency; data science methods and algorithms for monitoring, processing, interpretation, simulation, and optimization; and applicability of AI tools. According to Sepasgozar et al. (2021), concerning the connection, IoT technologies can act as integrators of lean-BIM systems, supporting DT development. Moreover, the future availability of 5G will facilitate the transfer of large data streams (big data) for real-time controls and immediate scenario optimizations. On the other hand, Sacks et al. (2020) pointed out that BIM has satisfactory tools for product design representation but lacks essential elements regarding DT for construction, such as full semantics. For example, their geometry models use object-oriented vector graphics, which is not ideal for dealing with point clouds.

Furthermore, the BIM object models do not accurately represent aspects of the construction process (Sacks et al., 2020). Another challenge worthy of investigation refers to decision-making processes. There is a need for studies focusing on machine learning algorithms to create accurate prediction models for construction (Marocco & Garofolo, 2021; Sacks et al., 2020). Regarding lean, Sepasgozar et al. (2020) indicate a gap in understanding the synergistic interactions of lean concepts and the combination of digital information and sensor-based technologies in construction applications. According to these authors, there are many advanced technologies commercially available, and there is a high demand to use them for lean purposes. However, the number of validated case studies using advanced technologies is still limited.

3-SUPPORT TOOLS

According to Sepasgozar et al. (2021), the literature suggests some types of tools already available for DT in other industries, especially in three layers: communication, protocols applications, and platforms for data analytics. According to Sacks et al. (2020), preview studies evaluated many digital site monitoring technologies, and some have become available commercially. Lee et al. (2021), Jiang et al. (2021), and O'Grady et al. (2021) tested some commercial tools used for DT development in their specific use cases. Lee et al. (2021) suggested a framework for integrating DT and blockchain for construction. They used IoT sensors to collect data from the construction and Azure (Microsoft) as the cloud service platform, providing the blockchain service modules. For building DT, the authors used Unity, a game engine that supports plug-ins for BIM data transfer, sensor synchronization, and real-time visualization (Lee et al., 2021). Jiang et al. (2021) described the MiC blockchain's steps. They mentioned Revit, Maya, or Solidworks as commercial solutions to create the 3D models imported into Unity to build DT functions. DT was converted into JavaScript language through Web Graphics Library (WebGL). O'Grady et al. (2021) proposed a new approach with VR, BIM, and DT to advanced learnings and experiences of the circular economy in construction. They prepared the BIM model in Revit and then exported it for Unity. DT can benefit from solutions provided as services, such as web-service platforms (Marocco & Garofolo, 2021; Boje et al., 2020). According to Sacks et al. (2021), DT for construction are based on systems that incorporate hardware, cloud, and advanced information processing resources, which remain invariant independent of construction project type variations. As such, DT for construction could be delivered as a platform business model, in which an external company provides the infrastructure and integrated hardware/software service. Although several support tools have been identified, the literature review indicates that, despite efforts in this direction, there is still a gap regarding robust and integrated commercial DT solutions for construction that could be implemented on construction sites.

4-STANDARDS AND SPECIFICATIONS

DT can involve various data collection devices storing information in diverse formats, which leads to fragmentation, data heterogeneity, and a lack of interoperability. These issues can decrease the construction industry's readiness for DT adoption (Marocco & Garofolo, 2021; Sepasgozar, 2020). According to Sacks et al. (2020), data standardization in consistent syntactic and semantic formats is essential for the DT workflow in construction projects, so protocols and algorithms development for this purpose are critical topics for future research. According to Boje et al. (2020), the interoperability problems have already been the topic of studies on BIM and multi-dimensional (nD) modeling, which refers to BIM domains, uses, or use cases in different contexts. For example, 4D modeling is related to the "time" dimension, so all the analysis of the represented processes occurs from a temporal perspective. The complex nature of nD models, general problems of cohesion, and poor synchrony have left BIM lacking in interoperability and automation. This lack can hinder the required real-time connection in DT. Schemes such as the IFC have improved the exchange of information and collaboration in BIM applications. Still, the authors point out that an eventual transition from the IFC format to a more open and web-linked data paradigm would ensure that the correct data will be available at the right time. According to the authors, solutions to link data in BIM have been proposed in the literature. For example, semantic web-compatible formats, such as OWL and RDF. Therefore, developing a common semantic web platform for DT with IoT and AI could be a big step towards interoperability and expansion into future lifecycle stages. Following another approach, Jiang et al. (2021) mentioned that blockchain could provide unified standards and protocols to support transparent and secure information sharing in DT.

5-COST CONTROL AND MANAGEMENT

Many authors have discussed the cost savings generated by DT adoption in the project life cycle management (Marocco & Garofolo, 2021; Weber-Lewerenz, 2021; Lee et al., 2021; Sepasgozar, 2021; Jiang et al., 2021; Schimanski et al., 2020; Boje et al. 2020). Smart and lean construction supported by DT can further reduce waste and energy consumption, for example. However, despite the relevance of this aspect, only Opoku et al. (2021) briefly considered the cost implications of implementing the DT. According to the authors, an adequate cost estimate for the application of DT depends on the scope and objectives involved so it can vary depending on the level of sophistication required. Generally, despite involving high initial investments, DT tends to present a cost reduction throughout the project life cycle, in addition to the compensation generated by the savings resulting from its application. No further details are provided.

6-CYBER SECURITY AND INTELLECTUAL PROPERTY RIGHTS

Some aspects that require attention in the design of DTs are data security, data protection, data ownership, level of accessibility by each stakeholder, privacy, and prevention of cyberattacks (Weber-Lewerenz, 2021; Marocco & Garofolo, 2021; Boje et al., 2020; Sacks et al., 2020; Mêda et al. 2021; Sepasgozar, 2021). The responsible sharing of information among the stakeholders involved in DT applications requires that all data transactions be tamper-proof, transparent, traceable, and reliable, minimizing any possibility of manipulation (Lee et al., 2021). Blockchain integration with DT can provide needed decentralization and security to ensure immutable data exchange among various stakeholders (Sepasgozar, 2021; Marocco & Garofolo, 2021; Lee et al., 2021; Jiang et al., 2021). Lee et al. (2021) proposed a DT integrated into a blockchain framework to support responsible information sharing in construction projects. A possible application is in the execution of smart contracts, a self-executing contract protocol capable of automatically facilitating, verifying, or enforcing established terms, including purchase and payment agreements. For example, a smart contract can automatically signal the supply chain to stop production/shipment of offsite products if there is any delay in the onsite assembly schedule. This action can save logistics costs, ensuring that only the right material is in the right place and at the right time, following lean principles. Jiang et al. (2021) proposed a blockchain-enabled cyber-physical smart Modular Integrated Construction (MiC) platform. The authors also pointed out that blockchain facilitates security and privacy for exchanging data and sharing services in DT workflows.

7-INSUFFICIENT DEVELOPMENT OF DT

DT adoption will require many multidisciplinary skills. In addition, new business models will be critical to ensure the delivery of technical aspects of DT. The analyses by Sacks et al. (2020) indicated that the Construction Tech startup companies would probably be better positioned to promote the expected transition to DT than traditional construction companies. Although many startup companies that monitor construction sites have emerged in recent years, the efforts still have been isolated, not achieving a coherent DT whole. Currently, there is a lack of a common framework for creating DT models on a large-scale (Sepasgozer, 2020, Boje et al., 2020). Concerning lean construction, Sepasgozar's et al. (2020) findings suggest "a large clear gap in understanding synergetic interactions of the lean concepts and the combination of digital information and sensor-based technologies in specific fields of construction". This topic should motivate future research. Currently, researchers have been investigating requirements for value creation, provision of insight, security, quality, federation, and curation to support DT adoption (Sacks et al. 2020). Weber-Lewerenz (2021) also suggests a strong need for future guidelines, standards, and binding rules, also in legislation, to support the construction digitalization process (including DT adoption) with moral and ethical principles.

DISCUSSION AND FUTURE DIRECTIONS

The discussion in the literature about the cognitive and technical levels required of people is still developing. There will be a need to clarify individuals concerning the value delivered by the DT, considering that it is an emerging concept. An awareness strategy can help as a first step to reducing problems with possible cultural or psychological boundaries. Besides that, while there is a need for educational approaches to help with the required new multidisciplinary skills, the construction industry still faces old challenges related to workforce skills. There are still existing problems with waste, low productivity, and organizational fragmentation that require a change in the workflow basis. Therefore, complete DT integration with the lean construction principles will be essential to achieving an effective digital transformation in construction.

Many authors have discussed the technology and infrastructure aspect and pointed out future directions for research and development in areas such as data science, IoT, and BIM semantics. However, the review suggests that related technologies have not been tested enough in the complex environment of the construction site, which involves the dynamic interaction of diverse physical resources on many work fronts. In environments such as smart manufacturing, the main product generally moves along production lines at the pace of machines. In construction, the main product remains fixed while physical resources move around. This aspect becomes a challenge in DT modeling compared to other industries. To ensure DT's usefulness, the simulations must consider many variables linked to the behavior of many people working on construction sites and the flow of many materials and equipment, which can involve a high level of complexity. Besides that, currently available DT support tools are poorly integrated. For example, there are technologies, such as laser scanners, to derivate BIM models from point clouds, but few solutions make this model fully operational. There are also solutions for displaying sensor data in the BIM model. Still, the possible analysis does not leverage all the model potential – the model only organizes which entities pertain to a specific dataset.

On the other hand, there are efforts in the literature to deal with standards, complex challenges, and specifications, which will probably be reflected in practical application problems. Insufficient information about the related cost is another practical problem that can hinder DT adoption in construction. Users need to consider the balance between costs and benefits brought by DT before adopting it. The costs involve at least hardware/software/services to monitor and manage the entire construction site, including many work fronts. Considering the complexity, the cost to implement DT on the construction site will probably be higher than the cost to implement DT on the shop floor, for example. DT can benefit from the existing blockchain and BIM frameworks concerning cyber security. The results suggest that there is still a large field for further research on DT with lean integration. To Sacks et al. (2020), implementing the DT will require overcoming technical, sociological, organizational, and commercial barriers. The present study explored some aspects related to the challenges for practical application in the construction site that should be considered for future implementations of the DT for construction. Some future research directions for DT with Lean Construction are suggested in Table 2.

Table 2: Research directions based on the seven challenges.

Challenges	Research directions
1	What skills and training types will be required to adopt DT? How can DT with Lean contribute to improving workflow and reducing waste, considering different levels of knowledge of workers and different work fronts? Investigating the experience with other Industry 4.0 technologies can provide some insights.
2	How can the existing practice of BIM nD support simulations in DT for construction sites? How can Lean (and approaches such as location-based management systems) organize and make the results more predictable? How to implement the continuous information loop from the construction site and management actions to ensure that the work execution follows the pace planned? How predict or manage the behavior of a work team? How to include and model the supply chains?
3	What are the main commercial tools available for DT layers and their current maturity level? Considering lean principles, what are the requirements for enabling its integration into business model platforms?
4	What standards and specifications are required to integrate models, interfaces, protocols, and data involved in DT for construction?
5	What services and elements should be represented in DT? Does it make sense, for example, to consider only the services that are on the critical path, aiming to reduce the costs of construction site monitoring? What is the required maturity level for the DT development to balance the processing cost and the added value to the construction project?
6	How can workflows adopted in the BIM context contribute to cyber security and intellectual property rights in DT implementation?
7	There are still many gaps for future research, such as clarifying concepts; developing guidelines, standards, and binding rules; creating new business models, and increasing the synergy with lean principles.

CONCLUSIONS

This paper contributes to the body of knowledge by reviewing the current research on the integrated use of DT and lean for construction projects, considering existing practical challenges. A total of 14 articles were identified and reviewed. The content analysis of the existing literature suggests that although DT is a recent research trend, there is still a large field for further research, mainly on practical integration with required technologies and lean principles. The results indicate that while the construction industry is probable to face the same general challenges as other industries in implementing DT, such challenges may become more complex due to the dynamic and unique nature of the construction site. This article contributes to some future research directions based on the seven related challenges. It is expected that they can guide other studies on the subject. It is recommended that the academic community and practitioners consider these challenges to support a deeper investigation of the synergy between lean construction principles and DT in future work.

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ROBUSTNESS OF WORK SAMPLING FOR MEASURING TIME WASTE

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ABSTRACT

Construction can be considered a socio-technical system, which is challenging to model due to the many agents interacting either in a managed way or autonomously. Therefore, cause and effect models are hard to validate, and a traditional correlation approach is insufficient. In this study, the method of robustness testing was applied to test the effect stability when assumptions of a model are changed. The research objective is to apply robustness testing on WS data to assess the robustness and validity of the WS method. An actual refurbishment project was the case for this study, where data was acquired through nine days of continuous WS application. Time-series data were grouped into Direct Work (DW), Indirect Work, and Waste Work. Several different robustness tests were applied. It can be concluded that the WS method is robust, i.e., the effect (DW) is stable even if the assumptions are changed severely. Deleting 90% of the sample does, for instance, almost not change the effect. Likewise, if errors are infused into the sample, the effect is stable. Also, if certain structural parts are excluded from the sample, e.g., observations during morning startup, etc., the effect is still stable.

KEYWORDS

Value stream, Waste, Trust, Robustness, Work Sampling

INTRODUCTION

Construction is often described as a complex project system (Bertelsen, 2003; Lindhard & Wandahl, 2013). The concept of why and how a project is complex has developed over time. Williams (1999) describes two dimensions of complexity. Firstly, structural complexity (Baccarini, 1996) is the number of elements in a system and the interdependence of the elements. Elements can be both organizational and product-wise. Secondly, the degree of uncertainty in both how well defined the project's goals are and how well defined the methods of achieving those goals are. Later, three additional dimensions of complexity were added to the understanding (Geraldi et al., 2011). The first, dynamics, refers to changes in projects, i.e., changes in specifications. Changes are enforced on a project from both outside and inside. Changes lead to rework, disorder, and

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inefficiency. The second, pace, is a type of complexity, as urgency and criticality of time and goals require managerial attention. The third, socio-technical complexity, is supported by a strong stream of research that stresses that projects are carried out by human actors with potentially conflicting interests and incompatible personalities.

All of the abovementioned dimensions of complexity are often present in large construction projects, sometimes resulting in poor performance. Both an effort to analyze root causes of low performance and an effort to improve performance by infusing new innovations, structures, procedures, etc., depend on the rationale that nothing happens without reason, i.e., effects have causes. Due to the complexity of construction, it is difficult to use a simple correlation of one effect based on one cause. Thus, it is very hard in construction to prove a causal relationship of performance and cause.

Nonetheless, academics often try to develop different models of construction that attempt to show how a complex socio-technical system like construction works. The purpose of a model is usually to visualize, understand, or optimize. They can range from simple models with few variables and components (e.g., input-output model or a black box diagram) to larger and more complex models with many variables and components (e.g., Building Information Modeling (BIM) including time). The beauty of a model is that it is not reality; it is a simplification. This fundamental understanding of the abstraction is frequently forgotten or misunderstood, as some researchers and practitioners tend to think that a model is a one-to-one representation of the real world. Many models are either misinformed. i.e., contain errors, wrong assumptions, etc., or are under-informed, i.e., too little data and information levels are too low. It can rightfully be assumed that most models are misinformed or under-informed; thus, they are challenged on their validity (Neumayer & Plümper, 2017).

Accepting that models are only a simplified representation of a social-technical system gives rise to the importance of assessing a model's validity. Determining the strength of a correlation of two variables as a means of validity for a cause and effect is insufficient given the complex nature of construction projects. Instead, robustness can be introduced to determine how valid a model of a social-technical system, like construction, is. Robustness is a way of assessing the effect stability of a model when assumptions and structures of the model are gradually changed (Neumayer & Plümper, 2017).

The objective of this research is to devise a method for assessing the robustness and validity of the WS method.

The following part of the paper describes the theoretical background in two parts. First, Work Sampling as a way of measuring and modeling time waste in construction. Second, Social Complexity and Robustness as a method of assessing a model's validity.

MODELING TIME WASTE IN CONSTRUCTION

One of the areas, the Lean Construction community has struggled to model, is measuring time waste. Questions like 'how can time waste be measured?', 'what are the root causes of time waste?', and 'how does implementing Last Planner and other Lean approaches reduce time waste?' are addressed in several research studies, e.g., (Bølviken & Kalsaas, 2011; Kalsaas et al., 2014; Lerche et al., 2022; Neve et al., 2020; Wandahl et al., 2021).

Bølviken & Kalsaas (2011) recognized a need for a more valid method for measuring time waste. Thus, they reviewed a number of direct and indirect measurement methods, and Kalsaas (2011) concluded on the method selection that a suitable method for measuring workflow should mainly be based on the Work Sampling (WS) method.

WORK SAMPLING TO MEASURE TIME WASTE

The WS method has been used for decades to collect data on the amount of value-adding work time, referred to as Direct Work (DW) in the WS method (Gong et al., 2011). WS is a quantitative method applying direct observations to obtain data on how workers use their time on the construction site. In general, WS has been applied throughout time to improve, often single construction projects regarding efficiency, construction labor productivity, and construction cost and time. Thomas (1981) provides relevant insights on how a WS study can be planned and how the collected data can be analyzed. In this research, the present authors apply a more statistical approach to WS in order to validate the robustness of the method in general. However, the authors still acknowledge that WS should mainly be applied to improve a single construction project.

The WS method quantifies how much time workers use on direct work and other categories of preparatory work and waste work. All WS studies apply a DW category. However, the picture is more blurred when it comes to the preparatory and waste work categories. Some studies categorize all none direct work time as waste, while other studies have a more detailed view of non-value-adding work. Generally speaking, non-value-adding work time can in WS be divided into Indirect Work (IW) and Waste Work (WW), resulting in WS having three categories of time; DW, IW, and WW. Work Sampling and, in particular, the share of DW's relation to productivity has been debated throughout time, as DW directly influences the denominator and indirectly the numerator of the productivity equation. However, recent studies conclude that DW is statistically significantly correlated to construction labor productivity at activity, project, and national levels (Araujo et al., 2020; Neve et al., 2020; Siriwardana et al., 2017) and, thus, can be applied as an acceptable indicator for productivity.

CRITIQUE OF WORK SAMPLING

Wandahl et al. (2021) identified 474 case studies where WS was applied in construction. Thus, it can be concluded that the method is widely used. Nonetheless, a severe critique of the method exists, e.g., Josephson & Björkman (2013). Several of the critical points are related to the robustness of the WS method and the potential lack of causality.

Categorizing work activities into direct work and subcategories of preparatory and waste work is very inconsistent (Josephson & Björkman, 2013; Wandahl et al., 2021). This makes cross-case comparison difficult, like any longitudinal meta-analysis (Horman & Kenley, 2005; Josephson & Björkman, 2013). However, it seems that the consequence of inconsistent categorization has not been further researched. In relation to the categorization, Johansen et al. (2021) discovered that, in particular, preparatory work is often considered as direct work by many practitioners and also by some academics. This despite that Ohno (1988) clearly articulated which kinds of activities are value-adding and which are not. The inconsistent understanding of value-adding and non-value-adding work has also led to a critique of WS relying on individual observers (Jenkins and Orth, 2004; Josephson & Björkman, 2013). These observers might be biased and have a non-aligned understanding of waste and value (Neve et al., 2020).

CAUSAL COMPLEXITY AND ROBUSTNESS

When developing a model based on empirical data, it is an interpretation of the actual phenomenon. To capture the true processes of a complex world, researchers would need to precisely know the set of regressors, include all relevant variables and exclude all irrelevant variables, operationalize and measure these variables correctly, etc. (Neumayer & Plümper, 2017). This is not possible. Researchers today agree that a model cannot be specified correctly due to causal complexity. Traditionally, the strategy is to apply assumptions and to accept underdetermined models. The aim of an underdetermined model is a simplified model. However, underdetermination often ends in misspecification, as it requires intensive knowledge to simplify in a valid way (Neumayer & Plümper, 2017). The misspecification of models is a well-known problem, and as Box & Draper (1987) concluded: "*All models are wrong, but some are useful.*" Therefore, researchers must find the optimal trade-off between simplicity and generality to ensure models are not misspecified, as misspecified models lead to biased conclusions.

Causal complexity is an extension of the causality concept, which is often related to correlation. Causality is the study of how things influence one another and how causes lead to effects. There are a number of basic assumptions in a classical (and physics-related) understanding of causation. Firstly, things (effects) have causes. They do not just happen of their own accord. Secondly, effects follow causes in a predictable, linear manner. E.g., concrete cures faster if you increase the ambient temperature. Thirdly, big effects can grow from several small causes, e.g., several minor variations in activity durations can suddenly cause a delay of an entire construction project. Having identified a cause-effect relationship, it often becomes relevant to measure the strength of this relationship. As elaborated later in this paper, it can be difficult to precisely express and measure the strength of such a cause-effect relationship. Often, statistical measures are applied to consider the relationship between two variables, a course variable (the predictor variable) and the effect variable (the response variable). This is referred to as the statistical correlation of cause and effect. However, correlation does not always imply causation. It is two different measures that can, however, be coinciding. In the world of classical physics, this is often the case, and correlation can be a good indicator of, e.g., the causation between ambient temperature and concrete maturity.

CAUSAL COMPLEXITY

Causal complexity is the interpretation of cause-effect in social science. It differentiates from the classical understanding of causation on five important dimensions (Neumayer & Plümper, 2017): (1) Cause-effect relationships in the social world are probabilistic instead of deterministic, therefore, the probability of an effect is a continuum from 0 (a cause does not have an effect) to 1 (the cause is deterministic); (2) Causal complexity is the existence of conditional causal effects and heterogeneous causal effects. Some causes only have an effect if certain conditions are satisfied (Franzese, 2003); (3) The timing of cause and effect. Scholars all too often implicitly assume that an effect occurs immediately after a cause. Yet, effects can occur with a delayed onset; (4) In the real world, effects can precede causes. Human beings have rational expectations about potential future effects and may already act on their expectations rather than on the cause itself. This is called the Cause-precedes-law; and (5) Effects can affect non-treated causes. In the social world, spill-over effects from the treated to the untreated are likely.

ROBUSTNESS AND ROBUSTNESS TESTING

Acknowledging the existence of causal complexity as the boundary conditions for causes and effects on construction sites, another measure than the traditional correlation assessment is needed to assess the strength of a relationship between variables in a model built to simulate construction. Instead, the model's robustness must be tested by systematically removing or changing the assumptions. However, it is difficult to give an unequivocal definition of robustness, as this concept is differently defined in several domains. When investigating the different application domains of robustness, the lack of a unique definition becomes visible. In project management, Robust Decision Making is defined as "*a set of concepts, processes, and enabling tools that use computation, not to make better predictions, but to yield better decisions under conditions of deep uncertainty*" (Lempert, 2019). This is similar to the definition of robustness in statistics, which is "*Robust statistics addresses the problem of making estimates that are insensitive to small changes in the basic assumptions of the statistical models employed*" (Fabozzi et al., 2014). Insensitivity is also the core of robustness in scheduling, as "*a schedule is robust if its performance is rather insensitive to the data uncertainties [...]*" (Billaut et al., 2008). In this research, robustness is defined in a simple way as "effect stability." In WS, this equals measuring DW and $CI_{95\%}$ stability when assumptions and sample size are altered.

When acknowledging construction sites as a phenomenon in which causal complexity exists, a need to investigate any model of that phenomenon for robustness arises. The robustness testing is to test and analyze the uncertainty of a model and test whether estimated effects of interest are sensitive to changes in model specifications. The literature describes an extensive range of robustness grouped into model variation, permutation, limit, and placebo tests. The following method section describes which robustness tests were applied in this research.

RESEARCH METHOD

The WS method was used in the case study to collect a data set that could be used for robustness testing. The case consisted of a social housing refurbishment project of 24 five-story buildings. The main renovation tasks were related to carpentry work, such as replacing windows and roofs and installing new ventilation and electrical systems.

WS data were collected during nine days, named Day 1 to Day 9, with observations from work begins in the morning until work ends in the afternoon (i.e., from 07.00-15.30, excluding break times from 09.00-09.15 and 11.30-12.00). Two different observers, named Observer A and B, randomly toured the construction site. The WS method was applied in seven trades, constituting 40 workers. After completing the nine days of data collection, 1,550 random observations (representing a sample of N=1,550) were recorded with a 95% confidence interval ($CI_{95\%}$) of ± 3.42%. In order to avoid patterns of behavior and to reduce the variability of the measurement, the authors collected a homogeneous sample. The average of the sample was 172 observations per day, with a standard deviation of around 43 observations, through the nine days of data collection (see the table in Figure 1), resulting in around three observations every 15 minutes. In this study, a six-work category classification was adopted. The applied categorization follows the method of Activity Analysis (CII, 2010), which outlines which work activities must be put into which categories.The six categories are: (1) production, e.g., installing gypsum boards; (2) talking, e.g., discussing the installation process; (3) preparation, e.g., measuring with a ruler; (4) transportation, e.g., carrying tools; (5) walking, e.g., moving empty-handed; and (6) waiting, e.g., delaying action until receiving material.

ROBUSTNESS TESTING

After data collection was completed, robustness testing was applied. Robustness testing was conducted in four steps, according to the approach outlined by Neumayer & Plümper (2017): (1) Define the subjectively optimal specification for the data-generating process at hand, i.e., the baseline model; (2) Identify assumptions made in the baseline model, which are potentially arbitrary; (3) Develop models that change one of the baseline model's assumptions at a time; and (4) Compare the estimated effects of each robustness test model to the baseline model and compute the estimated degree of robustness.

Step 1: Defining the baseline model

The first step consisted of defining the baseline model. In this case, the baseline model was the actual WS data collected, consisting of the 1,550 random observations collected. Figure 1 shows the results of the baseline, including a stabilization curve, 95% confidence interval, split between the WS categories, and information on the data collection.

	N	DW	IW	WW
Day 1 (Tue)	210	25%	51%	24%
Day 2 (Wed)	245	15%	49%	36%
Day 3 (Thu)	161	30%	60%	9%
Day 4 (Fri)	110	34%	55%	11%
Day 5 (Mon)	207	24%	62%	14%
Day 6 (Tue)	156	19%	58%	23%
Day 7 (Wed)	184	32%	45%	23%
Day 8 (Thu)	152	20%	51%	29%
Day 9 (Fri)	125	30%	46%	24%
Total	1550	25%	53%	22%

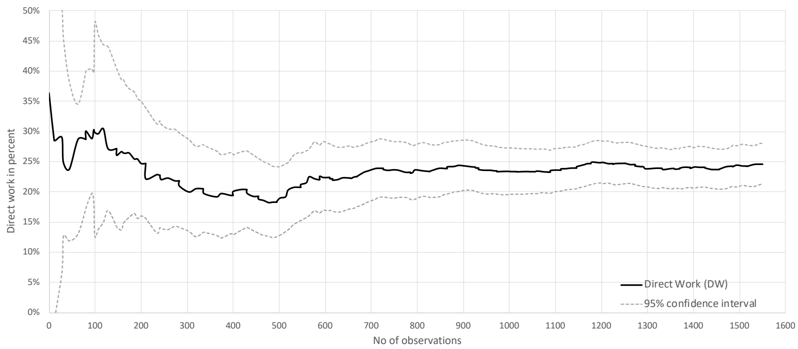

Figure 1: Baseline of work sampling data.

Step 2: Defining assumptions in the model

The second step, defining assumptions in the WS model, was a brainstorming session to identify important assumptions. Five fundamental assumptions in the WS model were identified (i) Each workday is similar, i.e., observations are uniform; (ii) Direct Work stabilizes after around 550 observations; (iii) Productive and preparatory work can be distinguished based on momentary observations; (iv) A few observation errors do not influence the overall result; and (v) Results are independent of the observers.

Step 3: Defining Robustness test models

Three different types of robustness tests were applied: (1) Model variation; (2) Randomized permutation; and (3) Structured permutation. In the Model variation tests, assumptions (i) & (ii) are tested. In the randomized permutation tests, assumptions (iii) & (iv) are tested. In the final structured permutation test, assumptions (i) & (v) are tested.

Firstly, the model variation tests change one, or sometimes more, model specification assumptions and replace them with an alternative assumption. Our analysis changed the sample size, both reversibly, by deleting data points from the end of the data collection period towards the beginning, and randomly from 0% to 100%. A Monte Carlo Simulation of 500 simulations was conducted for each alteration to analyze the effect stability (change in DW and 95% Confidence Interval, $CI_{95\%}$).

Secondly, a randomized permutation test was conducted on different assumptions. Random permutation tests change specification assumptions repeatedly. Errors were infused randomly into the sample to monitor effect stability in one analysis. Again, 500 runs of Monte Carlo Simulation were conducted. An error is a faulty observation, i.e., interpreted or noted into a wrong category in the WS study. It is common that production, preparation, and talking get confused and wrongly noted. This was analyzed, applying Monte Carlo Simulation to investigate the effect stability.

Thirdly, a structured permutation test was conducted on the specific assumption in the WS model. Structured permutation tests change a model assumption within a model space systematically. Changes in the assumption are based on a rule rather than random. Different structures, i.e., parts of the sample, were deliberately excluded in the Monte Carlo simulation, like specific days, the first hour, observation after lunch, observer 1, observer 2, etc. Again, the effect stability on DW and $CI_{95\%}$ were observed.

Step 4: Robustness testing analysis
The fourth and final step, comparing results to the baseline, was conducted to discuss and interpret the results. Lastly, the authors presented some of the main implications for practitioners of the present analysis.

FINDINGS – INTERPRETING THE ROBUSTNESS TESTING

MODEL VARIATION TESTS

The model variation tests investigated the effect of stability when changing the sample size. The first test was to reduce the sample size reversibly, starting from N=1,550. The effect is illustrated on the stabilization graph, cf. figure 1. DW is stable from N=700, which is after day 4. In other words, reducing the sample size by 55% did not influence DW or the 95% confidence interval. Another approach was to reverse the sample size until DW exceeded the final 95%-confidence interval. At N=1,550 DW is 24.65% and $CI_{95\%}$ is ±3.42%. The sample size was, thus, reversed until it exceeded 24.65%±3.42%, which occurred at N=559 (after day 3), where the lower confidence interval was exceeded.

A second model variation test reduced the sample size randomly. A random reduction is an irreversible reduction of the sample size. Table 1 illustrates the effect stability of DW and $CI_{95\%}$ corresponding to a random deletion of observation, i.e., a random reduction of sample size. Results are based on 500 Monte Carlo simulations.

Table 1: Random deletion of observations resulting in a random decrease in sample size.

Sample	N	DW	$CI_{95\%}$
Baseline (N=100%)	1,550	24.65%	3.42%
Random (N=90%)	1,395	24.54%	3.49%
Random (N=80%)	1,240	24.61%	3.62%
Random (N=70%)	1,085	24.51%	3.74%
Random (N=60%)	930	24.57%	3.91%
Random (N=50%)	775	24.56%	4.18%
Random (N=40%)	620	24.47%	4.48%
Random (N=30%)	465	24.61%	5.01%
Random (N=20%)	310	24.45%	5.81%
Random (N=10%)	155	24.78%	7.51%

Table 1 shows that a random decrease in sample size had almost no influence on DW but clearly increased the $CI_{95\%}$ interval, making the data less valid. Nonetheless, reducing the sample size by 50% only increased the $CI_{95\%}$ by 22.22%.

RANDOMIZED PERMUTATION TESTS

The first randomized permutation test investigated assumption (iv) by looking at the effect stability if the observer made mistakes. There are two types of mistakes;

misinterpreting an observation and assigning an observation to the wrong trade or work samling category. 500 Monte Carlo simulations were conducted for each change, cf table 2. Table 2 shows that randomly changing categories affected both DW and $CI_{95\%}$, however, the impact was insignificant. 20% error equals 310 errors or 4.6 errors per observed hour, which impacted DW with 10.5%.

Table 2: Random error in categories.

Sample	N	DW	$CI_{95\%}$
Baseline	1,550	24.65%	3.42%
5% error, Random category	1,550	23.92%	3.37%
10% error, Random category	1,550	23.39%	3.32%
20% error, Random category	1,550	22.07%	3.21%
30% error, Random category	1,550	20.85%	3.10%
40% error, Random category	1,550	19.58%	3.02%

The second random permutation test was more realistic, as it is not likely that the observer mistakes, e.g., walking for production and so on. Realistically, the observer could misinterpret preparation with production and vice versa, and talking with production and vice versa. The effect stability of such confusion is shown in table 3. Once again, the results in table 3 were based on 500 Monte Carlo simulations.

Table 3: Production to preparation and vice versa.

Change	Baseline $DW \pm CI_{95\%}$	5% $DW \pm CI_{95\%}$	10% $DW \pm CI_{95\%}$	15% $DW \pm CI_{95\%}$	20% $DW \pm CI_{95\%}$	25% $DW \pm CI_{95\%}$
Preparation to production	24.65% ±3.42%	25.87% ±3.47%	27.11% ±3.51%	28.13% ±3.55%	29.47% ±3.60%	30.72% ±3.64%
Talking to production	24.65% ±3.42%	24.80% ±3.42%	25.41% ±3.43%	25.96% ±3.44%	26.32% ±3.45%	26.50% ±3.45%
Production to talking or prepa.	24.65% ±3.42%	23.30% ±3.31%	22.11% ±3.21%	20.71% ±3.09%	19.79% ±3.01%	18.39% ±2.88%

Table 3 shows that a change from the value-adding DW category to the preparatory category of Indirect Work or vice-versa influences the DW. Johansen et al. (2021) concluded that the observer misinterpreting preparation as production is the most common error. If 25% of the preparation observations are misinterpreted or wrongly assigned to production, DW is 30.72%, which almost equals one-third of the work time. One-third of the work time being productive is often referred to as state-of-the-art.

STRUCTURED PERMUTATION TEST

A structured permutation test infuses structured and logical changes in the baseline model. Table 4 shows that most of the structured exclusions had a limited impact on the stability.

In this case, assumptions regarding the uniformity of observation days and time of the day, and the independence of the observer were analyzed. The sensitivity of DW and $CI_{95\%}$ were analyzed based on excluding designated parts of the sample as described above. Only excluding the first, the last, or both the first and last hour of the day had an impact on the DW stability higher than 1 percent point. Most significant is the result when observer A or B is excluded. This has a significant impact on the average DW and the confidence interval.

Table 4: Exclusion of structured part of the Work Sampling.

Sample size	N	DW	$CI_{95\%}$
Baseline	1,550	24.65%	3.42%
Excluding mornings (from 07.00-11.00)	676	24.70%	5.08%
Excluding afternoons (from 11.30-15.30)	874	24.60%	4.66%
Excluding first hour (from 07.00-08.00)	1,310	26.95%	3.76%
Excluding last hour (from 14.30-15.30)	1,443	25.71%	3.61%
Excluding both the first and last hour	1,203	28.43%	3.99%
Excluding observer A	398	25.88%	8.26%
Excluding observer B	697	27.40%	4.32%
Excluding Mondays	1,343	24.72%	3.76%
Excluding Tuesdays	1,184	25.34%	4.11%
Excluding Wednesdays	1,121	25.60%	3.99%
Excluding Thursday	1,237	24.41%	3.68%
Excluding Fridays	1,315	23.35%	3.62%

DISCUSSION

In WS, there is an assumption that the share of DW is an effect of efficient management and planning. However, there is no single cause variable, as multiple factors will affect the DW share. Therefore, WS does not fit well with the traditional concept of causality. Josephson & Björkman (2013) argues that WS can not be used for cross-case comparisson as there are too many factors influencing the share of DW. In other words, a single cause-effect relationhsip can not be devised based on WS, which is a limitation of the method. This research confirms that limitation. WS and DW as a response variable should instead be understood in the light of causal complexity.

The five dimensions in causal complexity suit well with WS. Improved management and planning have a probabilistic impact on DW and cannot be modeled with 100% precision. In addition, the effects are heterogeneous and depend on an unknown mix of conditions. WS is time-sensitive because one cannot expect the effect (improved DW share) right after implementing new management and planning initiatives. It might be delayed, and it might fluctuate. As construction is a social-technical system with many actors, improved DW might be measurable without any causes implemented, merely due to the expectation of effects among workers. Moreover, there is a likely spill-over as one trade with optimized planning and management can improve DW of other trades that have not received implementation. Based on these five dimensions, causal complexity can be used to understand and reject some of the critique of work sampling that has been raised based on a traditional correlation and cause-effect thinking.

The robustness testing of WS also can reject some part the WS critique, i.e. lack of causality. However, the critique rasied that the misinterpretation of VAW and NVAW will influence the WS result still remains. Also the dependence of the observer was raised as a critue, and this has also not been possible to reject based on the robustness testing.

IMPLICATIONS FOR PRACTITIONERS

The results provided a new angle to the body of knowledge for WS by utilizing the robustness method to understand WS measures, contributing to the ongoing discussion of productivity in both construction (Neve et al., 2020) and offshore wind (Lerche et al., 2022). However, it also raises a question regarding the levels of productivity that today are considered state-of-art. In particular, if DW is not adequately separated from IW and WW. As the random permutation test in table 3 showed, an incorrect categorization of an observation (production vs. preparation and talking) will have a direct impact on DW. That is, 10% faulty registration will result in a change in DW of 10%. Therefore, the WS method is still considered sensitive toward the categorization of observations.

On the other hand, the structured permutation test showed that the WS is robust towards structural changes in the observation patterns. Most structural changes in observation patterns only had a limited effect on DW. However, excluding the first and last hour of the day did have some impact. This can be explained by the start and stop of the day, where less production is going on, as time is spent on preparing, moving, cleaning, etc. This is in line with Neve et al. (2020), who concluded that inparticular starts and stops are critical to gaining high labor productivity.

From a practical perspective, the findings show how misinterpretation of work categories can transform less promising results into state-of-art results. Meanwhile, the robustness testing also revealed that random sampling, even with fewer observations, can still be considered significant and provide a proper indication of productivity. Therefore, the methodology can easily be applied by practitioners without being too worried about the potential faulty application.

CONCLUSION

This research aimed to apply robustness testing on a WS data set gathered in a real construction project to assess the robustness and validity of the WS method. That objective has successfully been achieved.

This paper discussed that the widespread assumption considering that the share of time spent on DW in the construction process is an effect of efficient management and planning cannot be explained considering a single cause variable, as multiple factors will affect the DW share. Because of that, the robustness test can be considered a suitable method to test and analyze the uncertainty of the work sampling method.

After analyzing the data collected in a single case study, it can be concluded that the WS method is robust. Three different types of robustness testing were conducted, and most changes in assumptions, sample size, structure, and internal logic in the WS method only had a limited effect on the average DW result and its confidence interval. Most of the critique of WS cited in this work can, thus, be refuted. Only the dependence of the observer and the categorization of DW and preparatory work need attention and require more research in the future to conclude upon finally.

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COLLABORATIVE METHOD FOR TRAINING AND IMPLEMENTING THE LINE OF BALANCE

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ABSTRACT

The Line of Balance (LOB) is a planning technique that has been used for more than 30 years in construction. However, what is rarely discussed is how the LOB should be applied in projects already in progress. This research was developed in the Design Science Research (DSR) format and sought to analyze how LOB can bring about significant changes in the management of collaboration, planning and production. This paper puts forward a collaborative method of training on LOB in projects that are already in progress for which it draws on a two case studies on multifamily residential building. The benefits of LOB for those involved in the workshop were collected by gathering multiple pieces of evidence and analyzing the correlations. In the participants' perception, there are three main benefits concerning to adopting LOB: (i) understanding the sequencing of activities and how to achieve the uninterrupted flow of teams; (ii) assessing the risk of mobilization and remobilization; (iii) assessing milestone dates and constraints. Moreover, participants´ perception, the training had a excellent evaluation, and it contributed to increasing their collaboration and engagement in relation to the planning of the project.

KEYWORDS

Lean Construction, Line of Balance, Collaboration, Visual management, Design Science

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INTRODUCTION

Several authors have pointed out the low application of more visual long-term planning techniques, which enables both collaboration between the management and production teams and a better understanding of the flow and rhythm of activities has been pointed (Bulhoes; Formoso, 2005; Viana et al., 2010).

One of the techniques that has been acknowledged by bringing more transparency to the long-term plan is the Line of Balance (LOB). It graphically represents production flows over time, where the y axis refers to the location units and the x axis to time (Biotto, 2019). For Mendes Jr; Heineck (1999), in the LOB, the trajectory of the teams, the durations and the locations of the tasks at a given moment can be visualized.

According Olivieri et al., (2019) and Lucko (2014), LOB belongs to a family of location-based planning methodologies that are workflow-oriented, such as the Linear Scheduling Method (LSM) or flowline, repetitive scheduling method (Harris;Ioannou, 1998), and location based management system (Kenley;Seppännen, 2010). These methodologies show similarities in objectives such as reduce WIP by fixing a production rate between activities, (Biotto, et al. 2017) and to increase the continuous use of resources and how uniform these resources are distributed (Ungureanu et al., 2019; Lucko et al., 2014). However, Su;Lucko (2016) claim that the graphical visualization of multiple teams is only feasible for LOB.

Over time, several studies have been conducted that seek to strengthen applying LOB in civil construction, and have sought to demonstrate the tool's potential assistance in simulating scenarios (Kemmer, 2008; Valente et al., 2013), papers that provided evidence that less interference between teams results in productivity gains and less risk of demobilizing and remobilizing on the construction site (Kankainen;Seppänen, 2003). In the field of theory, Moura et al. (2014), based on a literature review highlighted that the LOB has a strong relationship with the concepts and principles of Lean Construction, as for example the concepts of production and tranfers batches, the importance of production leveling, the visualization of work-in-progress and the focus in reduce this type of waste, and the focus of synchronization in production.

Few studies assess teams' understanding of the benefits of LOB during their first contact with it. Moreover, studies do not usually discuss the implementation process when the project is already in progress. There are many contracts and teams already mobilized and of activities in execution. With regard to this, Mendes Jr (1998) proposed a methodology for applying LOB in buildings with multiple floors. The focus of his study is to draw up a pre-plan of the macro activities of the entire works, but the paper does not point out any evidence of the evaluation regarding the step-by-step process from the perspective of the teams that took part; Valente et al., (2014) propose guidelines to apply LOB in non-repetitive works, but the evaluation of the applications in a case study showed only either difficulties related to physical interferences that prevented the teams to attend the planned rhythm, or the need to increase the tools to support LOB when drawing up the schedule; Seppänen (2005) studied the benefits of using LOB in a commercial building, by applying site-based production control tools, the greater focus being on comparing control data and computer simulations, but with few interactions with project teams during construction and does not assess the construction team´s understanding of the proposed method.

Recent studies of LOB implementation take into account complex mathematical and statistical models for scheduling and balancing teams. Tokdenir et. al., (2019) presents a risk assessment of tasks based on scenarios with LOB, the analysis takes into account a

Monte Carlo simulation. Damci (2020) revisits the concept of natural rhythm of production, arguing that there is an optimization of team size for different tasks and that multiples of these teams transformed into workload must be used to calculate the necessary pace. Ammar (2019) proposes an interesting and counter-intuitive use of the LOB, where some tasks are interrupted to promote project optimization. However, these researches do not evaluate the understanding of the concepts that the tool proposes for the project stakeholders who make decisions based on the schedule information, also most of the research takes into account the application of LOB in an initial phase of the project and not discuss collaboration and commitment to the planning process in a hostile scenario.

Despite the growing use of LOB in companies in the sector, there are still few studies that present a method of implementation in works already started. The application of LOB “as imagined” suggest the start of this in an initial phase of the project, as many studies propose. However, sometimes the application of LOB “as done” happen when the project already started, and these projects presents, within the scope of planning, traditional methodologies already implemented, such as the critical path method (CPM). In addition, scenarios of delays in activities, interference between teams and WIP are expected in these situations. This is where the need for training the concepts and a change management strategy for stakeholder engagement arise in the face of the adoption of the new planning method using the LOB.

This study puts forward a collaborative method for training and implementing LOB in repetitive residential buldings that have already started. In addition, the project aims to train the management and production team in the concepts and techniques of developing the LOB. In the end, an evaluation was proposed based on two case studies of the perception of the people involved in the implementation concerning the processes of the framework and to the benefits pointed out in the literature.

This research aims to contribute with a methodology for projects in progress that wish to use the LOB to readjust the schedule, balance the teams and optimize resource deliveries.

RESEARCH METHOD

Design Science Research (DSR) was adopted in this research, which strategy is related to development and evaluation artifacts with a focus on solve practical problems (Hevner, et.al, 2004; Holmström et al. 2009). DSR was used as an interactive process between understanding a problem and developing a solution which are undertaken in incremental learning cycles (Lukka 2003). The artifact developed was a collaborative method for training and implementing the LOB in works that are in progress. The evaluation of this artifact was based on the employees' perception of the usefulness of the steps of the method and the benefits of applying LOB.

The method was applied in two case studies carried out in residential projects of company X, located in the Brazilian state of São Paulo. Company X was selected because it has been implementing the concepts and principles of Lean Construction and Last Planner ® aided by the authors of this paper who have acted as consultants to this company. Table 1 gives a brief description of each case study and the scope of action in relation to improving the method.

Table 1: Description of the projects and the scope of each case study

Case Study 1 – Project Description	Case Study 1 – Scope	Case Study 2 – Project Description	Case Study 2 - Scope
Low-end residential project, horizontal condominium, 13 towers with 4 floors	- Implement proposed method for collaborative Line of Balance Workshop;	Low-end residential project, horizontal condominium, 28 towers with 4 floors.	- Refine proposed method for collaborative Line of Balance Workshop;
Four apartments per floor, ranging from 43.06 to 56.98 m².	- Collect participants' feedback about the Line of Balance method;	Four apartments per floor, ranging from 43.06 to 46.7 m².	- Collect participants' feedback about the Line of Balance method;
48.4% executed from schedule		51.6% executed from schedule	
-14.3% deviation from the initial schedule		-15.0% deviation from the initial schedule	

The research followed the following steps: (i) determine the research objective theoretical framework; (ii) develop a method for applied LOB in projects in progress; (iii) evaluate the method based on the employees' perceptions; and (iv) tabulate and analyze data and draw conclusions. For the development step of the method, an artifact was developed and tested in two case studies (Table 2). The main sources of evidence and data collection procedures are summarized in Table 2.

Table 2: Main sources of evidence

Case Study	1	2
Duration	10 weeks	9 weeks
Participant observation in planning meetings	2 Line of Balance meetings	2 Line of Balance meetings
Direct Observations	20 one- to four-hour site visits	20 one- to four-hour site visits
Document Analysis	Schedule, weekly plans, control charts	
Interviews	Discussion of data with production managers	
Survey with participants	Survey related to benefits and collaboration of Line Balance workshop with 9 participants	
Total Hours	30	27

The development step of the method started with a literature review, a first version of the method was proposed on the basis of Kenley;Seppanen (2010), Mendes Jr;Heineck (1997) and Valente et al. (2014). In the first test round of the framework implemented in case study 1, it was necessary to collect data from the current scenario of the activities in progress in order to identify interferences between crews and remaining activities, this information would be the input for the start dates in the LOB in the current state. This collection was done through interviews with the participants and field observations, however, many noises in communication and conflicting information appeared. For the second round of the experiment, it was necessary to insert a subphase focused on analyzing the work-in-progress. In this subphase, the participants were gathered to map activities and units remaining in a visual board, the purpose of the tool was to facilitate the use of implicit knowledge and generate consensus on the information collected. At the end of the case study, the final version of the method was presented.

To evaluate the training method developed, an analysis of the benefits of applying the LOB included in papers already published by the International Group for Lean Construction (IGLC) was carried out. 17 articles were consulted. The list of benefits considered will be presented in the results.

COLLABORATIVE METHOD FOR TRAINING AND IMPLEMENTING THE LINE OF BALANCE

The final version of the method was presented, it is consists of two phases (Preparation and a Workshop) that together include 8 subphases as shown in Figure 1.

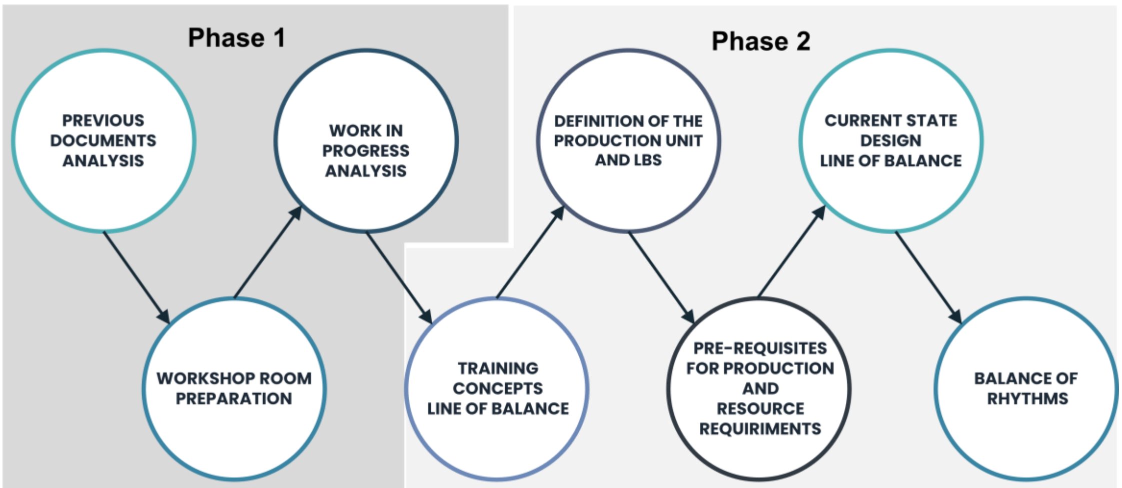

Figura 1- Method for Collaboative Line of Balance

Phase 1: Preparation

This phase includes three main subphases: (i) preliminary study of the project: a quantitative survey was carried out according to the physical locations of the project and the scope of the services. The productivities of construction services are estimated based on a historical company database, characteristics and size of the project; (ii) preparation of the "war-room" with visual management boards for the collaborative dynamics of the Line of Balance and the Balance of the Services; (iii) As these were construction services that were already in progress, a workshop of the work in progress analysis had to be carried out: the dynamics aimed to let the construction team clearly see the amount of work-in-progress of each service in each place of work. Based on this identification, the remain units of outstanding services in each location unit were recorded (Figure 2).

We can see the example in Figure 2 of the Pipes and Ducts / Shaft EPS activity pack with balance of 12 units in tower 3 side A and side B while the subsequent package Gypsum Plastering has balances in all towers before the third, that is, too much WIP.

	Tower 1 - Blocks A,B,C,D,E					Tower 2 - Blocks A,B,C,D,E,F						Tower 3 - Blocks A,B,C,D,E,F					
	1A	1B	1C	1D	1E	2A	2B	2C	2D	2E	2F	3A	3B	3C	3D	3E	3F
Structural Bricklaying	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Slab Concreting	0	0	0	0	0	0	0	0	0	0	0	4	4	4	4	4	4
Aluminum Window	0	0	0	0	0	0	0	0	0	0	0	4	4	4	4	4	4
Pipes and Ducts / Shaft EPS	0	0	0	0	0	0	0	0	0	0	0	12	12	8	8	8	8
Gypsum plastering	0	0	0	3	0	2	3	0	5	9	8	16	16	16	12	12	12
Waterproofing floor	0	0	0	0	0	4	4	0	4	8	4	16	16	16	16	12	12
Subfloor	1	4	1	3	1	7	6	6	2	6	4	16	16	16	16	16	16
Ceramic wall coating	0	0	7	0	2	7	8	4	12	12	12	16	16	16	16	16	16
Ceramic Floor coating	16	16	16	16	16	15	16	16	16	16	16	16	16	16	16	16	16
Gypsum lining	1	0	4	12	12	16	16	16	16	16	16	16	16	16	16	16	16
Heavy cleaning	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
Painting (1st coat)	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16

Key to Figure 2
16 — 16 units remaining
2F — Tower 2 and Block F

Figure 2: Board of units remaining used during the Workshop of the WIP analysis

Phase 2: Collaborative Workshop of Line of Balance

The second phase begins with training on long-term planning and the Line of Balance technique. This training seeks to present the concepts and principles behind the theme and to level up the knowledge of members of the construction team.

After this subphase, a start is made to define the size of the lot and where work will take place (Production Unit/ Location Breakdown Structure) collaboratively with the workshop participants. During this moment, participants are also instructed to reflect on the project execution strategy between the blocks (Figure 3).

Figure 3: Project Execution Strategy

Schramm, et al. (2004) define project execution strategy as a segmentation of smaller projects in order to create continuous flow of work, but these segments have limitations with some design decisions. For the case of Figure 3, the execution strategy was defined in towers, whose deliveries were defined from towers 1A to 2F due to the earlier delivery of the leisure areas and entrance of the condominium as a project limitation due to business constraints, and 3F to 3A moving to 5A to 5E and finally 4A to 4F by logistical priorities of access of materials and release of the construction site.

The next subphase is to define the network of precedence and dimensioning of resources, which seeks to map the ideal flow of activities for carrying out the services in the production unit and to dimension the resources available for each activity of the sequence of construction based on the quantitative survey and on historic productivity. The resources needed were defined in the preparation phase.

The subphase about the Design of the Current State of the LOB involves a collaborative workshop in which participants are encouraged to fill in the visual board of the LOB by using sticky notes, representing the workflow of teams across locations over time. At this point in time, they are used like the balance of services prepared in phase 1.

The last subphase of the method is to balance the rhythms and draw the future state of the LOB (Figure 4). At this point in the dynamics, participants were instructed to eliminate work- in-progress between activities, thereby aiming at a continuous flow between activities, and they were encouraged to optimize the flow of services, thus avoiding work being interrupted as this could result in demobilization and remobilization.

Figure 4: Balance of the work crews' rhythms

RESULTS

The survey carried out with 8 participants from the two case studies brought relevant information about the visualization of the benefits that the line of balance generates in the management of the works.

The benefits assessed by the survey were selected based on an analysis of the literature of IGLC community. Initially, 17 papers were identified that discuss the Line of Balance, of which 7 were selected that listed the benefits on the use of the technique. Table 3 presents the list of benefits that were evaluated at the end of each case study along with the evaluation of the usefulness of each step of the proposed method.

Table 3: List of the Benefits of LOB in the literature

Authors, Year	Formulated Questions
Valente et al., 2013	01. Ease of managing teams
Seppänen, 2005	02. Lower risk of team demobilization 03. More realistic plans due to the ease of analyzing buffers
Mendes Jr; Heineck, 1998	04. Negotiation of work between crews
Kankainen; Seppänen, 2003	05. Schedule of supplies with date as early as possible 06. Schedule of supplies: better visualization of restriction dates.
Moura et al., 2014	07. Improves task sequencing
Kemmer et al., 2008	08. Ease of simulation of scenarios and analysis

In the evaluation of the benefits of the LOB each participant chose 3 benefits that they would consider the most important of the 8 in the questionnaire. Figure 6 showed that the 3 main benefits perceived by users, among the 8 possible questions, were: (1.6) Understanding the best sequencing of activities and how to achieve continuity of tasks which received 75% of the votes; (1.3) Identify when the mobilization and desmobilization of teams should take place - 50% of the votes; and (1.8) Understanding of milestone dates for project constrains - 50% of the votes. In summary, 6 of the 8 participants (75%) chose question 1.6 as one of the 3 most relevant benefits of the LOB; no participant chose question 1.4; and the other results per question can be found in figure 5.

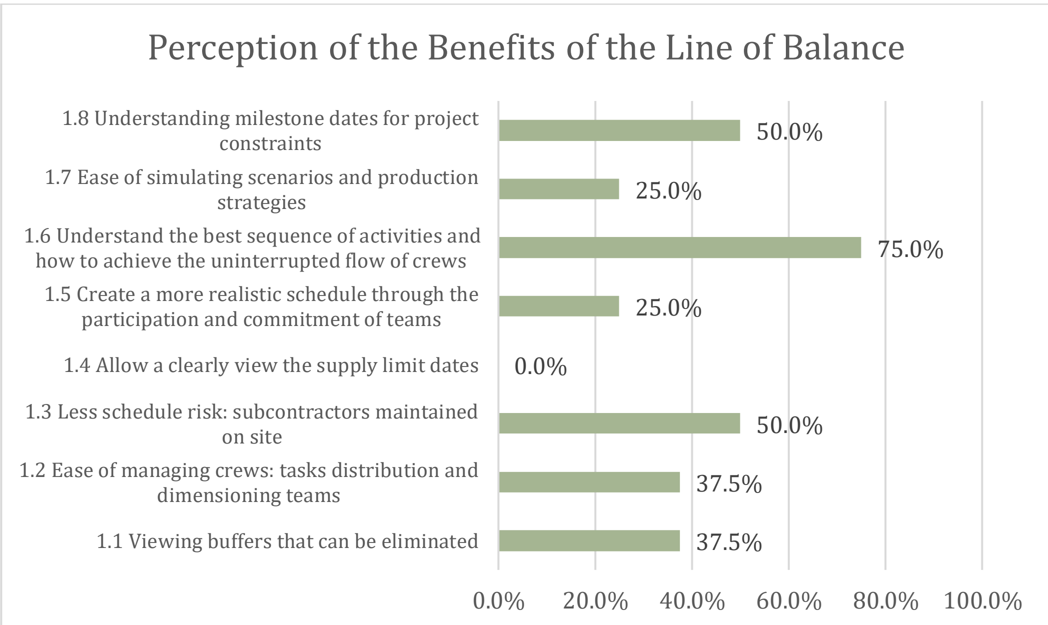

Figure 5: Perception of the Benefits of the Line Of Balance

The cross-analysis data from the perception of benefits between managers and production positions, it is observed that benefit 1.6 was the one most pointed out for both areas – 22% and 29% of the responses, respectively. Benefit 1.6 was also the only one mentioned by the two areas. In second and third place in the list of benefits observed by production position are: 1.1 and 1.2, both of which were preferred by 21% of respondents. Among the managers, the evaluation pointed to benefits 1.3, 1.7 and 1.8 in the sequence of preferences, both of which were preferred by 22% of respondents.

The questionnaire was also used to seek to understand if, after the training, there was an increase in participants collaborating with the planning of the works. The average of the participants' evaluation was 4.78 on a scale of 1 to 5, thereby demonstrating the methodology managed to increase collaboration and engagement, post-training. As to what the main change brought about by LOB was, managers reported that traditional planning stipulated monthly goals only for the physical-financial progress of the tasks. It was not possible to understand the workload and correct sequence of activities by using this method, which generated a large amount of work-in-progress on the project. Among the feedback comments made, the following stand out: “We were able to visualize how to recover some overdue activities, such as ceramics”, “The biggest advantage is that everyone can visualize the project execution strategy of the schedule and when to start the tasks so that we finish on the deadline needed".

As for the evaluation of the main activities involved in the collaborative method, the overall average was a score of 4.61 on a scale of 1 - 5, with a standard deviation of 0.59 and a coefficient of variation of 13%, thus representing a low deviation, which means a satisfactory result (very good). The following issues stood out: (2.3) Definitions of the sequencing of macro activities, the average score being 4.85 points, (2.5) Designing the LOB in the current state, for which the average score was 4.75 points and (2.8) Improvement of scenarios in the future state, which received an average score of 4.75 points (see Figure 6).

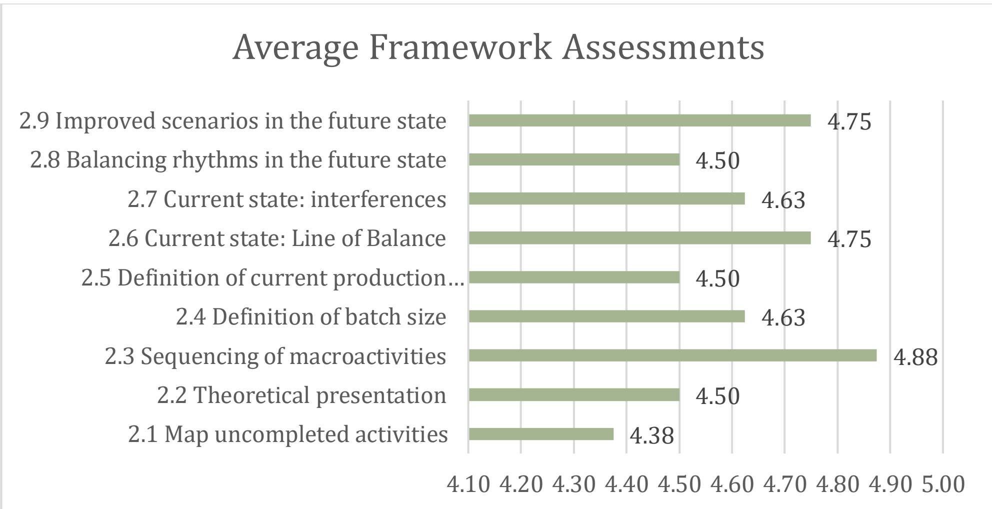

Figure 6: Average Framework Assessments

DISCUSSIONS

Combining the analyzes of the benefits, some similarities are observed between the highest scores of the questions 1.6 Understand the best sequence of activities and how to achieve the continuous flow of tasks unanimous preference among the participants and the evaluation 2.3 Sequencing of macroactivities with a score of 4.88 points for a total of 5.00. These similarities reinforced the methodological increment of case study 2, where the board of remaining units was used to understand the sequence and work in progress of activities in the current scenario that finally allow the creation of the future state by defining a standard sequencing and balancing the rhythms of production.

The cross analysis demonstrate some interesting about the results, the numbers indicate that the benefits most mentioned by the managers include strategic aspects, such as risk management, scenarios of production. On the other, the benefits most mentioned by the production engineers include operational aspects, such as control and dimensioning of teams. This reinforces the importance of the tool being shared by both areas, in order to favor an integrated and complementary action.

A single question: 1.4 Allow a clearly view of the supply limit dates does not receive preferential voting by both the managers and production sectors, we infer that this question is closely related to the current moment of the research, where the Covid-19 pandemic and supply chain disruption results in a lack of confidence about delivery times.

CONCLUSIONS

This paper presents a collaborative methodology for training and implementing the Line of Balance in residential projects which have already started and with a traditional system of planning based on Pert-CPM, a context that is little addressed in current articles. The article then analyzes the acceptance of the methodology from the user's perspective.

The paper has shown that the Line of Balance can be implemented in this context and that users see the benefits of its use. The collaborative methodology proposed for constructing the LOB creates greater team engagement, thereby disseminating information on the rhythm, the sequencing of activities and the dimensioning of resources. Thus, the interference between consecutive tasks becomes clear, and it becomes possible to assess the risks for the current scenario with greater precision and, consequently, to project the future state.

The evidence gathered shows that crews who used the tool and participated in implementing the methodology noticed benefits such as: (i) understanding the sequence of activities and how to achieve an uninterrupted flow; (ii) the ability to assess the risk of demobilization and remobilization of work teams; and (iii) clarity about the milestone dates of the project and the constraints involved in order to comply with these. The fact that both construction works feature repeatability and several buildings are distributed on the same site may have contributed to the choice of the 3 main benefits identified, since both works presented excessive WIP due to the distribution of the teams without following the correct sequence of attack.

Another important point that was evaluated by having the responses of the participants is that among the activities that are part of the method, sequencing macro-activities, drawing up the current status of the LOB and improving the LOB scenario were the best evaluated by the participants, thus demonstrating the importance of the method for increasing the transparency and the capacity of the LOB to facilitate the simulation of scenarios as suggested by the literature.

One limitation of the present research is that the potential for reducing the size of the lot was not considered in the case studies (in case study 1, a floor was adopted and in case study 2 a tower was adopted). Despite this practice being an important asset for reducing construction time, for the training of case studies 1 and 2, the team of researchers considered it more appropriate to address this aspect in a second moment, since the current problems of the works were closely related to the dispersion of teams in the works without following a standard sequence for the flow of production This was identified by analyzing the balance of services table. Another limitation is due to the survey, the fact that it contains only 8 evaluations prevents a quantitative analysis that validates the questionnaires, and then this research is qualitative.

Given that the study considered case studies with similar scenarios, such as evolutions of approximately 50% advance in the schedule and belonging to the low-end residential project with horizontal condominium market, future research can explore to what stage of a work in progress the methodology is still valid, for the same product or testing the framework in different construction projects, such as road projects, infrastructure and sanitation.

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CHALLENGES AND IMPORTANCE OF HUMAN BEINGS WITHIN THE LAST PLANNER SYSTEM IN COLOMBIA: A CASE STUDY

Maria Alejandra Diaz Amado[1]

ABSTRACT

The Last Planner® System (LPS) is a system that optimizes the workflow through the measurement of the reliability of commitments made by workers on a construction site. This system has achieved various benefits in the control of production in construction projects, such as minimizing execution times, reducing variability and uncertainty. However, when applied, obstacles have arisen, which leads to a revision of the methodology and/or partial implementations. In 2021, an update of the system was made in order to expand the scope of the system and respond to doubts and concerns. Therefore, this article seeks to identify the main challenges and give a proposal to solve them from the implementation and use perspective, according to the Colombian context through the identification of the possible causes of these difficulties found during the literature review and interviews to construction professionals. In the investigation, it was found different challenges consisting of 13 main obstacles in terms of the implementation and use perspective (divided by user type), and 8 needs which can be solved with the LPS update and other proposed solutions that holds the organization transformation (human perspective) and a detailed explanation of the whole process (practical perspective**).**

KEYWORDS

Last Planner® System, Culture, People, Implementation, Case study.

INTRODUCTION

Last Planner® System (LPS) was developed as a system to control the production of construction projects and overcome the variability and uncertainty that leads to cost overruns, higher execution times and disarticulation between project actors (Botero & Álvarez Villa, 2005; Durdyev & Hosseini, 2020; Viles et al., 2020).Although LPS defines a series of principles, indicators, and process to manage and use the system, a series of obstacles and challenges have arisen. These problems do not allow people to know the system correctly and do not implement some specific elements required of each project. 7advantage of it and to improve the quality of production on a construction site (Ballard & Tommelein, 2021). Consequently, in 2021, an update was developed with the aim of resolving the obstacles and difficulties presented and to adapt LPS to the actual environment.

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The Colombian industry, like many other construction industries, has faced cost and time overruns, delays, or variability. These problems have been improved by the implementation of technology, new methodologies, in process and, in some companies, by the implementation and use of the Last Planner System, and as other companies around the word, the Colombian industry has faced obstacles and challenges with the system.

Nevertheless, some guides have been developed which explain each step of the system as well as the indicators and planning around the world (Ballard et al., 2007; Daniel & Pasquire, 2017; Davidson, 2015; Ebbs & Pasquire, 2019), in Colombia there are not many guides. And, considering the world guides and others, no one has evaluated the new approach of LPS, which can be call Last Planner System 2.0. Therefore, this case study makes a complement to what is proposed (propose solutions to the challenges) considering all the factors from the social transformation and preparation a company may go through to adopt the system, the details of every process and the new elements of the system.

LITERATURE REVIEW

Research on LPS shows evidence of other studies that have found problems which are specific to certain contexts, such as the study of "Last Planner System: Experiences from pilot implementation in the middle east" (Alsehaimi et al., 2009), "Collaborative implementation of Lean planning systems in Chilean construction projects"(Alarcón et al., 2002) or "A survey on the Last Planner System: impacts and difficulties for implementation in Brazilian companies" (Viana et al., 2010), and others have found problems that are persistent in various places, but there are not many studies that identify the problems in the Colombian industry and they do not explain if the Colombian industry also faced the same problems or if it has new ones that can enhance the perspective of the system and bring new ideas and solutions to other contexts.

On the literature review, 41 articles were revised including guides, implementations, metrics, key factors, and case studies were found. Based on this, the main obstacles of both perspectives (implementation and use). These obstacles were grouped according to their description and meaning, so in the end fourteen challenges were identified and selected (See table 1).

Table 1. Obstacles found in the literature review about LPS implementation and use.

Challenge	Papers	No. Times
Lack of training (Social Skills and knowledge)	(Hamzeh, 2011); (Alarcón et al., 2002)Fernando solis et al (2013); (Fernandez-Solis et al., 2013)(Dave et al., 2015; Mejía-Plata et al., 2016; Porwal, 2010; Porwal et al., 2010; Viana et al., 2010)	9
Resistance to change	(Alarcón et al., 2002; Alsehaimi et al., 2009; Dave et al., 2015; Fernández-Solís et al., 2018; Mejía-Plata et al., 2016; Porwal, 2010; Porwal et al., 2010)	8
Partial Implementation	(Dave et al., 2015; Fernández-Solís et al., 2018; Fernandez-Solis et al., 2013; Mejía-Plata et al., 2016; Perez & Ghosh, 2018; Porwal et al., 2010)	6
Lack of support and leadership	(Alarcón et al., 2002; Fernández-Solís et al., 2018; Fernandez-Solis et al., 2013; Mejía-Plata et al., 2016; Perez & Ghosh, 2018; Porwal et al., 2010)	6

Time of execution	(Alarcón et al., 2002; Brady et al., 2011; Dave et al., 2015; Fernández-Solís et al., 2018; Porwal et al., 2010; Viana et al., 2010)	6
Compromise	(Brady et al., 2011; Dave et al., 2015; Fernández-Solís et al., 2018; Fernandez-Solis et al., 2013; Porwal et al., 2010; Viana et al., 2010)	6
Information	(Brady et al., 2011; Dave et al., 2015; Fernandez-Solis et al., 2013; Perez & Ghosh, 2018; Viana et al., 2010)	5
Role definition	(Brady et al., 2011; Dave et al., 2015; Fernández-Solís et al., 2018; Fernandez-Solis et al., 2013; Porwal et al., 2010)	5
Visualization	(Alarcón et al., 2002; Dave et al., 2015; Fernandez-Solis et al., 2013; Porwal, 2010)	4
Strategy	(Alarcón et al., 2002; Dave et al., 2015; Fernández-Solís et al., 2018)	4
PPC Misinterpretation	(Alarcón et al., 2002; Fernández-Solís et al., 2018; Perez & Ghosh, 2018)	3
Contract	(Fernández-Solís et al., 2018; Fernandez-Solis et al., 2013; Porwal et al., 2010)	3
Standardization and guides	(Brady et al., 2011; Dave et al., 2015; Perez & Ghosh, 2018)	3
Lack of experience	(Fernández-Solís et al., 2018)	1

RESEARCH METHOD

To proceed with the investigation, the case study method developed by Robert Yin (Yin, 2017) were used in two Colombian construction companies that use LPS. The steps were:

1. Find the obstacles and barriers.
   a. Review the obstacles and barriers from the literature.
   b. Identify the obstacles and barriers in Colombian construction companies through interviews to construction professionals.
2. Relate and find solutions to the main challenges
   a. Compare and integrate the barriers to find the main challenges.
   b. Seek solutions and improvements on the update of LPS.
   c. Literature review to find solutions not covered on the update.
3. Conclusions
   a. Conclusions on the update of LPS.
   b. Presentation of the solutions.

The first step was the revision of the bibliography between 2010 and 2021, specifically on subjects related to implementation of LPS, adoption's obstacles, critical success factors and uses found in: IGLC conference papers; LCI Congress; Journals such as ASCE Library; Engineering, construction and architectural management; Journal of Construction Engineering and Management; and others like Harvard Business Review; Lean Project Delivery and Integrated Practices in Modern Construction Book; The Lean Builder and Lean construction; investigation center such as (P2SL) Project Production Systems Laboratory.

The second step involved guided interviews to professionals of the Colombian industry such as general contractors, construction managers, Senior project managers and

Project administrators from construction companies that built high-rise residential projects and that had implemented LPS in their projects. In these interviews, it was inquired about knowledge, perception, and experiences with LPS, from the implementation and use perspective.

For the identification of solutions, a review of the bibliography with emphasis on case studies was done. Additionally, it was analysed the Benchmark developed in 2020 by Glenn Ballard and Iris Tommelein and published by P2SL, to define the new proposals and solutions they presented. From the next figure (See figure 1), the grey squares are the first stage, which is the collection of information; the blue squares are the integration with the update of the Last Planner System; the orange squares are the conclusions.

Figure 1. Research process method.

RESULTS

The results were identified and reviewed the challenges on the literature and in the interviews in order to find the main obstacles in the implementation and use of LPS and present the main obstacles and needs found in the Colombian construction industry.

REVIEW OF THE OBSTACLES IDENTIFIED

As mentioned above, a review of different documents was carried out to find the obstacles that the industry has faced. This information was related to the obstacles found in the guided interviews to find the most significant challenges of the Colombian industry. In total, 41 obstacles were found in the two stages; 20 in the implementation stage and 21 on the use stage (See Figure 2).

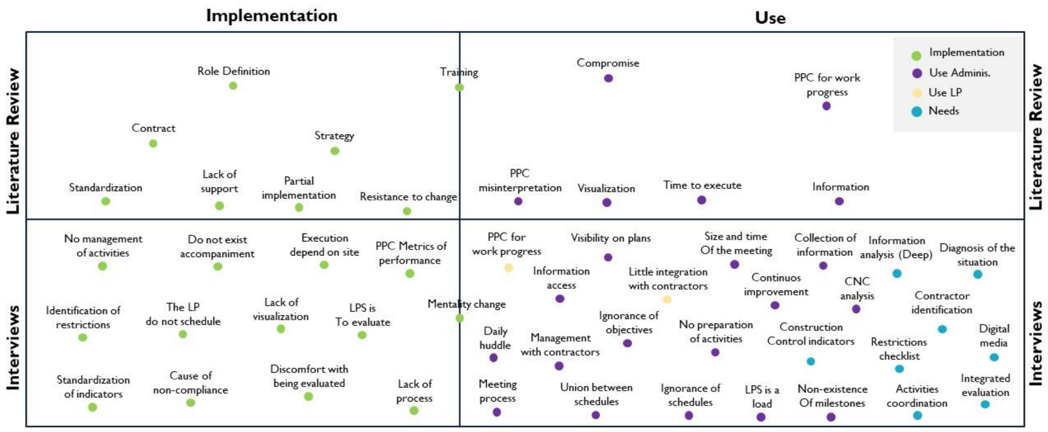

Figure 2. The 41 challenges found on the literature review and Literature review.

Nevertheless, when we began to analyse the obstacles, it was detected that some of them were similar or were a consequence of another, so it was decided to relate and combine them to find the main challenges. For example, the obstacles "lack of support" (from the Bibliographic review) and "do not exist accompaniment" (from the interviews) mean the same. At the end, thirteen challenges were selected. The Figure 2 shows the source of information of each obstacle and the stage of the Last Planner System it belongs. So, the stage of LPS (Implementation and use) is on the X-axis and the source of the information (Bibliographic and interviews) is on the Y-axis.

Another significant finding which was possible due to the interviews, was not only to determine the Colombian obstacles, but also to determine the obstacles experienced by each user of LPS; Also, during the interviews, the needs of the industry were found, which it will be explain below.

Obstacles identified by user type in LPS

The first findings of the interviews were the obstacles faced by each type of person in LPS. First, there are obstacles faced by the people who implement the system in an organization, then the obstacles faced by the people who execute the system in the construction projects, and finally, the obstacles faced by last planners. In the beginning sixteen obstacles were found, but when combined them, the case study ended up with thirteen (See Table 2).

Industry needs

The other interesting finding of the interviews were the factors that the administrative staff and construction contractors (Last Planners) require and consider appropriate for a better application, use and usefulness of the system. This information could help to overcome some challenges in use and be the key factors in the adoption (See Table 3).

MAIN OBSTACLES AND NEEDS

In the development of LPS it was found two moments in which challenges could appear. The challenges associated with the implementation of the system, which are challenges related to the administrative, strategic and management part at an organizational level; and the challenges of use that are associated with the use of the system on the construction site, which means at an operational level. Despite both challenges being different, it is important to consider that some challenges encountered during the use phase are due to gaps in the implementation phase. Therefore, to overcome them it is important to create a work plan that establishes the goal and objectives of the implementation, the phases, processes, methodology and steps to follow to know and establish LPS in an organization.

Moreover, it is important to understand the human context in which LPS is going to be implemented. When implementing LPS, work must be done to train the team with skills that allow them to overcome the change in the way they work, to coordinate with the other actors and to understand how the social network within the team is, in order to identify possible leaders in the process. At the same time, work needs to be done with the administrative staff to manage conversations, in which through negotiations agreements are reached. On the other hand, it must be understood that this process is iterative and that is depends on the collection of data to propose improvement plans.

So, the main challenges in implementation and use by user type in LPS are:

Table 2. Final challenges identified by user in LPS on each stage of the Last Planner System after literature review and interviews.

Stage	Challenges
Implementation	Partial implementation, Strategy, Lack of support, Culture, Contract
Use - administrative	Training, Visualization, Information, PPC Misinterpretation, Standardization, Self-management

Use – Last Planner	Training, Teamwork

Moreover, the needs found in the Colombian industry are presented below. It is important to point out that the needs are those elements that the users expect of the LPS system. These are also divided by needs of administrative staff and needs of Last Planners.

Table 3. Second finding of the interviews, the needs identified by user in LPS.

Staff	Needs
Administrative	Construction control indicators, Detailed checklist of restrictions, Deep information analysis, Contractor identification, Digital media
Last Planners	Integrated evaluation, Coordination of activities, Diagnosis of situation

A total of thirteen challenges and eight needs were found, for a total of 21 elements to find solutions.

DISCUSSION

Based on the challenges found, the next step was related them to the Last Planner System 2.0 to find which one it covers and propose solutions to the challenges that were not covered or developed in the LPS 2.0.

RELATIONSHIP WITH LPS 2.0

LPS 2.0 through its five research points (The five base papers for the benchmark 2021) broadened its scope, deepened the relationship between schedules and solved some obstacles presented by users(Ballard & Tommelein, 2021). However, the update only managed to present solutions to six and a half of the challenges out of the thirteen found.

When analysing the challenges solved, they are challenges that address the proper use of the system, that is, its operation. However, challenges associated with the intangible part such as the human and social organization part (culture, diagnosis of the environment, teamwork, etc) have not been addressed yet since this new update. These challenges, which are not an explicit part of the operation of the system, prepare the organization and people to address the change and the new working method.

For all the above, it was considered pertinent to emphasize that LPS is a system that proposes production control in the construction industry, through three plannings(Ballard & Tommelein, 2021) that modify the way people usually work. Now, when any tool (in this case system) intrinsically seeks to modify the way people work, what it is doing is modifying the organizational culture. For this reason, it is necessary to understand that culture is not only who we are or how we behave, but culture considers all the patterns of experiences that people develop over time as they face and overcome obstacles and difficulties day by day(Christensen & Shu, 1999; Tushman & O'reilly, 2002). For this reason, although LPS is a system that helps us control production, it also involves modifying the organizational culture of the organization where it is implemented.

Therefore, although the found solutions in the update, these solutions are mostly related to the practical part of the system (its use), for example, new metrics, how to visualize the information or how to standardize it, but they are not totally focused on preparing people and teams to work under this new way of doing things, such as how to develop a strategy and objectives or how to coordinate teams to work towards a common goal. These can be seen on the figure 3, on the right side the challenges that LPS 2.0

addressed and proposed solutions; on the left side, challenges that are still not resolved on the update.

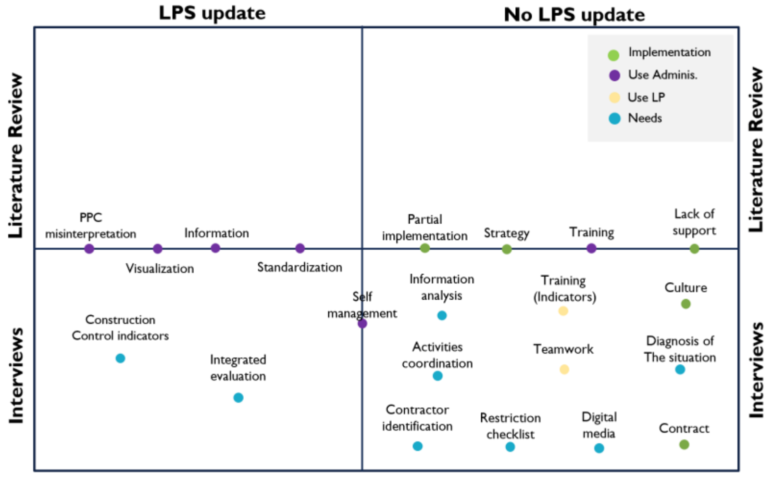

Figure 3. Figure about which challenges (by user type) are addressed in the LPS 2.0 version and which ones are not.

PROPOSED SOLUTIONS

The solutions to the challenges which were not developed in the LPS 2.0 version, cover the human and social part of the system. These are solutions that invite to know and prepare the organizational environment, and from this finding the best strategy to implement and use LPS.

Implementation challenges

1. Partial implementation: The partial implementation is the adoption of certain elements of the Last Planner® System. However, LPS must be understood as a holistic system, in which, if one of its parts is missing or is overlooked, the process has a high probability of failing. For this reason, the propose is to emphasize the least implemented elements of LPS, create a leadership team(Ibarra & Lee Hunter, 2007), standardize guidelines and formats, and for the implementation to be gradual.
2. Strategy: This challenge refers to the lack of planning and creation of a plan for the implementation and execution of the system. So, the solution is to create an action plan based on the desired objectives developed by the organization, which is the reason why the company wants and needs to implement this methodology. Once the objective is set, it must be communicated it to all the members of the organization and to the last planners.
3. Culture: This challenge refers to the resistance of change or predisposition to the adoption of the system by people, for which it is proposed to do a diagnosis of the current situation of the organization, in which it can be identified how the processes occur, who the people that communicate the most are, what the behaviour of the staff is like and also to know the organizational network. With this information, a work plan is created according to the organizational culture (Christensen & Shu, 1999; Tushman & O'reilly, 2002).
4. Lack of support: The challenge refers to the lack of accompaniment by the organization towards the people who are implementing and using the system. Hence, it is proposed that in order to get the team to adopt this new methodology

it is necessary to train them with theoretical and social skills. In addition, it is important to make them participate in the achievement of the organization's objective, creating a supportive and safe work environment in which people can express themselves and share their concerns, doubts, and observations (Wilkinson et al., 2020)

5. Contract: Due to the traditional form of executing the construction projects, each participant thinks first about how they can carry out their own activities and then, how to collaborate and work with the other coworkers, so instead of the project being a work composed by several parts, it becomes a project made up by different parts that are uncoordinated, leading to delays, failures in the executions and reprocesses (Porwal, 2010).Therefore, it is proposed to include within the employment contracts, a clause related to the use of LPS by each last planner, in which the rights and duties that they have are specified.

Administrative challenges

6. Training: This challenge refers to the lack of training received by the team to use the system and see its benefits. Lack of training that is not only theoretical but also human, therefore, its solution is to approach the training of the work team from two perspectives. The first from the theoretical perspective, which begins from understanding the Lean principles, through LPS, until knowing what indicators use, and the second perspective is from the human and social side to be prepared for change and new challenges.
7. Self-management: it refers to the ability of the team to self-know its activities and schedule them. Therefore, what is sought is to develop skills that allow the last planners to identify their future activities, possible inconveniences and create commitments. For this, it is proposed to have parallel meetings with each contractor, in which the administrative staff teaches how to visualize future activities, the flow of these is evaluated and restrictions are identified. The duration of this accompaniment will depend on the adaptability of the contractor.

Last Planners' challenges

8. Teamwork: Teamwork has two sources, the first is the teamwork of the administrative group, and the second is the teamwork by the contractors. As for the first team, this is addressed by working on the transformation of the processes and the way of executing the activities, from a cultural perspective. For the second team, networks of trust and communication must be identified and created to allow integration and cooperation between them; in this way, the point of view of the last planners changes from being a stand-alone entity to being an entity that is part of a workflow.
9. Training: Contractors are the last planners and are an essential part of the system because they are the ones who execute the activities (Ballard & Tommelein, 2016). However, sometimes they do not participate in the entire process and only know or are integrated in the result. This disconnection with the organizational change (that the company is undergoing) creates confusion and disorientation at work. Therefore, to address this challenge, it is sought that the last planners be invited to the training sessions so that they can learn what the new system is, how the organization is going to evaluate them and resolve their concerns and doubts in time. This integration, in turn, goes hand in hand with the strategy, lack of support

and training. It should be noted that this training is about understanding the system and the meaning of the metrics, it is not a training on how to calculate or carry out the processes.

Administrative needs

10. Detailed checklist: Restrictions are actions that are required to be solved so that an activity can be scheduled and executed. These are identified in the lookahead schedule and must be managed to prevent delays in activities and, therefore, in the project. So, to identify them, it is suggested to propose a checklist that facilitates and reminds the administrative staff as well as the last planners about the minimum requirements to start an activity.
11. Deep information analysis (restrictions and CNC): This challenge addresses the issue of how to analyse the information that is collected in the schedules to improve the workflow in the construction site. For which it is proposed to create a table that allows knowing in detail the causes of the restrictions and the causes of the CNC. This table that is developed seeks, in turn, to standardize the information and allow a common language between the teams of the organization.
12. Contractor identification: The identification of contractors for the execution of activities in a construction project is related to the process of selecting and awarding contracts for each company. Therefore, it is a unique and independent process that cannot be standardized nor provide a general solution for this need. However, the following recommendation is, in case the contractor is not available at the time of scheduling the work: carry out an analysis of the execution times of this activity in other similar projects to know an estimated performance, time and schedule; once the contractor is known, negotiate with him about the planned time and agree on the new schedule.
13. Digital media: To allow collaboration and transparency in the flow of work and information, it is proposed to implement and use digital tools that will allow access to information at any time by all the people involved in the work. The ideal is to move the physical LPS board to a digital board. However, it is recommended that before adopting these technologies such as digital boards or specialized software, there is a training and time to use the system in a physical way, to empower the last planners and administrative staff.

Last planners' needs

14. Activities coordination: The coordination of activities allows to improve the workflow and be efficient in the processes. However, this requires the team to be willing to share their way of working, needs, obstacles and requirements to modify them and create a new efficient way of working for everyone involved. That is, a change in the way of thinking about work, from individual to teamwork. Part of this process is carried out in the training and education sessions that the contractors receive, both for the system and for the human and social part.
15. Diagnosis of the situation: LPS proposes continuous improvement in its processes and operations, however, to be able to observe what the changes and improvements have been in a quantitative and not qualitative way from the point of view of the last planners, an initial diagnosis of its situation is proposed in which the team writes down the workflow, performance, and times of the contractor before LPS is implemented. In this way, the last planners can observe

the changes and improvements in their processes, and in this way find the system useful not only for the company, but also for them.

CONCLUSIONS

Last Planner® System is a system that provides tools for workflow optimization in construction projects, however, for it to work properly, it must be understood as a holistic system that, due to the interconnection of its parts, manages to cover the entire production control process and improve its performance. LPS is not just a sequence of steps to optimize the workflow, it is an organizational transformation process that, if it does not have a strategic route, it can have results that generate bad experiences for people and organizations.

To be able to develop an adequate route for organizations, it is not only necessary to understand the process of the system, but also to identify the obstacles that are found in the environment, analyse how LPS can address them and thus create a route of action that is adequate and prepare the environment in which it will be implemented and used, and at the same time the staff. In this way, the system is shaped and adjusted (without losing its essential elements) to the organization and the people.

In this case study and because of the bibliographical research and the interviews addressed to professionals in the field within the Colombian context, it was possible to identify the main challenges presented by professionals in two moments, implementation and use of the system, fourteen in total. These challenges in turn responded to administrative challenges (processes) and social challenges (human management).

Additionally, new needs were identified that presented an opportunity to expand the range of action of the system, and to model it to the Colombian environment and its expectations, in total eight needs. Part of these needs were identified in the group of last planners or contractors.

Based on these obstacles and needs, the next step was to analyse the general framework of Last Planner System 1.0, with the new solutions and ways of approaching the system developed in Last Planner® System 2.0, to find solutions to the challenges and needs found. However, of the fourteen identified challenges, a solution to six and a half challenges were found, and in terms of the needs of the other eight identified, a solution to two were found in the update of the system; that is, part of the challenges and needs were not solved or addressed in the update of the system. Thus, a second bibliographic review was carried out to provide answers and generate a framework adapted to the context.

It should be noted that, as the Benchmark 2020 states, this process is unique, iterative, and evolutionary, for which, although this case study proposes solutions, it is pertinent for each organization to discover and test what solutions and steps are the appropriate ones according to its structure, environment, and way of working (culture and objectives).

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WHY IS FLOW NOT FLOWING IN THE CONSTRUCTION INDUSTRY?

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ABSTRACT

The concept of flow, a core notion of lean, has been proposed and discussed throughout the construction literature for over three decades but is not yet widely applied and disseminated across industry. This paper sets out to perform an exploration of potential underlying root causes of this problem by examining a number of concepts across varied disciplines: (i) metaphysics and ontological assumptions (already discussed in the construction context), (ii) particle/wave duality (from quantum physics), (iii) co-emergence (or non-duality) (from Buddhist philosophy), and (iv) cognitive biases and fallacies (based on the work by Tversky and Kahneman). A set of six preliminary and non-exhaustive hypotheses are formulated seeking to provide insights to the problem at hand, namely, "*Why is flow not widely understood and applied in construction practice?*". Two experiment designs are proposed to test the last three hypotheses, which are related to the pragmatic aspect of this question, and thus these findings can potentially assist in a more widespread adoption of flow in practice.

KEYWORDS

Flow, theory, ontology, construction physics, metaphysics.

INTRODUCTION

A meta-analysis involving data from 24 separate studies around the world, showed that, on average, 49.6% of time on site is devoted to non-value adding activities (Horman and Kenley 2005). This means that approximately half of the time is spent on waiting, rework, excessive transportation, etc, or on supporting activities. Similar statistics were also found in Kalsaas (2010) for a highly innovative construction company, thus further demonstrating the endemic nature of the problem. Recognising that construction does not involve only direct work, but also number of other activities, is the key to improve productivity. Such an understanding has been proposed under the "flow" perspective, one of the three pillars forming the Transformation-Flow-Value (TFV) theory (Koskela 2000). Flow entails the operations dimension as well as the process dimension (namely, the passage of information, materials, etc throughout the production system). Flow introduces

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the time element to the conceptual comprehension of construction and thus by observing the production of an object over time, it becomes clear that direct work is not the only activity happening.

Seeing production through a "flow" lens is key to recognise waste and inefficiencies that are intrinsically connected to low productivity. A survey carried out with construction firms further illustrates this view (McGraw Hill Construction 2013). The results showed that 62% of lean practitioners considered construction processes to be inefficient/highly inefficient compared to 14% of non-practitioners. Complementarily, 19% of lean practitioners considered construction processes to be efficient/highly efficient compared to 55% of non-practitioners. These findings demonstrate the importance of concepts such as "flow" to be as accessible as possible to industry so that its intended benefits are realized in practice. Furthermore, Spearman and Hopp (2021) indicate that operations management has relied on axiomatic models of simplified situations or in more extreme cases ad hoc methods and heuristics. Other disciplines have a clear link to a theoretical foundation, for example mechanics in structural engineering. This research further explores the potential of flow theory in contributing to a unified science that underpins construction management.

This paper examines the following question: "*Why is flow not widely understood and disseminated in construction practice*?". Conceptualizations from different domains including (i) metaphysics and ontological assumptions, (ii) particle/wave duality (from quantum physics), (iii) co-emergence (or non-duality) (from Buddhist philosophy), and (iv) cognitive biases and fallacies (based on the work by Tversky and Kahneman) are reviewed. Hypotheses are then formulated based on the revised notions and two experiment designs are outlined to test three of these hypotheses. This manuscript is exploratory in nature. It aligns with the concept of the "ripple effect" (namely, that science should create more questions than answers) discussed in the TED talk "The Pursuit of Ignorance"[4] by Stuart Firestein. Accordingly, the paper seeks to introduce a non-exhaustive number of angles that can help to explain the lack of understanding and dissemination of the flow concept in practice despite being proposed for thirty years[5] now. The importance and need for such type of in depth theoretical studies to advance knowledge has been highlighted in both operations (e.g Spearman and Hopp 2021) and construction management (e.g. Howell and Koskela 2000; Koskela et al. 2019; Seymour 1996) disciplines.

LITERATURE REVIEW

FLOW IN CONSTRUCTION

One of the early understandings of flow in construction was proposed by Koskela (2000) who presents a three-type flow model comprised of (i) material or supply chain (e.g. a window production and transportation until installation on site), (ii) location or space (e.g. a team moves through the building installing windows), and (iii) assembly or previous work (e.g. the building progresses through all construction or assembly stages). Bertelsen et al. (2006, 2007) contend that construction entails a myriad of flows (e.g. information, space, crews, etc.) that are interconnected serving a number of different projects at the same time. For example, the flow of procurement feeds the flows of materials, equipment and workers. As there is not only a single flow but rather several flows, the flow

[4] https://www.ted.com/talks/stuart_firestein_the_pursuit_of_ignorance

[5] Considering the formal introduction of "flow" in the construction literature context by Koskela (1992)

controlling the progress of a project (termed as critical flow) is constantly changing rendering the task of identifying and managing such a flow challenging, if at all possible (Bertelsen et al. 2007).

In a more recent study, Sacks (2016) presents a conceptual framework for good flow in production. The paper proposes two types of flows based on Shingo and Dillon (1989): (i) process flow (progress of a product along workstations or in the construction context the progress of teams completing construction tasks in different locations of a building) and (ii) operations flow (actions performed on the product or the building by a workstation or a team). Interestingly, a "task" (elementary and not a flow) in Koskela (2000), exemplified by a team installing one window, is converted into operations flow in Sacks (2016) as from a team's perspective that task is repeated over time in different locations. This latter notion can be expanded to different locations within a building but also across buildings, which is captured under the "portfolio" notion of different projects being built at the same time and a team flowing across all of them (Sacks 2016).

METAPHYSICS AND ONTOLOGICAL ASSUMPTIONS

The distinction between two basic world views, namely, (i) substance metaphysics (e.g. concrete, bricks, etc) and (ii) process metaphysics (e.g. heat, light, etc) dates from the pre-Socratic period of philosophy (Koskela and Kagioglou 2005). The referred authors state that construction is inherently a process-oriented endeavour, yet a majority of research and practice in this field measures the effectiveness of the process purely from the outcome or through a substance-oriented view. This results in problems such as the excessive focus on productivity as a measure and explanation of the efficiency in construction and the assumption that plans are deterministic rather probabilistic (Koskela and Kagioglou 2005). Transformation (as part of TFV) captures the substance-view by understanding construction to be a series of independent sub-transformations. On the other hand, Flow (also as part of TFV) embodies the process-view by conceptualising construction as the flow of material in space towards an output (Koskela and Kagioglou 2005). A different angle is introduced by Koskela et al. (2007) in proposing that TFV could be viewed from a substance (TFV^t) or a process (TFV^p) metaphysics.

Nonetheless, the disconnection between the ontological categories of "substance" and "process" is an acute barrier to understanding process phenomena (Rooke et al. 2007). The referred authors carried out two ethnographic studies (on structural design and quantity surveying) to explore the methods of reasoning, which are focused on objects rather than processes as the core elements for understanding construction projects. In the first study, it was observed that the explicit elements considered in pricing are the physical parts forming a building (concrete, its types, quantities, etc). On the other hand, task related costs (transport and placing of concrete, etc) were viewed as ancillary properties of the physical parts (Rooke et al. 2007). The second study highlighted the view of (i) design and (ii) implementation of design (construction process) as two independent entities rather than interconnected and iterative phases demonstrating an excessive emphasis on design in comparison to the implementation of design. This overlooks variability in size, shape, dimensions, whenever an object is translated from the idea domain (design) to the physical domain (actual constructed product), resulting in technical (quality, defects) and contractual problems.

The overarching dominance of a matter or substance-view in understanding phenomena and the world around us has also been observed in other fields, which might suggest that the process-view has challenges. Chi et al. (1994) discuss a recurring misconception of scientific conceptualisations belonging to the process ontological category such as light, electrical current, etc, to be placed in the thing (or matter) category. According to Chi et al. (1994), the confusion might stem from the fact that process entities involve components from things categories (such as wires, batteries, particles, etc in the case of the electrical current). But the involvement of these components does not mean that the electrical current remains in this category, nor is a property of the components (Chi et al. 1994). Therefore, the natural preference towards the conceptualisation of entities as matter (or things) may be due to the familiarity with concepts in this ontological category. The referred authors do not expand further on this idea, but it is proposed here that human beings perceive (via our senses and mind) the world as solid and atemporal to a large extent, and because of such first-hand experience we tend to frame most phenomena based on this ontological category.

CO-EMERGENCE

The Buddhist *koan* ("what is the sound of one hand clapping?") provides another angle to tackle the issue discussed in the previous section. The idea is that a hand does not have an inherent sound per se, namely, the sound will depend on the object with which the hand engages. If it is another hand, the sound would be of what we traditionally think of hands clapping, but if we clap our hand against a wooden desk or a glass window, we will have different sounds, meaning that the sound of a clap is a property that emerges from the interaction of two entities (the hand and the other chosen object), thus resulting in the term "co-emergence". Thus, matter entities are an intrinsic part of process entities: namely, sound only exists via the interaction of two objects. As a result, positioning the matter view (T view) in opposition or perhaps as a lesser view in comparison to the process view (F view) can suggest that these are independent and/or that the F view should be preferred. In fact, T and F tackle the same entities, namely, construction activities, yet the former has a microscopic focus (the individual activities as independent entities) whereas the latter has a macroscopic focus (the system formed by a set of activities and the features that emerge from such a system). Thus, similar to the *koan*, a hand (or activity) exists as an individual entity (T view), yet the co-emergence (or system features) only arises when two or more entities are combined (F view). In the case of a hand, this leads to different sounds. From a construction process perspective, it leads to less or more waste, efficiencies, etc, depending on the system delivering such activities.

PARTICLE/WAVE DUALITY

Overall, the matter and process views of the world seem to be presented in opposition, namely, an entity will either belong to one category or the other, or at best their interrelated nature is only marginally discussed (as in Chi et al. 1994). It is proposed here that this dual or binary rationale further hinders the understanding of the process-phenomenon: if something is not a physical part (as in matter entities), then what is it? And how can we perceive it? In that sense, the sound of one clap koan previously discussed and the double slit experiment and the particle/wave duality (from quantum physics) can shed some light. The latter demonstrates that at an atomic scale, light when going through a double slit assumes a particle behaviour and hits the screen as a particle but ultimately creates a wave pattern. This means that at such scale, light cannot be strictly classified as matter (particle) or a process (wave), thus creating a Particle/Wave duality. This prompts us to revise the binary perspective in which we usually operate in ("this OR that") and the possibility of a more open perspective ("this AND that").

COGNITIVE BIASES

Following on the rationale and notions presented in the previous sections, the first problem to consider is whether or not people are able to perceive the construction phenomenon from a process perspective. If the answer is yes, a second problem is whether (or not) they have an intuitive understanding of the fundamental properties of statistical distributions such as standard deviation, variability, queuing theory, etc. For example, this type of investigation would question whether a site engineer can interpret task duration distribution data to define an appropriate schedule. Furthermore, if the site engineer is able to understand the statistical distribution, it is key to measure the influence of risk attitudes and behavioral perceptions associated within the interpretation and the subsequent decision making. From a practical viewpoint, the second problem is as critical as the first one, as it will ultimately impact people's ability to make appropriate decisions and consequently obtain the benefits (reduced waste and inefficiencies). Comprehension and understanding of the flow perspective can potentially improve this aspect of the construction domain. This is in line with Spearman and Hopp (2021) who argue that the lack of a descriptive science for operations has resulted in a lack of intuition about the basic concepts (e.g. cycle time and WIP) among professionals in practice.

Research carried out by Tversky and Kahneman have also demonstrated people's bias and misconceptions of even basic statistical and probability notions. These have been observed in a number of professional areas such DNA testing, court trials, and medical prognosis, leading to poor decision making and affecting outcomes. One case is the conjunction fallacy (Tversky and Kahneman 1983), which explains that people tend to overestimate the likelihood of two events occurring in conjunction relative to each event occurring independently. In one of the studies by Tversky and Kahneman (1983), participants had to select the most likely statement (from a set of five options) based on the description of a fictional individual (Bill). A statement with two attributes (Bill is an accountant who plays jazz for a hobby) were selected as more likely than statement with a single attribute (Bill plays jazz for a hobby) (Tversky and Kahneman 1983). In a variation of such fallacy, the participants had to choose the combination for 20 successive rolls of a dice with four red faces (R) and two green faces (G) from three options: (i) RGRRR, (ii) GRGRRR, and (iii) GRRRRR. 62% of participants chose the second option as it appeared to be more representative of a random sequence despite the fact that the first option is contained within the second option and more likely to occur (Tversky and Kahneman 1983).

WHY IS FLOW NOT WIDELY UNDERSTOOD AND USED?

Based on the conceptualizations presented in the previous sections, six exploratory non-exhaustive hypotheses are proposed for unveiling root causes contributing to the limited understanding and adoption of flow in construction practice.

- H1. Flow is tricky to grasp (due to its inherent non-dual and co-emergent nature) and the difficulties observed in construction are no different than the ones detected for similar concepts in other fields (physics education, etc).
- H2. The dichotomy of matter and process views ("this OR that"), and the negative connotation of the former, hinders the understanding of the latter by introducing the misconception that the process entities entail elements other than the one found in the matter domain.

- H3. Flow and its more tangible manifestation (queues) as observed in other contexts (manufacturing of products, vehicles in traffic, etc.) enable such a concept to be more easily perceived.
- H4. The specific features of construction (production happens inside the product, immovable product, etc.) hide these more tangible manifestations, making flow invisible in this context.
- H5. Due to the invisibility of flow, cognitive biases related to statistical thinking are more prevailing in construction than in flow visible environment (manufacturing of products, vehicles in traffic, etc.).
- H6. Differently from manufacturing, time instead of inventory is used to mitigate flow variability and the former is less measurable/visual/tangible and more transient than the latter.

H1 and H2 are stimulating from a theoretical viewpoint, yet have limited contribution from a practical angle, namely, in enhancing the understanding of flow in construction practice and consequently in its widespread adoption and dissemination. The effect of moving workstations and a static product (instead of the other way around as in manufacturing) have been explored in Bølviken and Koskela (2016) in a similar vein to H4 and H6 but focused on waste. According to Bølviken and Koskela (2016), waste is constantly changing and thus not necessarily observable over time. For example, a worker is waiting for a drawing for two hours, but such waste disappears as soon as he receives them. In addition, waste has a dispersed nature due to work/activities being performed by distinct crews in different locations often hidden from each other due to structural and enclosed systems, thus further adding to its unobservable (or invisible) nature. The remainder of this paper focuses on the exploratory design of two experiments (under development by the authors of this manuscript) for corroborating or refuting H3, H4, and H5 hypotheses.

DESIGN OF EXPERIMENTS

INVISIBILITY OF FLOW IN CONSTRUCTION

Table 1 summarizes the experiment design structure for H3 and H4, which is comprised by a number of questions and by four simulation scenarios based on Figures 1 and 2. Options A and B (detailed in Table 1) would both show a production line (Figure 1), respectively, with a one piece even flow (thus no queues or WIP) and with an uneven flow (thus creating WIP between the stations). The same logic would apply for options C and D (also detailed in Table 1) but instead of products, trades would move across the different rooms of the building (Figure 2). The experiment has the same structure for the first and third blocks (Table 1) which seeks to identify if people are able to perceive flow and queues in these two contexts. This is followed by a decision-making question to identify if they are able to recognise the negative effect of queues. The second block aims to identify if participants can recognize such phenomena in construction prior to seeing the simulations developed for this context.

Figure 1: Sketch for manufacturing simulation

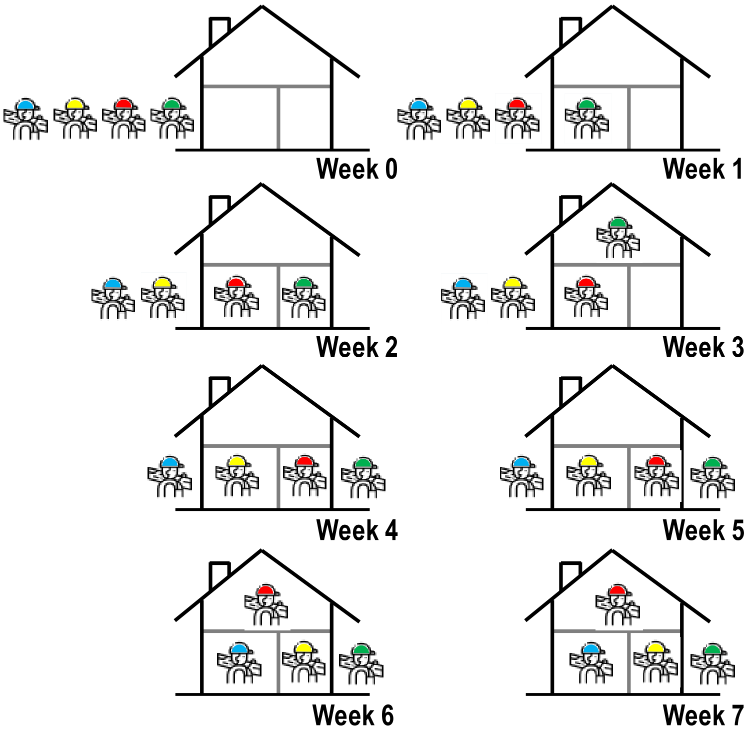

Figure 2: Sketch for construction simulation

Table 1: Experiment structure

Dynamics	Aim	Questions
Option A is shown (Figure 1 with an even and continuous flow of products) and questions 1 and 2. Same is repeated for Option B (Figure 2 with an uneven flow of products). Question 3 is asked.	Block 1 - Perception of flow and queues in manufacturing	1. Is there a flow? ( ) No ( ) Yes. Please describe it. 2. Is there a flow? ( ) No ( ) Yes. Please describe it. 3. If you are the factory manager, would you prefer option A or B? Why?
No image/simulation	Block 2 - Beforehand understanding of flow and queues in construction	4. Do “flow” and “queues” apply to construction? ( ) No ( ) Yes, for “flow” and “queues”. Please describe: What would be a “flow” in construction? What would be a “queue” in construction? ( ) Yes, for “flow” only. Please describe: What would be a “flow” in construction? ( ) Yes, for “queues” only. Please describe: What would be a “queue” in construction?
Option C is shown (Figure 2 with an even and continuous flow of trades) and questions 5 and 6 are asked. Same is repeated for Option D (Figure 2 with an uneven flow of products). Question 7 is asked.	Block 3 - Understanding of flow and queues in construction after analogy with manufacturing/ queues are made visible	5. Is there a flow? ( ) No ( ) Yes. Please describe it. 6. Is there a queue? ( ) No ( ) Yes. Please describe it. 7. If you are the site engineer, would you prefer option C or D? Why?

INCORPORATION OF COGNITIVE BIAS

A series of scenarios with four sequential construction activities (wall, flooring, windows installation, and painting) completed by two contractors (Tables 2 and 5) for a hypothetical high-rise building are proposed to test H5. Participants would be asked to select the preferred option: (i) *Contractor A*, (ii) *Contractor B*, and (iii) *Does not matter as both contractors will complete the building at the same time*. These scenarios and the answer provided can assess the understanding of underlying statistical assumptions (e.g. presence or absence of variability, effect of increasing levels of variability, etc) as shown in the captions for Tables 2 to 5. A “why” follow up question (after the closed ended ones) provides further insights on participants’ reasoning and rationale for the preferred option in each of the Scenarios.

Another experiment design related to cognitive biases in statistics can be also derived from the seven pre-conditions for task completion (Koskela 2000). Considering that the probability of each pre-condition being met is 0.95, the probability of completing the task, namely, having all six conditions met is only 0.70, resulting from 0.95^7 (Koskela 2000). This example presented in Koskela (2000) structured as an experiment has the potential to assess the misconception that the probability would be 0.95 (probability for each prerequisite condition) instead of the 0.70 (correct answer). Such bias is in line with previous ones such as the conjunction fallacy identified by Tversky and Kahneman (1983) in which people wrongly consider the likelihood of two events occurring in conjunction to be bigger than the likelihood of each event happening independently.

Table 2: Presence or absence of variability (Scenario 1)

	Contractor A	Contractor B
Walls	1 floor every 3 or 5 weeks	1 floor every 4 weeks
Flooring	1 floor every 3 or 5 weeks	1 floor every 4 weeks
Windows installation	1 floor every 3 or 5 weeks	1 floor every 4 weeks
Painting	1 floor every 3 or 5 weeks	1 floor every 4 weeks

Table 3: Effect of increasing levels of variability (Scenario 2)

	Contractor A	Contractor B
Walls	1 floor every 3 or 5 weeks	1 floor every 2 or 6 weeks
Flooring	1 floor every 3 or 5 weeks	1 floor every 2 or 6 weeks
Windows	1 floor every 3 or 5 weeks	1 floor every 2 or 6 weeks
Painting	1 floor every 3 or 5 weeks	1 floor every 2 or 6 weeks

Table 4: Effect of higher productivity upstream (Scenario 3)

	Contractor A	Contractor B
Walls	1 floor every 2 weeks	1 floor every 4 weeks
Flooring	1 floor every 2 weeks	1 floor every 4 weeks
Windows	1 floor every 4 weeks	1 floor every 4 weeks
Painting	1 floor every 4 weeks	1 floor every 4 weeks

Table 5: Effect of higher productivity downstream (Scenario 4)

	Contractor A	Contractor B
Walls	1 floor every 4 weeks	1 floor every 4 weeks
Flooring	1 floor every 4 weeks	1 floor every 4 weeks
Windows	1 floor every 2 weeks	1 floor every 4 weeks
Painting	1 floor every 2 weeks	1 floor every 4 weeks

The experiments discussed here are intended to explore a decision makers' comprehension of flow within the construction management domain. Though risk attributes and perceptions could be estimated by correlating and modelling demographic parameters of participants against the choices made in the second experiment (Wijayaratna and Dixit 2016), these fail to capture game theoretic scenarios that can occur (Kapliński and Tamošaitienė 2010). For example, "prisoners' dilemma" scenarios where individuals have an incentive to make decisions that are favorable for the individual but do not advantage the group/team objective are scenarios that need to be explored further in the context of flow. In addition, lack of incorporation of perfect and imperfect information is also a limitation of the experiments that are being designed. However, the experiments can provide valuable insights into comprehension of flow and the influence of statistical bias, which can lead to better educational tools built on the theoretical foundation of lean principles.

CONCLUSIONS

This paper presented a conceptual exploration on flow and why this concept is not yet flowing in construction practice. It started with the review of conceptualizations from different disciplines followed by a discussion of their connections with the construction context to understand and tackle the root causes of such a problem. The outcomes of the exploratory exercise were six non-exhaustive hypotheses that seek to answer the following question: *Why is flow not widely understood and disseminated in construction practice*? The lack of theory in flow (regardless if this entails more or less complicated conceptualizations) is likely to contribute to the problem. Koskela et al. (2019) has highlighted the emphasis (especially in the West) on developing practical methods and tools in education and training instead of investing in the clarification and establishment of fundamental theories. This can be an underlying reason for the lack of understanding of lean, including its application in construction. This resonates with Spearman and Hopp (2021), who criticise operations management for relying on simplified axiomatic models and/or ad hoc methods and heuristics, thus lacking a coherent science for how systems behave. Likewise, the emphasis on tasks (by the widespread use of CPM tools) as well as the matter view in costing and design areas (as reported in Rooke et al. 2007) further adds to the problem.

The first two hypotheses are not context specific and simply position that human beings would have an inherent difficulty (or perhaps a physiological impairment) in perceiving the world through a process-view, consequently meaning that flow and other process phenomena are intrinsically difficult to grasp. These hypotheses seem to be supported by research in other fields such as (Chi et al. 1994), yet a more systematic and comprehensive analysis of other disciplines needs to be carried out for more robust conclusions to be drawn. Another interesting avenue would be to examine the human perception process and cognition mechanisms. This can help uncover if the approach of separating a system into sub-components and to manage each sub-component individually (aligned with the matter or T view) is innate or wired in human brains to enable us to process and make sense of all the stimulus of the world surrounding us. The other hypotheses are context specific and assume that construction (further) hinders the comprehension of flow. To some extent, this second set of hypotheses is independent from the first one. H1 and H2 can be corroborated, but if flow in this setting is indeed invisible (or less visible than in other contexts), an additional hindrance in its realization applies.

Different from H1 and H2, which would rely on literature review, two experiments are proposed for the testing the other hypotheses: three blocks of questions (Table 1 and Figures 1 and 2) for H3 and H4 and a multiple choice repeated questionnaire for four different scenarios (Tables 2 to 5) for H5. The second experiment is in line and inspired by the work carried out by Tversky and Kahneman, and thus can be viewed as an extension of the exploration of cognitive biases related to statistical thinking carried out by the referred authors to the construction context. The first experiment on the other hand was designed to evaluate a new notion proposed here: the invisibility (or not) of flow and the impact of the specific features of construction in that regard. The next step of this research will entail the pilot testing and refinement of the two experiments followed by a large-scale data collection with industry practitioners to enable a statistical analysis to be performed. The open-ended questions will help understand the black box of such quantitative results, providing insights into the "why" and "how" behind the reasoning around flow in construction practice.

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PUTTING THE COLLABORATIVE STYLE OF A SUCCESSFUL FOOTBALL TEAM IN A LEAN CONSTRUCTION CONTEXT

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ABSTRACT

The Norwegian football club Rosenborg BK (RBK) was a well-recognized force in European club football during its heyday in the 1990s. Led by the legendary coach Nils Arne Eggen, they regularly shocked Europe's top teams with great results after implementing a successful philosophy based on collaboration. The importance of collaboration is well-emphasized in Lean Construction (LC) theory, but more discussion about creating a willingness and culture for collaboration seems to be lacking. Therefore, this conceptual paper suggests broadening the existing theory by presenting Nils Arne Eggen's "Best Foot theory" principles through a new theoretical lens. The collaborative "Best Foot theory" is seen in an LC context and discussed with the "Five Big Ideas" presented by Lean Project Consulting, Inc. as the starting point. The "Best Foot theory" expands current theory by giving successful practical examples to create a culture for the practitioners in a performance group to *want* to collaborate.

KEYWORDS

Lean construction, collaboration, culture, trust

INTRODUCTION

With the emergence of Lean Construction (LC) in the Norwegian AEC industry (Lohne et al., 2021), the term *collaboration* emerges in a new context. This paper seeks to present a different perspective to a collaboration-based theory used by a Norwegian football team by linking it up against the "Five Big Ideas" presented by Lean Project Consulting, Inc. The five big ideas are: 1) collaborate; really collaborate, throughout design, planning, and execution, 2) optimize the whole, 3) tightly couple learning with action, 4) projects are single-purpose networks of commitments, and 5) intentionally build relationships on projects (Macomber, 2004). The importance of collaboration is well-established in LC literature (e.g., Tzortzopoulos et al., 2020), and according to Simon and Varghese (2018), lean concepts can only be successfully adopted when they align with the organizational culture. Still, there is limited literature about creating a collaborative culture in lean construction projects. A search for papers at iglc.net with the search words "collaborative culture/mindset" returned only three papers. Therefore, this paper intends to encourage a shared discussion about implementing a collaborative culture/mindset by presenting the collaborative performance of a successful sports group and linking it to the LC theory.

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"No man is an island," John Donne famously wrote in 1624 (Donne & Robbins, 2014). This phrase significantly describes the essential part of Nils Arne Eggen's "Best Foot theory," which was the foundation of the Norwegian football club Rosenborg BK's (RBK) European success in the late 1990s and early 2000s. The collaborative RBK mindset is well known in Norway, particularly in RBK's hometown Trondheim. The term "collaboration" summarizes Nils Arne Eggen's ideas on how many people, in general, interact through a Nordic social-democratic mindset. One of the ground pillars in Eggen's theory about collaboration is to make yourself and your teammates better by playing on each other's strengths.

The term "Best Foot" is an expression of the principles in Eggen's theory, which is to understand and reinforce both individual and team members' core skills to get the best common result. The key is to give all an opportunity to expose their unique expertise. Everybody must be open and explicit about their skills and communicate with the other teammates to exploit this opportunity. Collaboration is far more effective if all actors willingly pull in the same direction, and the relational skills of a group are far greater than the sum of isolated individual skills. Eggen himself summed up the "Best Foot theory" on the front cover of his book: "collaboration – the road to success" (Eggen & Nyrønning, 1999). With collaboration based on the "Best Foot" principle at the core of their operation, RBK won the Norwegian league from 1992 until Eggen's retirement in 2002 and continued to win in 2003 and 2004, making it a total of 13 consecutive championships. In addition, the team qualified for the UEFA Champions League and competed with Europe's best teams during this period. While football was already professionalized in the biggest European clubs, RBK's success was achieved almost exclusively by local and regional semi-professional players.

This paper aims to conceptualize the ideas brought forward by Eggen by looking at them in an LC context, with a basis in the "Five Big Ideas." The ideas presented and analyzed in this paper are mostly taken from Eggen's book in Norwegian, "Godfoten," and supporting contributions from TV documentaries, podcasts, and articles related to his ideas. It is acknowledged that a limitation of the research is that the two main approaches in this paper, "Best Foot theory" and "Five Big Ideas," might not be applicable in other domains, as relatively few people constructed the approaches within their domain. The research question of this paper is: *Can collaboration techniques from another performance environment inspire lean construction theory?*

The paper has been structured as follows. First, LC theory about collaboration is presented. Next, the methodology is described. Then, the "Best Foot" theory is presented, and the ideas are discussed in an LC context. Finally, a conclusion is given.

COLLABORATION CULTURE IN A LC CONTEXT

A project's performance is affected by how well the principal (i.e., project owner/client) and agent (i.e., project manager/contractor) cooperate. According to Müller and Turner (2005), the best project performance is obtained through a collaborative approach. Collaboration is considered a vital element of LC (Engebø et al., 2020; Haghsheno et al., 2020; Garcia & Murguia, 2021). Collaboration is also a central element in the "Five Big Ideas that are Reshaping the Design and Delivery of Capital Projects," presented by Lean Project Consulting, Inc. at a Sutter Health conference in 2004. The five ideas can be considered as a foundation for creating a lean organization culture and are as follows (Kraakenes et al., 2019):

1. Collaborate; really collaborate, throughout design, planning, and execution. Reduce scope changes late in the project by close collaboration between teams early in the project development.
2. Optimize the whole. Collaboration at the project level reduces conflicts and disputes caused by push management and productivity management at task level.
3. Tightly couple learning with action. Secure continuous improvement.
4. Projects are single-purpose networks of commitments. Commitments bind teams and their members within projects.
5. Intentionally build relationships on projects. Improve project relations by establishing trust, openness, a willingness for innovation, and the ability to learn.

The term collaboration is sometimes confused with cooperation. Schöttle et al. (2018) examined the difference between these two terms in an LC context and found that the relationship between project actors is stronger in collaboration than in cooperation. In both terms, the actors are dependent on other actors to reach their goals. However, whereas cooperation is an inter-organizational relationship based on independent structures without a shared vision or mission, collaboration is created by developing a shared goal and a jointly developed project culture based on trust and transparency. Gomes and Tzortzopoulos (2020) divide the several developments that support collaboration in LC into:

- **Collaborative contracts**: new ways of arranging contracts and procurement procedures to facilitate collaboration among stakeholders. An example of this is relational contracts where risk and profit are shared across the project actors, "forcing" the project actors to collaborative activities.
- **Collaborative systems**: several conceptual approaches in LC theory are developed in a way where the execution of the process will require a certain level of collaboration. One example is Target Value Delivery, with joint decision-making to increase value of all aspects related to a project's outcome.
- **Collaborative approaches**: measures implemented to encourage collaborative decision-making processes. The use of a big room and co-location are examples of how projects can create an environment for multi-disciplinary and collective decision-making.

Garcia and Murguia (2021) classify collaboration into four dimensions: trust, project uncertainty management, client's operational capability, and business relationships. They argue that client attributes and supply chain capabilities are the most influential and uncertain factors in deciding the collaboration level in an inter-organizational relationship. Nguyen and Waikar (2018) stress the importance of a collaborative culture for a successful implementation of Lean but do not elaborate further on the subject. Ahmed et al. (2018) discuss the lack of collaborative culture in UK construction. By looking at the performance of quantity surveyors, they concluded that factors such as persistent practices, inefficient procurement approaches, and narrowed views on collaboration hindered a better collaborative performance. Hunn and Fyhn (2019) present a framework for building and sustaining a culture with a collaborative mindset for disruptive performance. They argue that, in addition to a structured set of rules, you also need experienced and ambitious leadership, commitment from leaders to reinvest and sustain the culture, and transparency and trust among all members of the organization.

METHOD

This paper has a conceptual approach by analyzing already accessible data from another branch of knowledge presented in a different context to offer another perspective to the LC literature. Jaakkola (2020) presents four types of research design for conceptual papers: theory synthesis, theory adaption, typology, and model. The research design in this paper is the theory adaption type. Theory adaption is described as "C*hanging the scope or perspective of existing theory by informing it with other theories or perspectives"* with a goal of *"Expanding the application domain of an existing theory or concept by introducing a new theoretical lens*" (Jaakkola, 2020, p. 22). According to Gilson and Goldberg (2015, p. 128), conceptual papers do not need to present new theories but rather "*bridge existing theories in interesting ways, link work across disciplines, provide multi-level insights, and broaden the scope of our thinking."* There are some things to consider before deciding to write a conceptual paper. Cropanzano (2009) argue that the authors need to overcome three problems to write a good theory article:

- **The "So what?" problem**: Additional theory on the chosen topic needs to contribute considerably to the reader beyond what is already accessible.
- **The integration problem**: If the author gathers various sub-theories with different research ideas and presents them without a unified purpose, the article may end up as a series of mini-reviews rather than an integrated whole.
- **The breadth problem**: Conceptual articles are targeted, leading to an article presenting a narrow set of ideas and a list of hypotheses more suitable as an introduction to an empirical study than an independent study.

A conceptual paper does not have empirical data. The conceptual paper data equivalent to data from empirical research is an analysis of chosen theories and concepts (Jaakkola, 2020). In this paper, the primary source is a book containing the theories and concepts brought forward by RBK's head coach, Nils Arne Eggen, during the club's most successful years (Eggen & Nyrønning, 1999). His theory is thoroughly explained with practical examples. However, the book is slightly outdated, so additional sources from more recent years have also been used, including two TV documentaries where Eggen and several former RBK players were interviewed (Hansvoll & Westereng, 2016; Toldnes & Grytøyr, 2019), two podcasts in Norwegian where Eggen was invited as a guest (Sundet & Lidbom, 2016; Sagbakken & Rasmus, 2021), and one Swedish podcast who thoroughly described Eggen's philosophy and the team's 1996/1997 season, but where Eggen did not participate himself (Niva & Andreasson, 2020). All the text in the "The Best Foot theory" section is based on the abovementioned sources. The author has assembled information from all the sources and, with the help of his understanding and knowledge of the theory, was able to write a summary suitable for academic work. In this way, additional and more recent information was added when Eggen's book proved insufficient.

Since the analyzed theory is placed in an LC context, a literature review on collaboration in Lean Construction has been conducted.

THE BEST FOOT THEORY

ROSENBORG BK'S IDEOLOGY/PHILOSOPHY

A central principle of the "Best Foot theory" is to acknowledge that all skill is complementary: you are excellent or mediocre together. To be good at something is not an individual achievement. With this in mind, you can develop relational skills. With

Eggen at the helm, RBK formulated several so-called *postulates*, short sentences that the organization was to live by and follow. Some of them are mentioned in this text as quotes by Eggen. The team's practical philosophy is based on basic ideas common to everyone involved in the organization. These basic ideas are described in the following.

Our success is the learning of skills

Eggen divides practice and learning into two different terms. Practice is considered a necessity for learning, but not every practice provides improvement. Learning in a team is about changing the attitude of individuals positively and long-lastingly. The most important aspect of learning in RBK is associated with the learning of individual skills related to the collective collaboration pattern. This is essential in football, where a complicated cooperative collaboration pattern, with principles, formations, and systems formed as a playing style, is crucial for performance. *Practice* needs to be arranged to clarify what is to be learned for the practitioner. First, he must *understand* the skill he will learn and perform it best. Next, he must *recognize* the current learning moment, the skill, in the learning situation. When these two principles are achieved, reinforcement can streamline learning. When the practitioner has understood, recognized, and positively reinforced the learning moment, the learning process must be repeated until the correct solution has stained the practitioner's brain. Only when that occurs has one truly learned.

This type of *convergent* learning is primarily applicable for creating individual and collective movement patterns for improved team play. RBK used it for improving every type of skill. The big drawback of the model is that it can prevent creativity and new solutions, ultimately excluding improvement. For higher quality practices, Eggen realized they also needed to consider *divergent* learning, which adds this creative dynamic necessary to search for better solutions, both collectively and individually. However, the convergent learning points create the foundation for where divergent creative learning can take place. Eggen compares it to jazz improvisation: "Only when the common theme is settled and under control, the creative improvisation and further development make sense" (Eggen & Nyrønning, 1999, p. 125).

According to Eggen, football skills are not limited to techniques in the sense of how shots, tackles, dribbles, etc., are performed. It is about how these technical attributes are used in collaboration with the team players' movements and technical skills, in specific situations, and relative to the opponent's movement. In short, football is an intelligent game, and what is happening inside your head might be even more important than what you can do with your feet. A wide specter of basic skills becomes prerequisites to perform a specific activity – for instance, the correct tactical and technical choices in football. According to Eggen, there are six essential factors for learning skills:

- **Technical**: These skills are the ability to perform the actual execution of an action, such as passing, shooting, receiving, heading, or dribbling the ball.
- **Tactical**: These skills are about understanding the technical skills' situation. An assessment of the situation with teammates, opposing players, the ball, and the field constitutes the overall picture.
- **Physical**: These skills are based on physical resources like endurance, strength, height, speed, etc.
- **Psychological**: These skills consist of a set of partial skills hugely connected to nature or nurture. In football, such skills could be fast recognition of correct solutions, the ability to calculate the speed of the ball, and other players'

movement at the same time (also called *timing*). Closely related are cognitive skills, such as processing and interpreting a recent observation.

- **Social**: These are collective consequences of individual psychological skills. It is these skills that transform individuals into team players. The most important attribute is the ability to cooperate, which develops into collaboration. The highest form of collaboration is achieved when a group of practitioners goes from *having to* and over to *wanting to* achieve the same.
- **Pedagogical**: The prerequisite to achieving that every group practitioner *wants* to pull in the same direction lies in developing the individuals' pedagogical skills. This is the ability to make other individuals better and take responsibility for the team's and other individuals' development and performance.

These skills develop over time. First, technical skills are learned. Next, you learn to exploit these skills tactically. In the end, you learn to use the skills to make your teammates and team better.

Our performance goals are a product of continuous improvement

The second foundation of the RBK philosophy naturally follows the first one. There is nothing more demotivating for a group than when leaders, far from the process, present way too ambitious performance targets without any plan for *how* to achieve those targets. The RBK model was inspired by Japanese management theory about quality-based process management, where workers and leaders work together with joint responsibility for the best possible result and performance. Eggen implemented this mindset with *involvement* as a key term, with the postulate "Involvement is the best quality assurance" (Eggen & Nyrønning, 1999, p. 148). The idea was that when the players are allowed to affect the process, they develop a responsibility for the quality of the process and its result.

The "Best Foot theory" is inspired by the Japanese mindset found in *Gemba* and *Kaizen*, two well-known terms in Lean theory as they are vital principles in the Toyota Production System. Gemba is the actual place where real added-value work is done, and Kaizen is the Japanese term for continuous improvement (Liker, 2004).

Be resolute, creative, and solution-oriented

The year before Eggen's first term as manager, RBK finished second in the league and lost only a few games, conceding only five goals. However, they barely scored goals (15) themselves. Their 18 matches had an average of 1,1 goals per game. As a result, few supporters attended the home games even with success in the league. This made Eggen realize the value of providing entertaining football. He said, "No supporter should pay hundreds of kroner just to watch throw-ins from the sideline!" (Sundet & Lidbom, 2016).

In 1988, RBK exposed how they wanted their appearance on the field to look. They wanted to be recognized for *fun, attractive, and supporter-friendly football*. Eggen said, "It is a fundamental difference in football if you aim at many goals or concentrate on preventing your opponent from hitting the goal. The former is *creative*, while the latter is *destructive"* (Sagbakken & Rasmus, 2021). For Eggen and the team, to be resolute and creative meant something more in a larger context. It is meant to be solution-oriented rather than problem-oriented. Winners are looking for opportunities in every aspect of the game, while losers pay attention to the problems. Problems often appear during a rapid change in the game. This is when we benefit from being creative and positive. People commonly resist change and waste much energy in this opposition, while a high-performance group with a resolute mindset is more forward-looking. Instead, they do not waste energy on past incidents and are more concerned about what is next to come. Even after his biggest victories, Eggen used to say, “our most important match has not been played yet.”

Have a high spirit and temper

Eggen argued that no one could perform if they are dead serious all the time. You need to see the laughter in seriousness and the seriousness of laughter. A good mood can be learned, and with a good mood, it is easier to tolerate a bad mood that is later destroyed by laughter. A good mood creates a culture of openness and trust in the performance group. It regulates tension, especially the temper and aggression necessary in a competitive context. Eggen formed a postulate: “In Rosenborg, you are allowed to lose your temper. But only for one second at a time!” (Eggen & Nyrønning, 1999, p. 157), and he meant that good mood and humor are every performance group’s life elixir. They fill the psychological energy tank and enable conflict solving. Take joking seriously. Cultivate humor and humorists.

Act admirable

Be humble and act normal and likable, no matter how good or bad you performed in the last match. Good performance needs to be recreated each game, and the last game quickly becomes history. Everyone is individually and collectively responsible for creating an image they want related to the club through behavior on and off the pitch.

RBK shall be accessible to everyone with an opinion and emphasize *accessibility* and *transparency/openness*. The symbol of this openness was the team’s clubhouse. During the height of RBK’s success, the clubhouse was open for a visit for everyone, particularly fans and journalists. There, they could drink coffee and chat with old and new players, coaching staff, fans, and old club members. Through this accessibility and transparency, the team created a culture for gaining valuable resources through watching and speaking with people with relevant skills. “Show us your skills and how to implement them in our team,” Eggen said (Eggen & Nyrønning, 1999, p. 168). His view was that such an attitude was a basic for all relational skills created and maintained as open and tacit knowledge.

An important aspect of Eggen’s philosophy was to entertain the local community. He said, “Rosenborg shall be a team of locals, for the locals” (Niva & Andreasson, 2020), meaning that the team’s core should consist mainly of talent raised in local and regional clubs. This was to make it a big honor for locals to play for the club and increase the local pride when it achieved success. Besides, Eggen was adamant in his belief that young local players were just as able to secure team success as expensive and established foreign players. In 1997, RBK beat AC Milan 2-1 at San Siro stadium in Milano, arguably their most memorable victory. They achieved it with a starting line-up that consisted of as many as nine (out of eleven) local players.

“The Best Foot”

“The Best Foot” is an expression that spins off that most football players are either right-footed or left-footed. In short, it means that, for instance, a right-footed player should be allowed to improve and exploit his right-footed skills, while it is sufficient for him only to maintain his left-foot skills. However, it is essential that his teammates know his strengths and put him in positions to do his job in the best possible way. In this example, the teammates should play the ball to his right foot. If his teammates do not know he is a right-footed player, they might constantly pass the ball to his weaker left foot. Short-term, this would hamper the team’s attack and scoring chances. Long-term, the player receiving the ball would need to increase his left-foot skills, which would prevent the improvement of his right foot. This is, of course, a banal example, simplified to make the theory understandable. Most people have more than one strength, a football player's "best foot" might even be that he or she can play well with both feet, and any person's skills are not limited to only physical or technical skills.

If each individual practitioner performs his role correctly, the player with the ball knows his teammates' exact movements and can act accordingly. Still, the roles did not necessarily limit any players' creativity. This creative freedom was likely an important reason RBK could repeat their success for a decade, even when they had to replace the players that went to bigger European clubs. New players could perform in their own way, within the limits of the designated role. However, the practitioners should not be too creative outside their role because that means a risk of putting their teammates in an uncomfortable situation.

Attacking play was the collective RBK's "best foot." In Eggen's eyes, it was "suicide" to play a defense-minded playing style, no matter the opposition or score in a game. This belief was based on the fact that they never practiced that type of play. This mindset caused some occasional ugly defeats, a 2-7 defeat against Paris Saint-Germain in 2000 being the worst, but it also gave the team many remarkable results. Among these results are wins against reigning champions from England (2-1 against Blackburn in 1995), Italy (2-1 against AC Milan in 1996), and Spain (2-0 against Real Madrid in 1997, the only game Real Madrid lost when they won the Champions League this season). They also humiliated SK Brann in the Norwegian league with 9-0 in 1994 and then 10-0 against the same team two years later (Transfermarkt, 2022a, 2022b).

To put these results in a Norwegian context to show the extraordinariness of the feat for foreign readers: the only other Norwegian team that has ever even managed to qualify for Champions League is Molde, once, in 1999. They won one match and lost five.

THE "BEST FOOT THEORY" IN A LC CONTEXT

How does the "Best Foot theory" fit in an LC context? The question is answered by evaluating the theory compared to Macomber's "Five Big Ideas."

Collaborate; really collaborate, throughout design, planning, and execution

Gomes and Tzortzopoulos (2020) divided collaboration in Lean Construction into collaborative contracts, systems, and approaches. There is much about facilitating collaboration in the Lean Construction literature, e.g., sharing risk and creating collective ownership of the task at hand. However, there seems to be a gap in theory on how organizations can act great at collaborating beyond being bound to it through contracts, systems, and approaches. The railroad construction project Venjar-Langset is an example of a project that achieved a collaborative culture without having formal structures primed toward collaboration (Klakegg et al., 2021). They meant that the involved participants were more vital for the collaborative culture than the formal structures. The "Best Foot theory" might have something to offer in such ways.

The "Best Foot theory" urges every actor to play on their absolute strengths while still having unity as a top priority. Play on your strengths to make your colleagues better and allow them to make you better. It is necessary to acknowledge that others can bring more suitable solutions to the table to achieve this.

Optimize the whole

The second big idea is to optimize the whole and avoid silo thinking, which is also the essence of the “Best Foot theory.” You allow yourself to use your core skills, but you do so with the collective performance in mind.

With a basis in Gemba, Eggen saw a value in aiming at product development by centering the organization around the actual producing part, the football players. The team also created a culture for the actual value-adding producers (the players) to bring forward ideas. The Kaizen mindset was evident in the continuous improvement of the collaboration between the players and their strengths and the will to strive to be better than the last game, both in terms of results and skills. Well-summarized with Eggen’s postulate, “our most important match has not been played yet.”

Tightly couple learning with action

The third big idea highlights the importance of learning from each action. Macomber (2004) mentions the *Deming Cycle* approach, Plan-Do-Study-Act for learning, which is interesting because Eggen also used this learning approach in the team (Eggen & Nyrønning, 1999, p. 205).

RBK believes a broad spectrum of basic skills becomes prerequisites to perform any specific activity. These skills are divided into technical, tactical, physical, psychological, social, and pedagogical skills, and they develop over time. First, technical skills are learned. Next, you learn to exploit these skills tactically. In the end, you learn to cooperate, which develops into the ability to collaborate, which is to use the skills to make your teammates and the team better. True collaboration is achieved when the practitioners take responsibility for their own and their teammates’ development and performance. Then, the whole performance group is pulled in the same direction.

Projects are single-purpose networks of commitments

We believe that the “Best Foot theory” can inspire organizations in construction projects to collaborate fruitfully. In a project, a group of strangers is put together in a temporary social system, where the project leader should *activate a network of commitments*.

The most significant difference between RBK and LC projects is that there is much practicing in a sports organization with only 90 minutes of actual production one or two times per week. In projects, there is constant production and minimal practicing. Still, the reality is that the practitioners in both cases have a common goal: to beat the opponent for RBK or achieve an excellent project performance in an IPD project. The key is to achieve the same commitment in a producing environment as in a practicing environment. For RBK, accessibility and transparency were crucial for achieving a collective commitment throughout the organization. The key with the “Best Foot theory” is to make the performers go from having to collaborate to wanting to collaborate, believing that all skill is complementary: you are either good together or bad together.

Intentionally build relationships on projects

Frictions and minor conflicts are expected in inter-organizational relationships. According to Macomber (2004), we cannot learn, collaborate, optimize or make commitments in a project without a relationship based on trust, respect, appreciation, care for each other, and practices for commitment-making. Projects will be faster on track to success when the team members become friends. Five steps are suggested in the fifth big idea: 1) explore each other’s personal intentions and ambitions, 2) cultivate practices for commitment-making, 3) make it your habit to acknowledge and appreciate team members,

4) foster an environment for healthy conflict, and 5) make the project setting a place where people can be their authentic selves without fear of judgment or mockery.

These steps are strikingly similar to much of what has been presented about the "Best Foot theory" above. However, the "Best Foot theory" also adds humor to the mix. A good mood creates a culture of openness and safety in the performance group. It regulates tension, especially temper and aggression, in a competitive context. A good mood kills a bad mood with laughter. In RBK, minor conflicts were used to positively improve the project by creating discussions where better solutions for all parties involved were found. You are allowed to be angry, but only for one second at a time.

The "Best Foot theory" is also applicable in a broader context. For RBK, attack-minded football was seen as their "best foot." Malvik et al. (2021) describe a project where the choice of procurement procedure did not suit the project's chosen collaborative project delivery method. The project chose what they believed to be the best contractor without considering if the best contractor was the best collaborator. The procurement method would be more suitable for a transactional project delivery method. A better choice would be to choose a dialogical approach, playing on the collaborative delivery method's "best foot" by considering the collaborative nature.

CONCLUSIONS

This paper set out to change the scope of existing theory by informing it with another existing theory introduced through a new theoretical lens. This was achieved by answering the research question, "*Can Collaboration techniques from another performance environment inspire lean Construction theory?"* To decide if the paper reached its intended purpose, we look at the research regarding the three problems that a conceptual paper needs to overcome (Cropanzano, 2009).

The "So What?" problem demands that additional theory contributes considerably to what is already accessible. The "Five Big Ideas" were used as a starting point for the Lean context to answer the research question. The "Best Foot theory" shows great applicability in a Lean context by possessing many of the same principles. However, the theory presents solutions that expand the existing collaboration theory in an LC project. Much of the current theory about collaboration in LC projects focus on collaborative contracts, systems, and approaches and fails to consider creating a collaborative culture among the performers. The "Five Big Ideas" are contemplating this, and the "Best Foot theory" adds more meat to the bones by giving successful practical examples for each idea.

The integration problem calls for an integrated whole rather than various sub-theories without a unified purpose. The unified purpose of the paper is to create a collaborative culture in an organization.

The breadth problem emphasizes that conceptual articles should not present a set of ideas and hypotheses too narrow to suit an independent paper. A collaboration mindset that can inspire further development of the LC theory is proposed, and the RQ is thus answered. However, the limited length of a conference paper has affected the scope, and more research is needed to prove that the theory works in a construction project, which should be positioned as future research. That would require creating an implementation strategy, which is the logical next step for putting the theory into practice. A good idea would be to test the theory in a construction project that plans to use a collaborative approach, such as an IPD or alliance project. Another plan for further research is to look deeper into how Eggen's six learning points can relate to learning in the construction industry.

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LEAN SIMULATION GAME WITH BIM-BASED PROGRESS MONITORING FOR TAKT CONTROL

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ABSTRACT

Lean Construction (LC) and Building Information Modeling (BIM) are two approaches that help to optimize, structure, monitor and control processes better. As a method of LC, Takt Time Planning (TTP) and Takt Control (TC) can lead to an increase in productivity and value creation, as the associated processes are an essential part of the value chain in the construction industry. But while there are already some solutions to link these methods in real life, simulation games in education are currently mostly done analogously and detached from the BIM model. As a result, the benefits of BIM in terms of regularly updated building data are not fully exploited within the simulation game and thus not made clear to the participants.

This paper examines how digital support for TC can be integrated within a LC simulation game. For this purpose, an analogue building model is linked to an associated 3D building model through QR codes and enriched with information about the stage of completion during the process of TC. The possibility of linking both models shown here manages to highlight the advantages of the BIM method and inspires the participants to apply this to their projects.

KEYWORDS

Serious gaming, Lean Construction, Takt Time Planning (TTP), Building Information Modeling (BIM), phase scheduling.

INTRODUCTION

BIM and LC can be considered state of the art in construction project planning and control, as they are promising methods to improve the whole construction process. Both methods pursue the same goals, except that BIM focuses on the product and LC on the process. Therefore, it makes perfect sense to aim for a combination of both (Melzner, 2019). Gradually, the continuous monitoring of performed data on the construction site to support planning is playing an ever-increasing role. It creates up-to-date information that forms the basis for checks on the progress of the project and for generating analysis and forecasts, so that informed decisions can be made on this basis (Jacobsen et al., 2021).

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Still, there needs to be a tightening of Lean and BIM Methods in relation to supplying actual data via tracking technology (Heyl & Teizer, 2017).

The situation in practice is also reflected in the simulation games on LC. While LC teaching usually focuses solely on teaching lean principles, digital issues often receive little attention. But a simulation game offers an optimal playground for testing ideas on a small scale. This paper presents an analogue simulation game concerning TTP and TC and shows employing a case study one way in which LC and BIM can be linked through QR codes. The aim is to see how feasible the link between LC and BIM presented here is and whether it adds value to the simulation.

STATE OF THE ART

TAKT TIME PLANNING

At present, digital models are often inadequate in practice and links with processes and resources are not fully digitally recorded. In addition, information on the determination of the Takt of manufacturing processes is often recorded in separate document-based systems (Frandson, 2019; Haghsheno et al., 2016; Yassine et al., 2014). The complex relationships between the BIM model and the TTP are therefore not digitally recorded (Leifgen, 2019).

TTP is currently carried out on this information basis in a predominantly manual way with standard software such as spreadsheet calculation software (Haghsheno et al., 2016). Lean software solutions are also used in some cases, for example VisiLean as an integrated Lean and BIM solution (Dave et al., 2011). But most of the time they are limited to the process level only and do not link to building models or other information domains, like for example BIM 360 (Autodesk, 2022) or vPlanner (Ghafari Associates, 2022).

TTP is a complex optimisation task with several target variables. The aim is to create a plan that makes it possible to build the building in the desired quality in the shortest possible time with an optimal use of resources and at the lowest possible cost. For the current approach several iterations with different variants usually have to be calculated before a decision for a plan is made (Leifgen, 2019; Schmidt & Teizer, 2020; Frandson et al., 2015).

Through a link with the BIM model, at least parts of the TTP could be automated, such as the determination of the Takt areas. Based on this, the always up-to-date planning status can make it possible to carry out regular plausibility checks and prevent implausible planning at an early stage (Schmidt & Teizer, 2020; Sommer, 2016).

TAKT CONTROL

In the execution phase, permanent monitoring and control of the construction processes takes place within the framework of TC. The basis for this is the constant monitoring, processing, availability and visualisation of information about the current status of the construction site (Haghsheno et al., 2016). As a central control tool, Takt Control Boards (TCB) are used for each Takt section in a construction project that is planned according to the Takt principle. Takt, floor plans, construction time schedules, etc. are displayed on them (Haghsheno et al., 2016; Sommer, 2016).

When working with analogue TCB, newly acquired information is initially only recorded daily and locally on the construction site (Binninger et al., 2017). In order to transfer this information into a digital system, such as digital construction models, digital schedules or digital construction diaries, it must be digitalised afterwards (Leifgen, 2019).

In addition, a major challenge is the spatial separation of the monitoring of data and its users. The collection of data gained through the TCB would theoretically enable detailed reporting. However, construction companies are often involved in several widely distributed construction projects. It is therefore not sufficient to present information on the progress of the construction site exclusively in analogue form on site (Benninger & Wolfbeiß, 2018).

LEAN CONSTRUCTION SIMULATION GAME

Experience has shown that purely theoretical training is not as effective as training that combines theory and practice. The reason for this is that theoretical knowledge learned in simulation games can be actively tested directly and is thus not only better remembered, but also allows the advantages of the methods learned to be recognized directly in a playful manner (Binninger et al., 2017). In this way, the transfer of lean principles to the construction industry can be made clear and engrained patterns of thought can be broken.

In the field of TTP and TC, various games have already been developed by consultancies or in-house (Teizer et al., 2020). One of these games is the hotel model presented here, which was created according to VDI guideline 2553 for specialists and managers as well as process managers from construction-related sectors such as building owners, architects, project developers, engineering offices, construction companies or construction suppliers. Figure 1 shows the model as a whole and Figure 2 shows the drywall components as an example.


Figure 1 and 2: LC game hotel model (figure by authors)

The aim of training with this model is to teach the basics of TTP and TC. An understanding of the Lean values is conveyed by the participants themselves experiencing what is value creation and what is waste. In addition, soft skills such as team building, appreciation of the customer, communication, and cooperation are also taught (Binninger et al., 2017).

So far, there has been no connection to a digital model. In the modern world, it is generally no longer sufficient to do the monitoring of the manufacturing process in analogue alone. Large construction sites are often so complex that several TCBs are needed simultaneously for different areas. In addition, a construction manager, like the subcontractors, often oversees several construction sites at the same time (Dlouhy et al., 2016). Only a digital solution about the current production status can provide the necessary overview and at the same time also support the formation of key figures, which in turn are the basis for decision-making for the further planning of the construction site (Sommer, 2016). Therefore, it is important to map the interaction of digital and analogue in the simulation as well.

PROCEDURE OF THE LEAN CONSTRUCTION SIMULATION GAME

The simulation game presented here has already been established in LC workshops. However, there are no publications on it yet. Accordingly, the process of the game is presented here in detail.

The entire game is divided into three stages, in which the participants try anew each time to finish the hotel. At the end of each stage, the participants themselves reflect on the points in the construction process where they see an opportunity for improvement. Through reflection and theoretical knowledge imparted between the stages, the participants acquire more knowledge bit by bit, which they apply directly in the respective game stages. This simulation game is accordingly orientated toward the five levels of reality like it is described in Binninger et al. (2017).

At the beginning of the game, each participant is assigned a different role: There is a client, a construction manager, a building inspector, and the trade partners needed for the construction of the hotel. The hotel commissioned by the client must be finished according to a specified schedule within 22 minutes, where one day corresponds to one minute. For this, the participants receive components, some of which still have to be manufactured. The execution of some trades depends on the decisions of the client, which he only makes during the course of the game.

FIRST STAGE - WITHOUT LEAN APPROACH

In the first stage, the participants start with the construction of the hotel according to the schedule. Yet, they have not received any introduction to TTP and TC. This inevitably leads to a very unstructured, uncommunicative and inefficient way of building. Typically, the participants therefore barely finish even one of the specified rooms.

In the debriefing of the first stage, the participants note that there were no clear agreements between the trades, which led to a lack of clear structures for who works on which room and when. As a result of this inefficient way of working, there is a lot of time pressure at the end of the construction stage, which in turn leads to poor quality.

SECOND STAGE - TAKT TIME PLANNING

In the second step, the participants are taught the eight steps of TTP similar to how it is described in Binninger et al. (2017) and Frandson et al. (2013). This leads the participants to finding the Standard Space Unit (SSU), in this case two hotel rooms, and defining work packages for every SSU in the right sequence. Next, they allocate detailed work steps to every package and calculate the amount of work for every step. They then agree to a Takt time, which in the game is one minute, and perform Takt levelling. Following this, the trade groups are staffed according to the results of the Takt levelling and a construction strategy plus the Takt schedule are determined. Each trade is given a Takt schedule as shown in Figure 3, on which it can view its operating times. In addition, the trades that are dependent on the client's decisions receive a sheet as shown in Figure 4 on which the client must have entered decisions by certain dates.

Figure 3 and 4: Takt plan of a trade and sanitary objects with client decision sheet (figure by authors)

In the debriefing of the second stage, the participants note that the construction phase went much better than before. This time, some rooms have already been completed, even if the entire hotel was not finished in the allotted time. Despite the strong improvement, the participants should look for further opportunities for improvement, true to the Lean approach. The lack of construction meetings between the Takts is usually mentioned, in order to determine whether the previous trade has actually been completed, or whether deficiencies need to be remedied so that other trades can continue to work.

THIRD STAGE - TAKT CONTROL

In the last stage, the participants are taught TC so that they now conduct regular (minutely) meetings on-site. These meetings are moderated by the construction manager and managed through a standardized TCB. That leads to another improvement of the building process as the persons responsible for execution are integrated in problem-solving processes.

The third stage of the simulation game is also carried out in an analogue way alone. In the course of the Continuous Improvement Process, it should be questioned to what extent a link with the digital model can lead to an increase in customer value.

IMPLEMENTATION OF THE DIGITAL MONITORING

The simulation game has already been played with hundreds of participants within two-day LC workshops. From these previous workshops, the question about the digitisation of the TTP and TC came up repeatedly in the feedback forms and discussions. This makes it clear that there is a need for a digital link from the participants' point of view. The aim is to teach TC in conjunction with BIM during the simulation game and highlight the principle of this link and the benefits this brings to the construction site, although this might not directly add value to the simulation.

To create a link between the analogue model and the BIM model, the rooms in the BIM model are equipped with additional attributes. On the one hand, they receive an attribute about the Takt to which they are assigned. Secondly, they receive attributes for each trade wagon that passes through the Takt area. These attributes are assigned logical values that indicate whether the trade has already been completed or not.

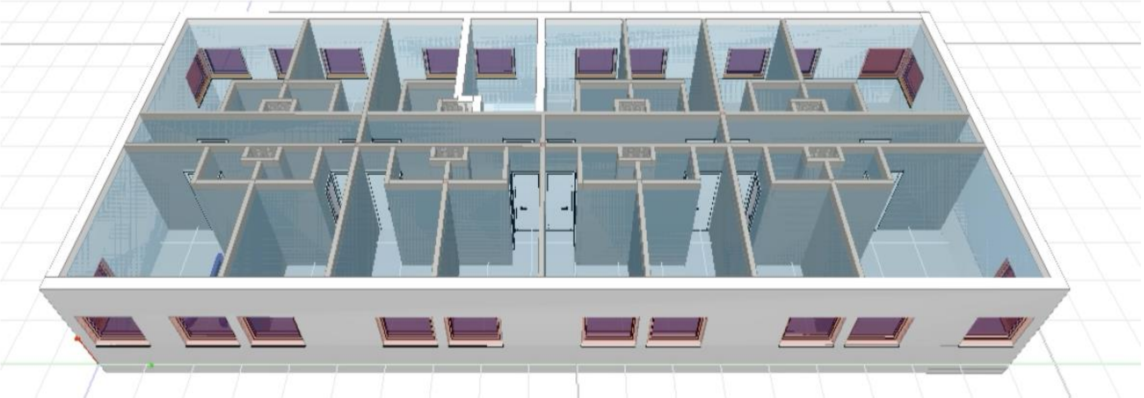

Figure 5: BIM hotel model (figure by authors)

In order for the trade teams to be able to easily indicate whether their trade has been completed, each Takt and each trade receives a QR code. Accordingly, the schedule that each trade receives for its trade at the beginning of the third stage is equipped with QR codes for each Takt area.

The possibility of tracking each component is waived here, as only the completion of trades and not of individual components is considered here for a start. Of course, in addition to the QR code technology, there is also the possibility of creating a link to the digital model via NFC (Li et al., 2018), RFID (Majrouhi Sardroud, 2012) or similar.

Each time the trade has completed a Takt area, it scans the QR code with its smartphone (see Figure 6). This takes the participants directly to a form where they can enter the completion. The information about the completion of the trade for the scanned Takt area is thus transferred directly to the BIM model as the form is linked to the rooms of the scanned Takt as well as the attribute of that specific trade.

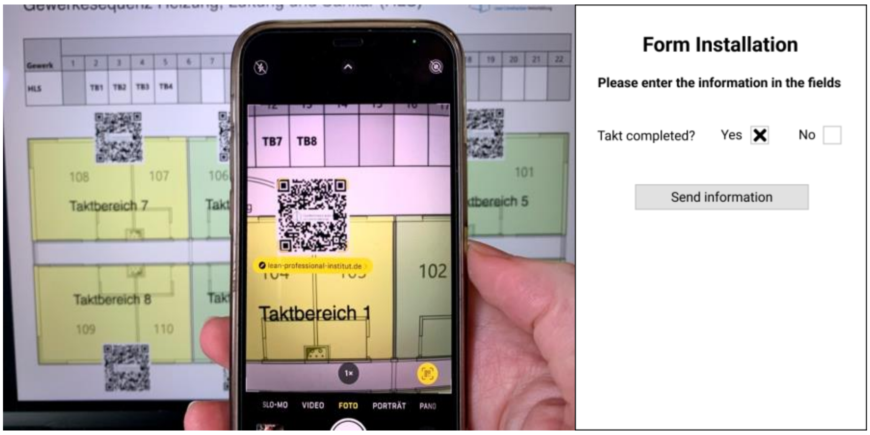

Figure 6: Scanning of QR code and installation form (figure by authors)

Information about the completion of the hotel model for each trade is accessible through the BIM model during the whole building process. Figure 7 shows the degree of completion using colour schemes in “desite md” (Ceapoint aec technologies GmbH, 2022), a software with which 3D building models can be visualised and analysed. In the middle there is the diagram of room 104, where you can find the attribute of the Takt and every trade attribute. The trade attributes indicate whether the respective trade in the room has already been completed ("true") or is still to be completed ("false"). On the left side the Takt areas that have already been completed by the plumbing and heating I trade on Takt day 5 are shown in green. On the right site you can see the total stage of completion for every room.

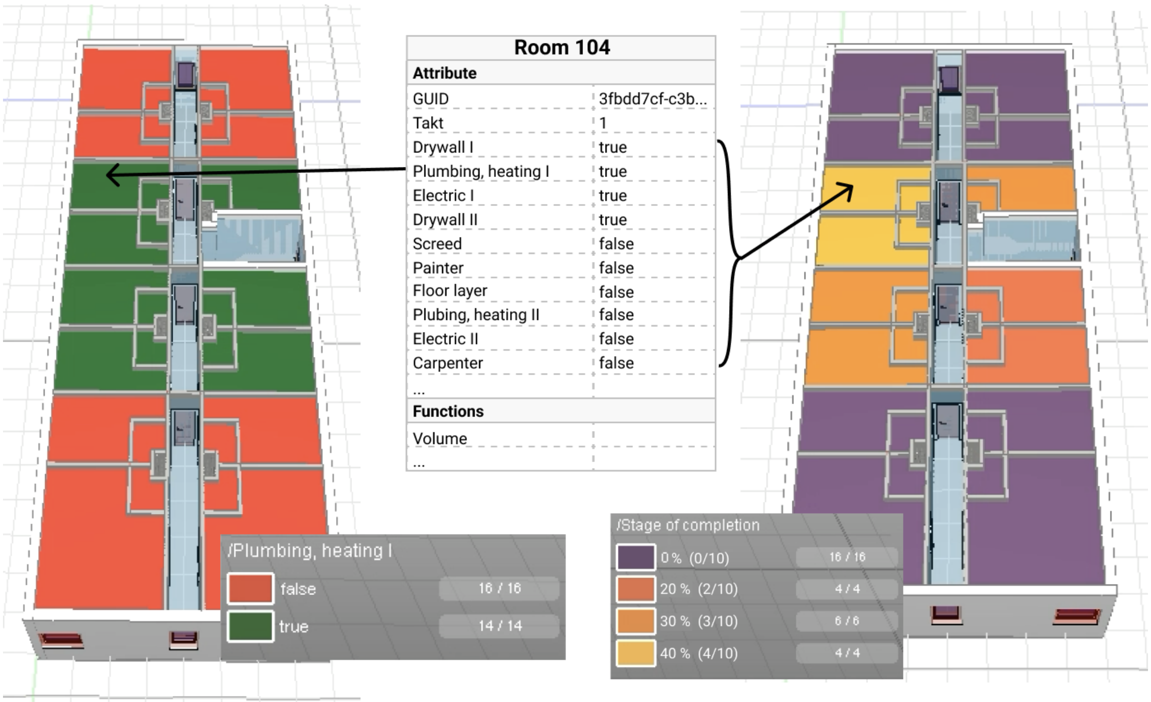

Figure 7: Colour scheme of the stage of completion for one trade and in total on Takt day 5 in "desite md" (figure by authors)

After each Takt day is over, the role of the construction manager can check in the BIM model for each trade whether the respective trade has done all its work. Checking which trade has completed which Takt area is made easier by the fact that it can be displayed visually in the 3D model (Schmidt & Teizer, 2020). Likewise, the owner can get a quick overview of which rooms have already been completed. The regular meetings are not replaced by the digital monitoring, but supported. A binding statement about the production status of each trade has then already been made in advance and the 3D model can be used as a basis for discussion in the meeting. The visual representation of the stage of completion in the digital model increases the quality of the meeting.

The installation form shown here is kept rudimentary, as it is only intended to convey completion in this context. Of course, there is also the possibility of transmitting further information via the form.

In theory, there is still potential to link further processes with the digital model. As mentioned at the beginning, it is also possible to track an individual component of the simulation game via QR codes or similar. This would make it possible to see via the BIM model which components have already been prefabricated and which of them are already on the construction site. The quality of the work carried out can also be noted directly in the digital model via a form and sent to the responsible trade (see schematic representation in Figure 8). However further discussion is beyond the scope of this paper.

Figure 8: Comparison of analogue and digital TC process (figure by authors)

RESULTS

The implementation of digital monitoring presented here was pretested with a group of 15 people and then discussed with participants as well as with a cross-section of teachers and practitioners of the construction industry. The outcome of the discussions was that the possibility of linking both models shown here manages to highlight the advantages of the BIM method for the participants. An information model that is always up-to-date and accessible from anywhere is the core of BIM, but brings added value to the TTP and TC as well. The participants realise that a visual representation of the Takt plan in the 3D model not only brings added value to the regular meetings, but also to the client, who can readily identify which parts of the building have already been completed. In addition, it has the potential to automate many processes such as the creation of key figures. If you think about larger construction sites, for which this training is ultimately designed, then it makes sense for these reasons to teach the participants directly one way on how to link the building with a BIM model. But the most important point is that this can help to inspire the participants to come up with their own implementation ideas for linking to a BIM model that fit their respective projects. The positive feedback leads to the fact that the developed teaching framework will be tested and improved on further participants of the LC workshops.

Figure 9 shows a comparison of the analogue model and the digital model with a colour scheme for the different Takt days during the third stage of the simulation, which provides a good visual overview of the production status of the individual rooms in the building.

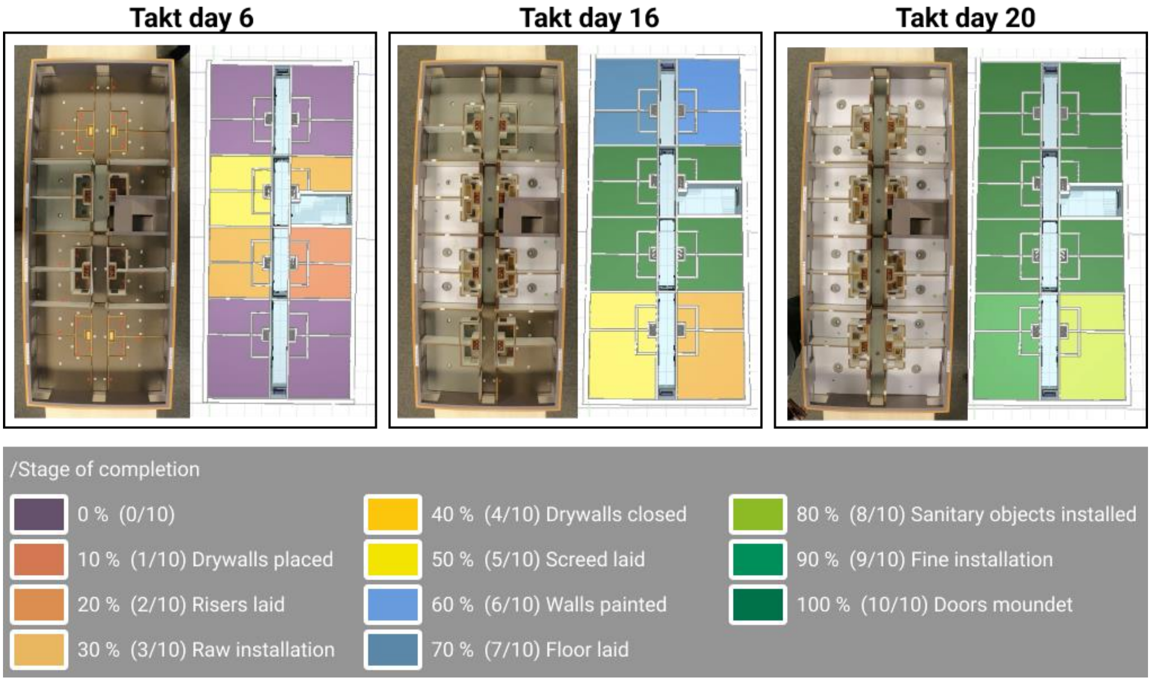

Figure 9: Comparison of the analogue model and the digital model of the third stage (figure by authors)

CONCLUSION AND OUTLOOK

In the modern world, it is generally no longer sufficient to do the monitoring of the manufacturing process in analogue alone because of the complexity of construction sites. Therefore, it is important to depict the interaction of LC and BIM in the simulation game. The possibility of linking both models shown here manages to highlight the advantages of the BIM method for the participants. An always up-to-date Takt plan that can be accessed from anywhere and its visual representation with the help of the BIM model not only add value to the TC in the simulation, but the concept can also inspire participants to apply this to their projects. The positive feedback of the pretest leads to the fact that the developed teaching framework will be tested and improved on further participants of the LC workshops.

As mentioned at the beginning, it is also possible to use the BIM model to improve the TTP, e.g. to automate the determination of the Takt areas. A workshop also offers suitable framework conditions for testing such concepts in a playful way. This approach could be explored in future work.

A schematic sketch was made of the further digitalisation potential of the simulation. Future work may find a way to incorporate these profitably into the simulation and further tighten the link between Lean and BIM.

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A FRAMEWORK FOR ENHANCING THE ENGINEERING REVIEW PROCESS IN OIL AND GAS EPC PROJECTS

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ABSTRACT

The construction industry, which has been for long suffering from schedule and cost overruns, is witnessing a growing focus on lean and digitalization as means to overcome process inefficiencies. However, the application of such concepts and tools in the specialized Engineering, Procurement, and Construction (EPC) Oil and Gas industry is still immature and lacks thoroughness. This paper illustrates how digital transformation and lean concepts can complement each other to enhance the engineering review process in a typical Oil and Gas EPC project. Namely, this study illustrates a unified platform that merges the traditional engineering document review stages and brings the stakeholders together for concurrent and collaborative engineering to reduce the nonvalue-added time in the process of engineering drawings review and approval. The platform shall act as a framework for Oil and Gas companies, based on which they can develop a flexible system tailored to their specific needs and requirements.

KEYWORDS

Obeya, oil and gas, engineering review, waste, collaboration.

INTRODUCTION

Engineering, Procurement, and Construction (EPC) is a popular contracting method adopted by the private sector to deliver large scale projects. Under EPC contracts, the contractor is responsible for the design of the project, detailed engineering, equipment and material procurement, construction, testing, commissioning, and sometimes the start-up of the facility for a fixed price and a fixed completion date. EPC projects in the Oil and Gas industry are characterized by their large sizes, uniqueness, intricate complexities, severe risks, and involvement of numerous stakeholders i.e., clients, contractors, suppliers, etc. (Rachman et al., 2018). The Oil and Gas industry currently faces daunting challenges as schedules and budgets are becoming tighter due to oil price high volatility and market instability. This industry has been plagued with waste and process inefficiencies that lead to significant cost and schedule overruns (Salama et al., 2008). To maintain competitiveness in today's challenging market, the industry witnessed a growing focus on waste elimination and efficiency improvements (Timilsina, 2017). The lean

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philosophy, which originated by Toyota out of similar challenges, can hence be a catalyst for improvement and a good tool to overcome the Oil and Gas industry inefficiencies.

Existing studies explored the synergies between Building Information Modelling (BIM) and lean and the advantages of applying lean and digitalization concepts in residential, institutional, commercial, and infrastructure construction projects (roads, highways, airports, etc.) (e.g., Tauriainen et al., 2016, and Koseoglu & Nurtan-Gunes, 2018). However, compared to other industries, the Oil and Gas sector remains one of the least mature world-wide in terms of digitalization (Fernandez-Vidal et al., 2022). Companies in the Oil and Gas sector have started to utilize various digital solutions e.g., Internet of Things (IoT), artificial intelligence, robotics and drones, wearable technologies (Wanasinghe et al., 2020), and software systems like Enterprise Resource Planning (ERP) (Gezdur et al., 2017). However, due to the numerosity and complexity of the processes in Oil and Gas projects, there is still a long way to go to reach maturity and reap the full benefits of digitalization and lean implementation (Rajagukguk et al., 2021).

This paper presents the application of lean tools and concepts along with digital initiatives to reduce nonvalue-added time in the process of engineering document review and approval in a typical Oil and Gas EPC project. Most Oil and Gas companies currently use traditional push methods for document preparation, review, and approval, where stakeholders work in silos and push the document to the next customer in the process with minimal collaboration throughout. Current digital solutions for the Engineering Review process are available in the form of Electronic Document Management Systems (EDMS) that aim at reducing paper usage. EDMS is a system that manages the flow of information, with the capability for storage, archiving, approval, monitoring, and control of documents to facilitate workflows (Pho et al., 2014). However, EDMS mimics the traditional push system but in an electronic form and hence does not address the dominant waste factors embedded in the process. This paper proposes a unified cloud platform that brings together all the stakeholders to allow concurrent work on Engineering documents, using live communication and collaborative commenting and review tools, resulting in shorter cycle times and less rework. This platform shall act as a framework for Oil and Gas companies, based on which they can develop a flexible system tailored to their specific needs and requirements.

LITERATURE REVIEW

The oil and gas industry is plagued with waste and process inefficiencies. 70% of activities in an EPC project are found to be non-value adding, which negatively affects productivity and profitability, causing project delays and cost overruns (Rajagukguk et al. 2021). The dominant waste factors during the Engineering phase, as identified by Rajagukguk et al. (2021) are: waiting for the needed documents, long and far meetings, waiting for feedback information, waiting for the document approval, producing document with outdated information, error of provided information, and producing dummy document to meet target. Lean philosophy is at the heart of value creation and waste reduction therefore several improvement methodologies for construction projects have been proposed in the literature based on its tools and principles. For instance, a study by Ko et al. (2014) analyzed the design workflow problems using the value stream mapping technique and showed that the systematic inspections of design correctness allow for the early detection of design errors and enhance the learning curve of team members. Tauriainen et al. (2016) studied the effects of BIM and lean construction on design management practices to increase efficiency of the construction process and reduce design errors and the number of review cycles. Their study emphasized the benefits of using the “big room” (otherwise referred as Obeya room) concept, where different designers work together on the same location to achieve a more effective information sharing among parties. This concept of impromptu sharing of information decreases the latency of decision making and shortens the overall design time. While it is well established that EPC performance can be improved by applying the lean construction model since it reveals the interdependencies of the Engineering, Procurement, and Construction phases (Ballard 1993), the application of lean concepts and tools in the specialized EPC Oil and Gas industry is still immature and lacks thoroughness. For instance, a systematic literature review by Rachman et al. (2018) on the state-of-the-art implementation of lean principles in the petroleum industry revealed that lean tools and techniques improved operational and technical aspects, contractor/supplier relationships, team organization and project management practice, and that the primary benefits included substantial cycle time reduction and cost savings. However, the authors found the subject to be still immature and lacking thoroughness in research methodologies as well as showing deficiency in the descriptions of the lean tools and techniques used.

Despite its challenges, digital transformation is a very promising topic in construction and in research, especially its synergy with lean practices. In the manufacturing industry, digitalization can be defined as the implementation of Information and Communications Technology (ICT) alongside data analysis (Lorenz et al., 2019). ICT enables organizations to gain a competitive edge in todays interconnected and highly competitive world (Pekarčíková, M. et al., 2019) and can improve the flow of processes, eliminate nonvalue adding steps, and shorten cycle times, rework, and errors (Von Heyl and Teizer, 2017). For large, complex, and repetitive-tasks projects, digitalization plays a key role. However, ICT inherently involves many complexities and if not used correctly could add to the process complexity (Bullock, S. et al., 2004). As such, the art is to integrate both lean and digital transformation to obtain an improved lean digital system (Lorenz et al., 2019; Stechert et al., 2020; Pekarčíková et al., 2019). A major area where digitalization supports Lean management is with largely distributed teams with different time zones where timely communication and exchange of information is essential (Stechert et al., 2020). Digitalization gives access to several communication and data-exchange alternatives such as commenting tools, emails, instant chat, and web conferences. However, having multiple digital platforms would confuse stakeholders and just introduce a digital mess, which accentuates the importance of integrating digital initiatives with lean philosophy (Stechert et al., 2020).

METHODOLOGY

This study adopted the design science research (DSR) methodology. This methodology entails the creation of a solution concept to address a set of challenges or to solve a practical field problem (Rocha et al., 2012). This study addresses the problem of the waste embedded in the engineering review process of a typical oil and gas project which is mainly identified through the authors’ observations within their 22 years of combined experience in EPC oil and gas projects. The proposed solution was developed through a multi-step process that includes data collection, data analysis, and framework development. First, the process for the Engineering document review for the contractor engineering documents and the suppliers’ originated documents was surveyed by accessing the Contractor’s approved Standard Operating Procedure (SOP) from the Contractor’s Quality Management System (QMS). The SOP titled “Preparation, Checking, Review, and Approval of Engineering Documents in Projects", is a set of step-by-step instructions compiled by an organization to help its workers carry out routine operations and is followed by all personnel in the organization. It is to be noted that this is a generalized procedure for engineering documents review and is broadly followed by Contractors in the EPC oil and gas industry. The QMS is a formalized system that documents processes, procedures, and responsibilities. Three mid-sized oil and gas EPC projects (values of around $500 Million) located in Kuwait, Iraq, and Algeria and executed by the same EPC Contractor company were randomly selected for data collection, being representative of typical midstream EPC oil and gas projects with a typical set of Stakeholders (Client, Contractor, Suppliers, Subcontractors, etc.). Then, the transmittal data, which is recorded in the EDMS repository of each project, was extracted to Microsoft Excel, and grouped by category (contractor originated or supplier originated) and stage (based on the document review stages) to work out the average durations and the average cycle times per document category and for each stage. Collectively, the three projects had 10,000 engineering documents. Accordingly, the current state of a typical engineering document review process is mapped to show the various review stages along with the corresponding data. The collected data was then analyzed for waste identification. Finally, a framework is developed to help achieve an enhanced Engineering Review process. The following sections elaborate on each of those steps.

DATA COLLECTION

During the Engineering phase of an EPC project, the document review process may take prolonged periods in both interdisciplinary checks and client approvals. Critical documents undergoing many revision cycles are considered as constraints since they impact the schedule and cost of the project. A typical EPC project includes three main stakeholders involved in the Engineering phase: a contractor which is the responsible entity of all the involved Engineering, Procurement, and Construction phases, a client, and many suppliers. In order to improve the Engineering review process, the document workflow needs to be comprehended along with all the corresponding activities and interactions. This helps visualizing the bottlenecks and constraints in the process so that opportunities for improvement can be realized. The process flow stages for a document preparation, review, and approval, as detailed in the Contractor's approved SOP are displayed in a flowchart form in Figure 1. Both Contractor and Supplier originated documents go through similar review and approval stages. But, if a document is being originated by the Contractor, the process starts with the preparation of the documents by the Discipline Engineer (DE) and ends with issuing it for design or releasing it for construction. If a document is from the Supplier side, it is prepared by the Supplier to be eventually either issued for design or released for the start of manufacturing. During the first review stage (i.e., Review Stage 1), the document which is either originated by the Contractor (by the responsible DE) or originated by the Supplier is reviewed by the responsible DE and by the Lead Engineer (LE) on the project. Every project is assigned one LE for each discipline (Civil, Mechanical, Electrical, etc.) and one or more DE to assist the LE depending on the workload. In the Review Stage 2, the document (if required) is issued for Interdisciplinary checking (IDC), whereby the responsible DE and LE (for the main document discipline) invite comments from other disciplines working on the Project. The originator then ensures the resolution of the comments from the other disciplines before re-issuing the document. For example, a drawing for a pressure vessel is the main responsibility of the mechanical engineering discipline. However, most pressure vessels include instruments (e.g., pressure and temperature instruments) that are installed on the vessel, hence some information and details for these instruments (i.e., bore size, flange rating, etc.) need to be communicated to the instrument discipline engineers, and vice-versa (i.e., comments from the instrument discipline engineers need to be captured on these drawings and communicated back to the mechanical discipline engineers to ensure incorporation by the vessel supplier). In Stage 3, the document (if required) is reviewed by Technical Authorities (TA) from the Engineering Department. Some documents may require additional review by an authorized person from groups other than the originating group. The originator shall then ensure the resolution of the comments before re-issuing the document to the next stage. For example, documents and drawings for high pressure turbine compressors are usually reviewed by TA who have more than 30 years of experience in turbines and compressors. This is required because of the criticality of such equipment for the plant operation, as well as the safety and commercial risks associated with them. In Stage 4, the document is issued to the Project Engineering Manager (PEM) for approval. Then, in Stage 5, the document is issued to the Client, either for information or for review and approval. In every project, a document review/responsibility matrix is prepared and agreed on with the Client in the initial 90 days of the project award date. This matrix specifies the review requirements for every document on the project. Some documents are not required to be reviewed and approved by the Client; hence, once complete, they would be issued to the Client for information purposes only and would not invite nor await comments from the latter.

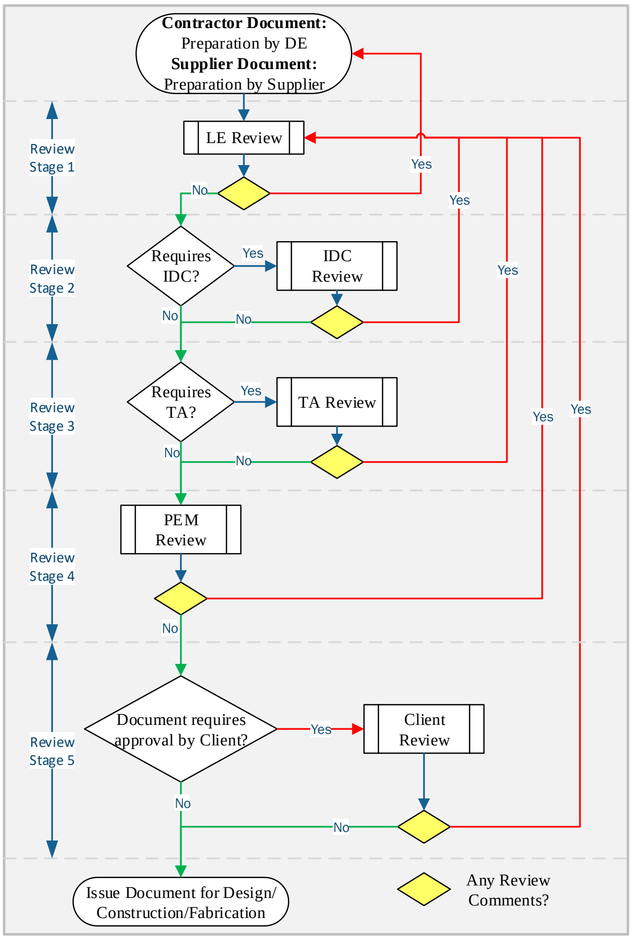

Figure 1: Document Review Process Flow Chart

The collected data is displayed in Table 1 and includes the average review time taken during each of the stages and the number of review cycles consumed by each document.

Table 1: Collected data

Category	Data	Duration (or Cycles)	Stage
Contractor Internal Reviews	Queue Time between “Start Draft” and “Issue for IDC”	up to 20 weeks	Stage 1
	Queue Time between IDC and “Complete IDC”	up to 2 weeks	Stage 2
	Queue Time between “Complete IDC” and “Issue to Client”	up to 3 weeks	Stages 3 & 4
Supplier Documents	Average number of Revisions	3 Cycles	
	Average Review Time by Contractor	2 to 3 Weeks	
	Average Review Time by Client	up to 2 weeks	Stage 5
Contractor Documents	Average number of External Revisions to Client	3 Cycles	
	Average Review Time by Client	2 to 3 Weeks	Stage 5

ANALYSIS

The data collected in Table 1 show a major issue with the contractor’s internal review. The time taken between the start of a draft document, IDC, and issuance to Client can take up to 25 weeks; this does not reflect the value adding time actually required for this process (time that excludes waiting time i.e., waste or non-value adding time). The root cause analysis revealed that the main reasons for this unrealistic timeframe are:

- The push technique that is inherent in the traditional scheduling process for the Engineering phase imposes unrealistic dates. The Engineering schedule is usually developed in the first 90 days of the project award and is rushed to get approved without involving all the stakeholders in the planning process.
- The Rules of credit (ROC) for progress calculation for engineering deliverables is devised in a way to achieve maximum progress as early as possible because (1) progress is related with payments and (2) to cover delay in other planned deliverables. For instance, the ROC might stipulate 10% progress for each document by symbolizing the start draft milestone. The Contractor tends to record the start of working on the drafts in the very early days of the project just to secure an easy 10% payment; hence the long duration from “Start Draft” till “Issue for IDC”, presented in Table 1.
- The technical documents prepared by the Contractor require a lot of information from different suppliers (e.g., foundation drawings require weights and footprint information from the suppliers of equipment) but are initiated without having sufficient information from the suppliers.

The documents generated by the Contractor can then take up to 3 weeks with the Client for approval. Supplier documents can take up to 5 weeks for review and approval, with an average of 3 review cycles. Most of this time is waiting time (waste i.e., non-value adding time) where the document is not actually being worked on.

The literature review highlights the importance of applying lean tools and concepts in the early stages of design to avoid cascading problems into the construction phase, reduce variability and waste, and add value to the customer. More importantly, the success of these tools, requires the commitment and buy-in of the involved stakeholders to guarantee transparency and information sharing. The following section presents the developed framework for enhancing the engineering review process in EPC oil and gas projects.

DEVELOPED FRAMEWORK

In a typical Oil and Gas EPC project, Stakeholders can include the Client and its project management contractor (PMC), the main Contractor and possible joint venture partners, Contractor Value Engineering offices, and the large number of Suppliers from bolt and nuts to massive gas turbine Suppliers (Badiru et al., 2016). The fact that Oil and Gas EPC projects are usually executed in different countries, time zones, and geographical areas, adds to the complexity of bringing those stakeholders together. Moreover, each one of these stakeholders usually have their own platforms and system adding waste and bottlenecks to move documents from one platform to another.

The framework in this paper presents a unified digital system or platform among all stakeholders that has collaborative commenting and review tools. This creates a digital Obeya room (Nascimento, D. et al., 2018) to resolve issues faster between the stakeholders and reduce nonvalue adding time, constraints, and bottlenecks in the documents review and approval process. The unified platform is accessible and operable by all stakeholders, eliminating the need for a document to go through different platforms. The platform features a list of all Contractor and Supplier originated documents and shows the whole life cycle of each document. The system enables live reporting and notifications which facilitates working in parallel and thus reduces the cycle times for each review stage. The platform also enables different stakeholders to communicate live with each other's, reducing delays due to conventional communication channels.

The framework in Figure 2 shows the different user-interface screens of the system and the navigation among them. The user starts by logging in to the system (User interface 1, Figure 2). A true single sign-on (SSO) feature is used so that the users will always be logged in to the system as long as they are using their operating system. This feature allows all stakeholders to stay online and available for any clarification needed, as if they are collocated. The user is presented with the option to choose the project he/she wants to login to from a drop-down menu, which features all the projects he/she is assigned to as per the Projects' Organizational Charts, Approval Hierarchy Charts, and the Responsibility Matrix. The responsibility matrix is created at the start of each Project, and it collects data from the Project Organizational Charts, Approval Hierarchy charts, and the Contract documentation requirements. It lists all the documents required as per the Contract along with the following attributes for each document: (1) the origin of the document (whether it is a Supplier or Contractor originated document), (2) the main discipline associated with the document, (3) the name of the main DE (Contractor) responsible for drafting the document, (4) the LE (Contractor) responsible for reviewing and approving the document, (5) whether the document requires a TA review and, if yes, the name of the TA approver (Contractor), (6) whether the document requires IDC review and, if yes, all the inter-disciplines applicable and the names of the inter-discipline engineers (Contractor) that are responsible for reviewing the document after the main DE(Contractor), and (7) the Client's Engineer's name responsible for the final review and approval of the document. The latter allows the document to proceed for fabrication (for Supplier initiated documents) or for construction (for Contractor initiated documents).

Once logged in, the system automatically detects the user's role on the specified project. The user can either go to the main screen to check his/her duties (i.e., User interface 2), or to the dashboard (i.e., User interface 3) to get updated on the overall progress. The main screen (User interface 2) then shows the user-specific notifications banner. For example, if a comment was assigned to the user on a specific document, it automatically appears in the notifications section where the user can either select to view the document and respond to the comment, or to close the notification. The main screen features also a table for “Pending Documents” and a table for “Documents Created (i.e., sent for review)”. These tables are linked and are continuously updated from the incorporated planning software database (from which it fetches dates and time milestones/deadlines) and from a responsibility matrix (from which it fetches the roles and responsibilities of the user). The “Documents Pending” table shows the documents that are pending for the user to initiate and start the reviewal process on, based on their role as per the responsibility matrix. The two actions available for the user are “Initiate” and “Delete”. The Delete action allows the user to delete a document which is deemed unrequired; this could be due to redundancy of information for example. The delete action will then send a notification for the next approvers to confirm. As for the “Initiate” action, the user clicks on it upon preparation of a document; accordingly, the document moves to the “Documents Created” table and is assigned the “under review” status. All respective stakeholders are accordingly notified that the document has been initiated. This action allows the dispatch of the document for concurrent review by all responsible users, ignoring the traditional stage/phase wise review and allowing all responsible stakeholders to collaborate and comment concurrently in one big digital room, simulating a digital Obeya room. The “Documents Created” table shows all the documents that have been initiated, along with their due dates, their statuses, and all possible actions that can be taken. Only the possible actions that are associated with the document’s status and role of the user can be shown in the “Actions” column. There are four possible statuses: “Pending Review”, “Pending Approval”, “Approved with no comments”, and “Approved with minor comments” (i.e., when a document is approved for manufacturing/construction but has minor comments that need to be resolved before the completion of manufacturing/construction).

If the document was “Pending Review”, the possible actions are “View”, “Edit”, “Delete”, “Issue for Approval”, “Resolve”, and “View History Log”. The “View” action allows the user to view the document and the comments. The “Edit” action allows the user to go back and edit the document based on the review and comments by the stakeholders. The “Issue for approval” action enables the initiator to issue the document for the next approvers; this is when all the comments are deemed responded to, actioned, and/or resolved. Additionally, the review period will be timeboxed as per the contract review cycle time agreed with the Client; consequently, the system automatically issues the document for approval once the review period is over. For example, if the review period is decided to be 21 days, then the document will have to be issued for approval within 21 days. Before 5 days of the deadline, the system sends reminders and notifications that the review cycle will be closed soon thus ensuring that all stakeholders finish their review on time. If a document exceptionally requires additional review time beyond the agreed review period (timebox), then a higher authority approval will be required, typically the Contractor’s and Client’s Project Directors and Managers. Also, the stakeholders will be able to monitor and control this through the dashboard where the document will be highlighted alerting that the deadline is close (within 5 days). The document will then be automatically issued for design/manufacturing/construction after all the approvals are obtained in the system. The resolve action is linked to the “Call for Conference” feature where it allows the user to choose and call one or more users that are assigned on the concerned document. This facilitates the communication among the involved stakeholders and the efficient resolution of pending comments. The “View History Log” action shows the tracking history of the document (including all comments and their resolutions/replies) from the moment it was initiated up until the current time.

If the document is pending approval, then the “Edit” action is no more available since the review process has already ended. The approved documents can have the following actions: “View”, “Delete”, “View History Log”, and “Issue for Design/Manufacturing/Construction”. Documents that are not directly used for manufacturing/construction but contain design information are issued for design (e.g., specification documents). The “Edit” and “View” actions from the main screen directs the user to the document screen (i.e., User interface 4). In this screen, the user may view the updated document, the comments created by the user, other stakeholders’ comments, and also reply to comments assigned to him/her. All the actions performed on the Document View screen (i.e., User interface 4) are automatically recorded by the system and are therefore captured in a chronological manner in the history log of the document. This feature allows for an automated, easy, and transparent tracking of delays, which can be later used as backup documentation for any possible contractual claim.

The dashboard (User interface 3) is linked and takes critical data from the system’s database, to help visualize and enable easy monitoring and control of the status and progress of the Project’s documents. The use of color cues and warning symbols helps alert all stakeholders, in real time, of any threats that need to be addressed and enables the mitigation of issues as soon as they arise. The dashboard is user friendly and customizable by the user, providing flexibility to meet all users’ specific needs. It would be accessible to all stakeholders with appropriate access control. Moreover, the performance of all stakeholders is presented in terms of documents reviewed on time and those which are delayed. Furthermore, the dashboard can present tiles, percentages, and statistical figures to give the full situation in a glance.

CONCLUSION

The Engineering document review process in an Oil and Gas EPC project can be very time consuming and involves a lot of waste. This issue is inherent to the nature of the process, which is designed to be a push system (even through EDMS). After collecting actual data from three EPC projects, the process flow stages (along with the corresponding data) for a document preparation, review, and approval, were displayed to help visualize the bottlenecks and constraints in the process. The current state of the document review process was analyzed and the constraints in the different stages were pinpointed. Accordingly, a digital framework is developed to enhance the current situation. The framework presents a unified platform that combines the different stages of the document review and approval process and transforms the system into a pull system (simulating a digital Obeya room) that facilitates concurrent Engineering, collaborative work, and “just in time” information transfer among different stakeholders. Namely, the developed platform integrates lean and digitalization concepts to facilitate working in parallel and reduce delays due to conventional communication channels, thus reducing the cycle times for each review stage. The framework includes also a visual management component (i.e., the dashboard) that allows the systematic monitoring and control of the engineering documents’ review cycles, enabling early detection of arising issues. Finally, the unified platform ensures a comprehensive and automated recording and extraction of the history logs, which establishes for indisputable proofs for any possible delay claims.

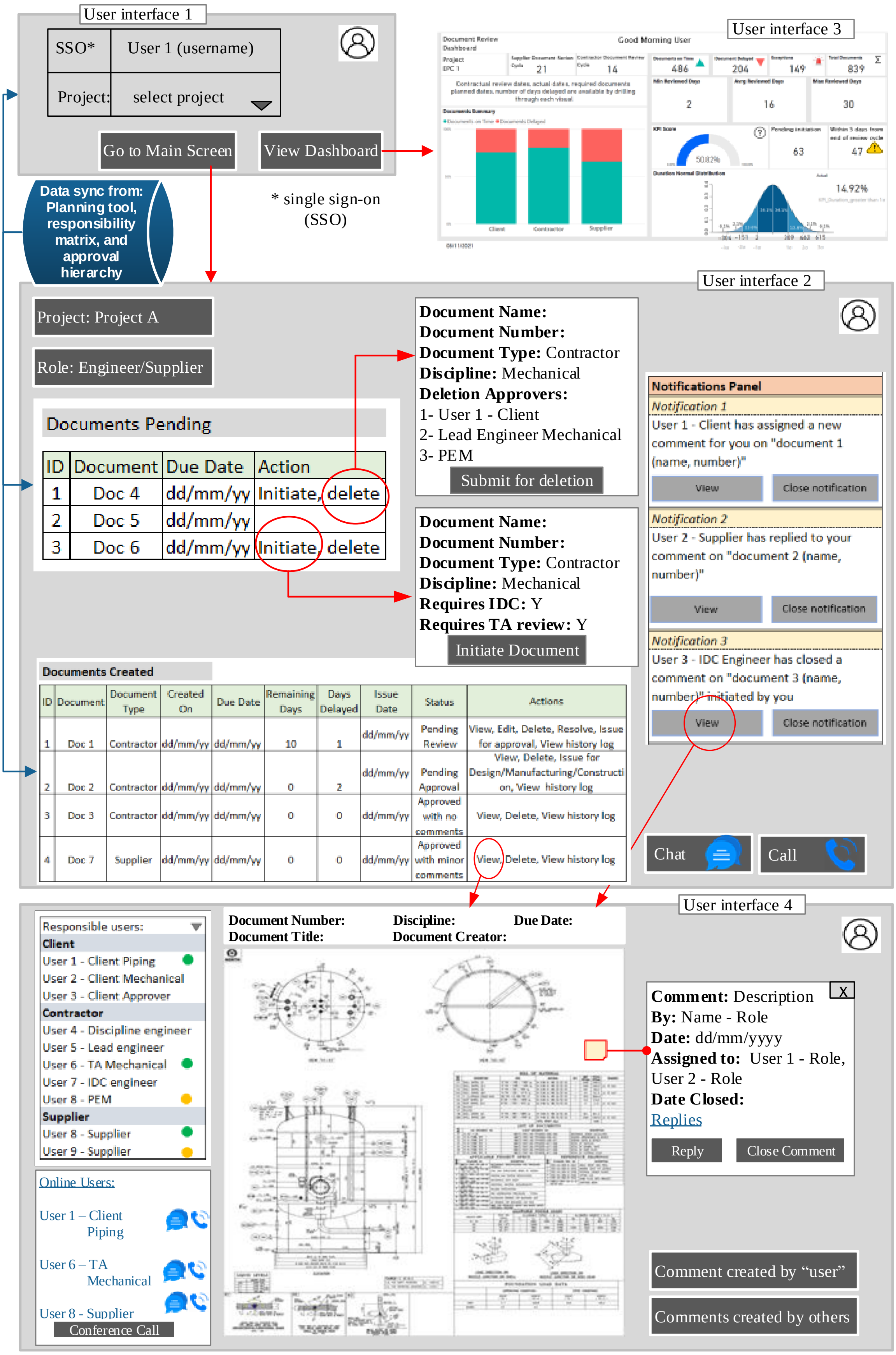

Figure 2: Unified Platform Framework

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STRATEGIC PARTNERING BETWEEN CONTRACTORS AND DESIGNERS

Sigurd B. Paulsen[1], Atle Engebø[2], and Ola Lædre[3]

ABSTRACT

In recent years, the concept of strategic partnering has gained attention in the Norwegian construction industry. As a project delivery method, strategic partnering shares similarities with the Lean project delivery perspective as they both seek to achieve more collaborative projects. The paper has structured strategic partnering into three essential Lean Construction (LC) elements: contract, organization, and collaboration. Consequently, this paper contributes to knowledge about strategic partnering between contractors and designers by answering the two research questions: 1) How is the current practice associated with strategic partnering, and 2) What are the experiences with strategic partnering between contractors and designers.

An exploratory case study was conducted to examine how strategic partnering can be improved in future projects. A combination of literature review and semi-structured interviews were used for data collection.

The findings reveal an improvement potential when implementing strategic partnering in the construction industry. The paper concludes that more attention should be paid to contract elements and the project organization at the company levels to improve strategic partnering. However, at the individual level, good effects have been identified. Findings also showed that external factors like political decisions can lead to postponements and thus changes in personnel in the organization.

KEYWORDS

Strategic partnering, collaboration, Lean Construction, relational, case study.

INTRODUCTION

Partnering is defined by Bennett and Jayes (1995) 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 in the project organization and is based on traditional forms of contract (Lahdenperä, 2012). There are essentially two forms of partnering: Those that seek strategic long-term relationships and commitments (strategic partnering) and those that are specific to a particular project (project partnering) (Cheng et al., 2004). Strategic partnering occurs when two or more firms use partnering on a long-term basis to undertake more than one construction project

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(Kumaraswamy & Matthews, 2000). Those who genuinely engage with strategic partnering have seen substantial success in results (Johansen et al., 2004).

Traditional projects are based on short-term relationships, while strategic partnering aims to utilize the expertise of different companies by promoting long-term relationships at both the individual and the company levels. Previous research argues that projects in the construction industry can be improved by giving the project partnering a more strategic focus (Moller & Bejder, 2004). In addition, Howell (1999) has said that partnering can be a solution to manage production in conditions of high uncertainty and complexity. As such, strategic partnering can be a way to get Lean issues effectively into companies so that Lean can evolve and become the "new tradition". However, compared to other industries, the construction industry is more reluctant to establish more permanent and strategic partnering (Moller & Bejder, 2004). According to Koolwijk et al. (2021), this may have to do with the dominant part influencing the system in its favour and, in the long run, creating mistrust in the project organization.

In Norway, partnering elements have become more common in construction projects over the last decades, and previous research shows positive effects (Tadayon et al., 2018; Falch et al., 2020). In recent years, strategic partnering has also become an increasing trend in Norway, but there is limited empirical research on the concept (Stene et al., 2016). This study aims to research strategic partnering between contractors and designers and identify areas of improvement in current practice and for further projects. The paper has structured strategic partnering into three elements: contract, organization, and collaboration, based on the LC triangle. Since the concept of strategic partnering is not much studied in Norway, this paper seeks to answer the following research questions:

1. How is the current practice associated with strategic partnering?
2. What are the experiences with strategic partnering between contractors and designers?

This study is limited to an in-depth investigation of four Norwegian school building projects. The project delivery method entailed a Design-build contract and early contractor involvement in all projects. Furthermore, the emphasis is on the relationship between contractor and designer as the strategic partnership between the same contractor and designer was followed over these four projects. The focus will be on the development phase and design phase. Only qualitative research has been used as a data collection methodology.

METHODOLOGY

There exists little previous research on strategic partnering between contractors and designers, and according to Thagaard (2018), qualitative methods are well suited for explorative purposes. Therefore, based on a qualitative approach, it was decided to conduct an exploratory study that uses a literature study and a case study with interviews as data collection methodology. The study design is based on Yin (2014)'s case study approach. The approach was suitable for gaining insight and understanding strategic partnering and answering the research questions, considering the literature's knowledge gap. The results from a case study will depend on time and place (Olsson, 2011). Due to the resources available and the availability of informants, it was considered most appropriate to do a single-case study and study it in-depth rather than taking a broader perspective. Flyvberg (2006) believes that a single case study that does not aim to provide a formal generalization also provides results and insight that will significantly contribute to its scientific field.

In our study, the case is defined as the strategic partnership between the contractor and the designers. The main author had a summer internship at the designer company, resulting in the identification and consequent access to the case. The two organizations (contractor and designer) conducted a strategic partnership on four successive school projects during a limited period (2014-2022) and within the same geographical region. Another contributing factor was that three of the projects were recently completed and that the fourth was still ongoing. As the strategic collaboration had existed for a while, more meaningful and nuanced data on the strategic aspects could be extracted. At the same time, the strategic partnership was still ongoing, ensuring that the experiences were still relevant, and the informants were still available.

The primary data source was interviews with individuals with major roles in the four projects. Table 1 shows the informants, their roles, and their involvement. Fifteen interviews were conducted, and "Numbers" in the table indicate the numbers of interviewed objects per role.

Table 1: Informants, their roles and involvement in the case study.

Role	Project A	Project B	Project C	Project D	Numbers
Project manager	x	x	x	x	1
Assistant project manager		x	x	x	2
Design manager	x	x	x	x	1
Client´s project manager			x	x	2
Technical Manager	x	x	x	x	1
Architects	x	x	x	x	2
Assignment leader design	x	x	x	x	1
Discipline leader electro	x	x		x	1
Discipline leader construction		x		x	1
Users	x	x		x	1
Subcontractors			x	x	1
Processing supervisor	x	x	x	x	1

The interviews were semi-structured, meaning that all of them followed a standardized interview guide (Blumberg et al., 2014). A literature review was conducted to identify relevant questions for the interview guide. Furthermore, the design and the structure were created through several iterations between the authors. Finally, the authors received input on questions from the various parties in the case study. The structure of the interview guide was divided into three main categories: contract, organization, and cooperation. The main category was further divided into subcategories. For example, some of the subcategories of cooperation were developments in collaboration, commitments, and relationships. Furthermore, the interview questions were based on the research questions. Therefore, for each subcategory, the questions were asked, "what was done?", "what are the experiences?" and "what should have been done?". During the interviews, audio recordings were made so that the interviewer could be more accessible to attend the conversation and ask relevant follow-up questions. Later the interviews were transcribed.

Lastly, the data were analyzed and sorted based on research questions, parties, and categories (contract, organization, and collaboration).

THEORETICAL FRAMEWORK

Projects can be delivered through various delivery methods, ranging from traditional design–bid–build to more integrated forms such as strategic partnering (Koolwijk et al., 2020). Amongst other aspects, the project delivery method dictates how the project team engages, the means used, and how different parties get involved (Engebø et al., 2021). However, this paper is limited to strategic partnering and so-called collaborative project delivery that seeks to integrate and align the parties early, i.e., already in the planning phase (Fischer et al., 2017).

COLLABORATIVE DELIVERY METHOD

A core principle of Lean project delivery aligns the contractual elements (contract), the project organization, and production (design and production). These three elements are also referred to as the LC triangle (Ballard, 2012; Howell, 2011; Thomsen et al., 2010). Lean project delivery seeks to align all project parties with available contractual elements to achieve a collaborative project organization and lead to a project culture for delivering value in production (Falch et al., 2020). In collaborative project delivery methods with early contractor involvement, the early stages of the project are centered around the notion of integrated design, organized around multi-disciplinary teams, with the actors often co-located to favour collaboration and innovation (Engebø et al., 2021; Forgues et al., 2008). Collaborative project delivery methods are a global phenomenon. Research has shown that such methods have emerged worldwide, from Integrated Project Delivery (IPD) in the US to Alliancing in Australia (Engebø et al., 2020). Furthermore, Lahdenperä (2012) showed that although the different collaborative project delivery methods are primarily geographically determined, they have adopted practices from each other.

In Norway, partnering elements in collaborative delivery methods have become more common in construction projects over the last decades (Stene et al., 2016). A literature study conducted by Tadayon et al. (2018) points to several benefits with partnering elements: fewer conflicts, increased productivity, and a better working environment. It is common in Norway to combine partnering with a two-step delivery method (Engebø et al., 2021). The first step starts with the client contracting a contractor with an architect, designers, and subcontractors for a development phase (contract phase 1). The development phase usually has an option for a design-build contract in step two (contract phase 2), provided that the contractor develops an adequate project (Engebø et al., 2021).

THE CONCEPT: STRATEGIC PARTNERING

Strategic partnering occurs when two or more firms use partnering on a long-term basis to undertake more than one construction project (Kumaraswamy & Matthews, 2000). Strategic partnering differs from IPD as it is not a multi-party contract between the client, contractor, and designer (Lahdenperä, 2012). However, partnering and IPD share similarities as they accommodate the construction industry´s need for more efficient collaboration between project participants (Lahdenperä, 2012). In the context of the construction industry, strategic partnering differs from the other industries as it is strongly linked to the local business environment, local economy, government regulation, and culture (Lu & Yan, 2007). According to Cheng et al. (2004), strategic partnering is also typically an informal voluntary agreement between the parties involved.

The literature points out that strategic partnering is, in several ways, an extension of project partnering (Lahdenperä, 2012; Sundquist et al., 2018). Nevertheless, Cheng et al. (2004) believe that the application of strategic partnering is different from project partnering. The latter focuses on achieving partnership goals and project performance, while strategic partnering is about reciprocity and continuity between the parties. Strategic partnering is thus considered more process-oriented, while project partnering is more results-oriented (Cheng et al., 2004). Therefore, the learning achieved in a specific project is more likely to be used in future projects, and it is clear that the advantages of project partnering are not regarded as equal to strategic partnering (Shimizu & Cardoso, 2002). Cheng and Li (2007)'s study found several benefits if companies expand from project partnering to strategic partnering. The benefits are related to tender competition, opportunities for long-term competitive advantage, and new market access. In addition, it is common to use interaction provisions such as access to each other's technology, long-term relationship establishment, and activities that improve the product and the process (Lu & Yan, 2007). Therefore, it can be argued that strategic partnering can improve all three elements in the LC triangle. However, to achieve these advantages, the project organization is dependent on the same people being transferred from project to project to ensure promising relationship developments (Lu & Yan, 2007; Sundquist et al., 2018).

STRATEGIC PARTNERING IN A LEAN PERSPECTIVE

Previous research shows that partnering as a project delivery method shares similarities with the Lean perspective as they both use available elements to achieve a collaborative project (Falch et al., 2020). Since strategic partnering in several ways is an extension of project partnering, the similarities with the Lean perspective are even higher with strategic partnering. The reason is that companies can, over a more extended period, eliminate many of their problems and ensure ongoing improvement through a more open, frequent, and accurate exchange of information (Shimizu & Cardoso, 2002). Thus, strategic partnering can reduce waste and increase value in construction projects in the long run.

Although some examples of strategic partnerships have led to improvements in construction project delivery (see Crutcher et al., 2001; Lönngren et al., 2010), these have been restricted mainly to client-contractor. Furthermore, most of the literature is now more than ten years old, making the topic fit for a revisit. Sundquist et al. (2018)'s study also 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 and Simonsen et al., 2019). Only one paper has been found from the literature study with strategic partnering between contractors and designers being the focal point (Lu and Yan (2007)). However, no papers were found that empirically document experiences between contractors and designers.

Thus, in this paper, the focus is on the contractor and the designers. In addition, the case study includes interviews with the other parties in the project organization to map their experiences related to the strategic partnership. Even if the Lean Construction concepts are more related to firms, they can be extended to the organization level (Shimizu & Cardoso, 2002), as the authors do in this paper.

FINDINGS AND DISCUSSION

This chapter presents results related to the research questions and discusses them based on the case study and the theoretical framework. The chapter follows the structure of the interview guide and is therefore divided into contract, organization, and collaboration.

CONTRACT

The client entered a contract with the contractor, while the contractor had contracts with the other parties in the project organization. Since the client was not part of the strategic partnership, a multi-party contract was not entered into as in IPD projects. Previous research also shows that multi-party contracts not necessarily is implemented in what has traditionally been called partnering (Lahdenperä, 2012). The strategic partnership between the contractor and the designer was implemented as an informal agreement, and separate contracts were signed for each project. A fixed-price contract was used on the first three projects, which means that the contractor relinquished the responsibility related to the price for the design work to the designers. In contrast, a reimbursable contract was used on the last project, meaning that the contractor retained the responsibility. Several partnering elements were stipulated in the contracts to improve the collaboration through the strategic partnership. The most important were start-up seminars, team-building activities, open book, and joint meetings with users. However, no contractual incentives were used between the parties. Table 2 shows the most central findings from the interviews associated with the contract.

Table 2: Advantages and challenges with the contract.

Advantages	Challenges
Increased quality of the contract	Disagreements due to a more elaborate contract
Increased financial gain for the designers	Power relations between the parties

The designers experienced improvements in their contracts through the strategic partnership. The designers said that the first two projects had almost no prerequisites, limitations, or clarifications in their contract with the contractor. Therefore, they were unsure what they priced, offering a too low price. Previous research is unclear on the willingness or value of proceeding with the strategic partnering if the initial efforts turn out negatively. In this case, the designers did, and through improvement in their contract, they increased financial gain in the strategic partnership. Previous studies have also shown that companies can eliminate problems and ensure ongoing improvement through strategic partnering (Shimizu & Cardoso, 2002). That makes an argument that the ability to tweak and improve is a beneficial feature of strategic partnering. However, the improvement of the contract also led to disagreements at the company level because the parties spent significantly more on creating more specific agreements, leading to irritation from the contractor as they were happy with the original contracts.

Interviews with designers, architects, and subcontractors revealed that cost savings primarily went to the contractor. In simple terms, in the original contractual framework entailing the strategic partnership, the contractor gained on the designers working faster and cheaper. In contrast, the designers gained nothing from the increased productivity. As a result, the designers tried to introduce, from their perspective, fair financial incentives in the last projects. Consequently, according to the informants, the move failed, which may have to do with the contractor being at the top of the hierarchy in the strategic partnership. Another contractual experience uncovered was the notion that subcontractors become involved too late in the projects. With the late entrance of the subcontractors, the designers experienced that they often designed something that did not match what the main contractor and subcontractor had agreed. The result was often that the designers had to redesign according to the wishes of the subcontractors, which was beneficial for the main contractors but had a negative effect on the margins of the designer. The designers told the contractor several times that the subcontractor had to be involved earlier. However, the contractor said in the interviews that it is too risky to enter a contract with the subcontractors earlier because there is uncertainty associated with the construction phase. These results are consistent with previous research, which states that the dominant party, the contractor, can use its power to influence the system in its favour (Koolwijk et al., 2021). According to Koolwijk (2021), the power relations between the parties are one reason why the implementation of strategic partnerships has been delayed in the construction industry. Thus, the power relations between the parties can make it challenging to eliminate all problems with the contract through strategic partnering.

ORGANIZATION

In all four projects, the parties used a collaborative project delivery method with early contractor involvement. In the early stages of the project, all the parties were centered around the notion of integrated design. Project hotels and BIM were used as digital collaboration tools. The insight from the interviews showed that keeping the same key personnel was a strategy the parties created at the beginning of the strategic partnership. For example, the project manager and the design manager were the same person in all four projects. In addition, other key persons in the project organization were involved in all or several of the projects in the case study, see Table 1. **Error! Reference source not found.** shows identified advantages and challenges with the organization from the case study.

Table 3: Advantages and challenges with the organization.

Advantages	Challenges
Technological development	Challenging to keep the same people
The design manager works in the design company	Postponements can lead to replacements in the project organization
Improved productivity	Unforeseen decisions by the client
Recurring effect	

From previous research, it has been found that it is common to use interaction provisions such as access to each other's technology (Lu & Yan, 2007). The informants said the same, and the focus on BIM and other technology has increased in the strategic partnership. The focus on BIM was a strategy from the start and has worked out positively for the organization, the informants said.

Previous research is unclear on how the contractor and the designer deal with the aspects of liability in a strategic partnership. However, the design manager worked at the designer company in this case study. Therefore, the contractor transferred the coordination liability between designers and architects to the designers. The informants from the designers pointed out that it has been positive because the design manager's focus has been on productivity, innovation, and continuous improvement. In contrast, based on previous experience, if the contractor is responsible for this role, the designers said the focus tended to shift towards economy and productivity (getting it done quickly).

The informants at the designers said that the focus on becoming more productive has been tremendous and that the designers have thus managed to increase productivity from project to project. They have also experienced recurring effects from project to project, but not as significant as hoped. Part of the challenges has been keeping the same people from project to project as people quit, leave, and are assigned to other projects in their mother company's portfolio. The contractor and designer interviews stated that good relations were developed when the same people were transferred to the next project. Previous research has also shown that personnel replacements could damage the development of relationships across the parties, which is a crucial factor in implementing strategic partnering in the construction industry (Lu & Yan, 2007; Sundquist et al., 2018). People are the backbone of the collaborative relationship. Therefore, the organization is dependent on keeping the same people from project to project to ensure continuous improvement through the strategic partnership.

Both the contractor and the designer informants said that external factors such as the client also made it challenging to keep the same people through the strategic partnership. For example, project D was postponed for more than a year due to political decisions. When the project was started again, parts of the staff were busy with other projects, and there were several replacements in the project organization. The contractor and the designer informants also mention that outdated requirements specifications and the client's indecision negatively affect the strategic partnership. Therefore, an insight from the case study is that external factors such as the client could significantly influence the relationship between the contractor and the designers in a strategic partnership.

COLLABORATION

The interviews showed that the contractor and the designer had the same strategic vision to carry out several school projects together, and both parties wanted to enter a strategic partnership. There were three main reasons why the contractor and the designer wanted to implement strategic partnering: 1) they had some prior positive experiences from previous projects, 2) together, they perceived 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 (*learning effect*).

The parties agreed that the team would try to qualify for a new school project approximately one year in advance through dialogue and customer meetings. Therefore, the team had plenty of time to plan how to pre-qualify and further win the tendering competition. Identified advantages and challenges with collaboration in the investigated case are shown in **Error! Reference source not found.**.

Table 4: Advantages and challenges with the collaboration.

Advantages	Challenges
Ability to win projects	Arrange experience transfer meetings
Increased quality of the work	Predict future projects
Relationship development at the individual level	Relationship development at the company level
	Make long-term commitments

The interviews showed that both contractor and designer agreed that they should have been better at continuously evaluating the collaboration during the strategic partnership. They also acknowledge that they had not managed to eliminate enough problems. As a result, the same problems primarily recur from project to project. Therefore, they failed to utilize the learning effect through continuous improvement. Unlike companies that have been studied in other research on strategic partnering (see Crutcher et al., 2001; Lönngren et al., 2010), the contractor and the designer, in this case, failed to take advantage of the same benefits. Thus, several issues identified could have been limited or eliminated if the focus on experience transfer meetings had been more priority. However, the informants at the designer pointed out that such meetings have not always been possible because of increased economic conflicts at the company level through the strategic partnership. Therefore, the case study showed that increasing conflicts at the company level could prevent continuous improvement through strategic partnering.

A positive effect documented was their strong performance in the tender competitions. Their strategic partnership was crucial to the team winning four school projects in a row, the informants said. Lu and Yan (2007)'s study also highlights advantages related to tender competition and opportunities for a long-term competitive advantage as underlying incentives for strategic partnership between contractors and designers. However, even though the team had the same vision to carry out several school projects together, the informants point out that such long-term collaborations still entail a degree of uncertainty. First, it is difficult to predict which future projects will be put out to tender (*market conditions*). Second, there will always be uncertainty about whether the tendering competition will be won. This challenge is typical for the construction industry, as strategic partnering is strongly linked to the local business environment, local economy, government regulation, and culture (Lu & Yan, 2007).

A particular characteristic worth noting was that no formal organizational agreement was drawn, making the intention and commitment to the strategic partnering purely relational. Instead, it was an informal voluntary agreement between the parties involved, which Cheng et al. (2004) state are quite typical for strategic partnering. The informants said that a long-term formal commitment could have improved the collaboration, but several barriers made it challenging. First, it is risky for the designers as an organization, due to their business model, to commit entirely to one design-build contractor because it varies greatly which contractors are awarded the different projects in the local market. The designers said they must be on the team with the best chance of winning projects. Second, it is challenging to commit to a large contractor. If they win three large projects, the designers may not have enough capacity to participate. Third, the informants also believe that contractors and designers need periods of disengagement after working closely together for a more extended period. The first two barriers agree with Lu and Yan (2007)'s study, but the last barrier has not been found in previous research work. Therefore, while the designers and contractors could benefit from strategic partnering - the partnering commitments should be on projects after they are awarded. Thus, both contractors and designers can pursue other interests in other projects and between projects.

However, the reason why the contractor and designers need a break from each other is likely because sustained strategic partnering over time creates tension between the organizations. The informants describe that there has been a good relationship development at the individual level and that people have built close ties across the companies. The informants are also aware that the professional collaboration has had a positive effect and increased the quality of the work. Previous research describes strategic partnering as positively related to relationship development and improving teamwork. However, little research describes the challenges strategic partnering entails concerning developing collaboration at the company level. This case study has shown negative relationship development at the company level due to financial and contractual conditions, leading to the strategic partnership now being over. Therefore, the overall assessment shows that strategic partnering appears to be positive on an individual level but that disagreements at the company level can prevent the positive aspects of strategic partnering from being built on for even more extended periods.

CONCLUSIONS

The litterateur on strategic partnering states that it is often related to the client and the main contractor. In this paper, an exploratory case study was conducted to examine how strategic partnering between contractors and designers can improve future projects. The elements of contract, organization, and collaboration were explored based on the LC triangle. As the study emphasized an in-depth look at strategic partnership, the results should not be viewed as a generalization of the phenomena. Instead, the results may provide deeper insight into the phenomena and be of value to those considering strategic partnering. In addition, this paper can contribute to the theory of strategic partnering.

Several of the case study findings support and agree with the existing literature. For example, achieving technological development, the importance of keeping the same people, and the benefits of tender competitions. However, the case study has provided some additional insights into the context of strategic partnering between contractors and designers. For example, it was found that contracts and financial disagreements can occur in the long run and that the parties need a break from each other after an extended period. This type of disagreement has also made it challenging to arrange experience transfer meetings, preventing the contractors and designers from eliminating problems. The case study also identified external factors such as market conditions and policy decisions that make it difficult to achieve good strategic cooperation between contractors and designers. Also, it was identified that the designer's business model and capacity prevent long-term commitment with a contractor. Therefore, the partnering commitments should be on projects and not long-term commitments.

To improve strategic partnering between contractors and designers, the parties must be more aware of relationship development at the company level, not just the individual level. If companies can maintain relationships at the company level, the collaboration period can be even longer, ensuring continuous improvement. The parties must also be aware of finding long-term financial solutions that benefit both contractors and designers, as the investigated case showed that the savings only goes to the contractor. The people who worked together on several projects experienced a positive development in relationships and the quality of the work. People are the backbone of the collaborative relationship, and the organization is dependent on keeping the same people from project to project to ensure continuous improvement.

Strategic partnering aligns with the Lean philosophy of continuous improvement because the concept seeks learning effects at the company level and between projects. However, there is still a lack of knowledge in making the concept work in practice. Therefore, more case studies and interdisciplinary research are needed to further clarify improvements with strategic partnering between contractors and designers.

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DEVELOPING & TESTING A VALUE STREAM MAP SIMULATION: HELPING THE CONSTRUCTION INDUSTRY LEARN TO SEE

Yasaman Arefazar [1] and Zofia K. Rybkowski [2]

ABSTRACT

Resources to interactively teach value stream mapping (VSM) to construction practitioners and students of lean are currently limited. While traditional value stream mapping methods make sense for those with a background in manufacturing or industrial engineering, they are arguably neither intuitive to construct nor easy to understand by those in the building industry. There is a need for a value stream mapping method that implements and communicates in ways that are already familiar to those in construction.

The objective of this research is to develop and test a VSM simulation as a preliminary study that makes intuitive sense for those in the construction industry and so can serve as a training method for the identification and removal of waste. A virtual simulation was developed and tested using a design research methodology to facilitate scalability and to enable on-line play.

KEYWORDS

Lean construction, value stream mapping, continuous improvement / kaizen, waste, workflow, lean simulation

INTRODUCTION

Value Stream Mapping (VSM) is a lean tool used for performance measurement and waste reduction. Rother and Shook (2009) entitled their book *Learning to See* because VSMs help visualize process flows in their entirety.

A VSM is a valuable tool for students taking lean courses because it enables them to identify the flow of processes, waste, and value. VSMs also help project managers develop an understanding of additional lean concepts such as takt time and value.

Construction engineering and management students sometimes find it challenging to grasp abstract concepts such as “waste,” “value,” “process,” “conversion,” and “flow” of processes common to Lean manufacturing. Because of this, experiential learning becomes essential for effective teaching and learning to occur in construction management programs (Ramalingam 2018). Unless the topic of VSM is presented correctly, practitioners may not be able to properly apply the technique to an actual situation.

A study conducted by Hamzeh et al. (2017) revealed that simulation games can be employed to facilitate classroom instruction, improve the learning experience, and

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increase understanding of the theory behind lean construction and its real-world applications among engineering students. Additionally, simulation games align with student expectations that education should be enjoyable (Kapp 2012, Prensky 2007).

Research conducted by Brouwer-Hadzialic and Weigel (2016) and Oberhausen and Plapper (2015) demonstrated applications of VSM through laboratory experiments and student teams. Ramalingam (2018) mapped their BIM process when teaching Lean for one of the course modules on Lean Construction at a leading construction management institute in India. While valuable, such studies are limited, which triggers further interest in using the VSM technique as a demonstrative tool for teaching Lean.

VSM is process-oriented, and unless students and practitioners are included in the process, they may not be able to apply the technique to actual practice (Lobaugh 2008). Lean consultants such as Petruska (2014) created a VSM simulation, "The Pizza Game," using poker chips and train tracks. Some of the tools discussed in this game included work balancing and spaghetti diagrams, where the team used a VSM to conceptually capture processes and improve them.

This research aims to develop a VSM to illustrate scenarios to observers where waste is embedded and needs to be eliminated. It enables students to learn by mapping current and future conditions, identifying wastes, and continually improving processes. This research intends to propose and test a graphical analysis method that is more understandable to construction practitioners to help them more intuitively understand opportunities to improve flow.

The proposed analysis method contains a Gantt Chart, timeline, and spaghetti diagram depicting processes and embedded wastes. The intent is to help construction practitioners to understand flow. Conventional VSM methods use flow charts for mapping the processes, which often require existing knowledge of VSM symbols. Since most construction practitioners do not already possess this knowledge, it can take substantial time and effort for an individual to read and understand the VSM and how to use it. Therefore, this research study proposes a more intuitive method for value stream mapping in construction.

VALUE STREAM MAPPING

The Value Stream Map (VSM) method originated from the Toyota Production System. It requires collaboration with the customer and a focus on their point of view with respect to process necessities (Haefner et al. 2014; Morlock & Meier 2015; Rahani & Al-Ashraf 2012).

The VSM was initially proposed to model production systems in a factory (Rother and Shook 2009) and then extended to supply chain modelling (Womack and Jones 1996). The process of value stream mapping can be categorized into six steps: 1) identify the process to improve; 2) create a current state map of the process; 3) determine an appropriate metric for improvement; 4) create a future state map of the process; 5) determine improvement methods to go from the current state to the future state that achieves the correct metric; and 6) initiate improvements (Lobaugh 2008). Simonsson et al. (2012) demonstrated that on-site practitioners can use VSMs to see the day-to-day flow of work, in order to understand the impact of improvements to workflow.

In the construction industry, VSMs can help identify the bottlenecks in the construction process and therefore minimize waste (Germano et al. 2017, Kanai and Fontanini 2020).

SIMULATIONS IN LEAN EDUCATION

According to Tsao and Howell (2015), serious games and simulations have traditionally played a critical role in teaching lean construction principles to outsiders. Experimenting with simulations began in the 1980s by lean pioneers Greg Howell and Glenn Ballard (Tsao and Howell 2015).

A simulation game supports teaching by mimicking miniature controlled experiments of actual processes that create opportunities for an “aha moment” among participants. In the world of lean, simulations are used to illustrate lean principles and create buy-in among those who will be implementing lean (Rybkowski et al. 2020). These games facilitate learning about the consequences of decisions and strategies through visual representation of processes and metrics (Shannon et al. 2010). This offers experiential learning of Lean principles in error-friendly, dynamic learning environments. Simulation games foster physical actions for learning by doing, which converts knowledge into a skill through the medium of realism (Galloway 2004). Maghool et al. (2018) stated that theorists such as Benjamin Bloom, David Kolb, Jean Piaget, John Dewey, and Paulo Freire believed that experiential learning should be integral to any educational system.

Moreover, according to a study by Bhatnagar & Devkar (2021), important themes such as waste reduction and value maximization are not key focus areas of existing lean simulation games. Games such as the Parade-of-Trades Simulation, LEAPCON, and Lego™ Airplane Game deal with waste along with various other learning objectives; however, they do not demonstrate waste reduction and analysis of value added / non-value added activities as the key learning outcomes (Pollesch et al. 2017).

In response to filling this gap, this research aimed to develop a VSM simulation that features a cook making spaghetti during two scenarios. A simulation video was developed to facilitate a participant’s recognition of the eight wastes, and analysis of value-added / non-value-added activities. The simulation facilitator is then encouraged to challenge players to brainstorm ways their newfound understanding can be applied to reduce wasteful activities in construction processes.

RESEARCH METHOD

This study reports on the development and testing of a lean simulation that focuses on value stream mapping for waste reduction and continuous improvement (kaizen). The simulation was inspired by the video “Toast Kaizen: An Introduction to Continuous Improvement & Lean Principles” by GBMP to introduce the concept of VSM and waste reduction to the simulation participants (Hamilton n.d.).

The study exposes to participants how they can efficiently and effectively map out current and future conditions that facilitate identifying wastes observed in the construction industry as a way to continually improve processes. This research aims to offer a VSM simulation that can help the simulation participants sharpen their intuition about waste identification, revise existing processes to eliminate waste, and quantify the impact of the newly revised processes.

For the simulation’s graphic design, Adobe Illustrator™ was used, and the animation was assembled in Microsoft PowerPoint™ and Adobe After Effects™.

This study used a design research methodology that involves iterative development and testing. The simulation was tested on: (i) 48 students without prior familiarity with VSMs during a course dedicated to lean construction in the Department of Construction Science at Texas A&M University; (ii) 9 experts from San Diego Community of Practice;

and (iii) 14 members of the Administrating and Playing Lean Simulations Online (APLSO) community where some of the participants were assumed to have prior familiarity with the concept of VSM.

Participants were asked to provide feedback on the VSM simulation. Modifications were made based on participant feedback.

DESCRIPTION OF THE SIMULATION

The simulation was designed to engage participants to watch a 7-minute-30-second long animated video that features a man cooking spaghetti for his girlfriend. The intent was to engage participants in a simple activity that is familiar to most, if not all, participants.

During his first attempt (Scenario I), the cook finishes within 4-minutes-12 seconds. The process intentionally consists of multiple types of waste such as unnecessary movement, material handling, and inefficient ordering of activities. Viewers are invited to actively identify these wastes. The eight wastes (Liker 2004, p. 28-29) depicted during Scenario I are shown in Figures 1, 2, 3, 4, 5 and 6. The first waste illustrated in the video depicts *unnecessary movement*, where the cook walks back and forth several times (Figure 1). For the second waste—*waiting*—the cook wasted time waiting for the water to boil, for the spaghetti to cook, and for the meatballs to grill (Figure 2).

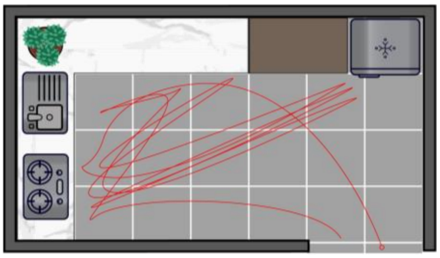

Figure 1. Unnecessary movement in Scenario I

Figure 2. Waiting

The third waste—*unnecessary transport or conveyance*—refers to the superfluous movements taken during handling of materials. The video depicts this waste by showing the cook walking back and forth to carry meatballs from the refrigerator to the stove and then back again to the refrigerator to return unused meatballs. The fourth waste is *overproduction*, which means producing more items than needed or sooner than necessary. During Scenario I, the spaghetti was cooked sooner than required, and as a result, extra food was stored in the sink and saved for further use (or disposal) becoming the fifth waste—*excess inventory*.

Figure 3. Unnecessary Transport

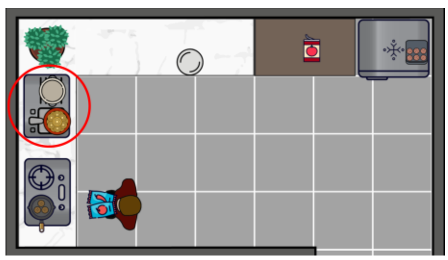

Figure 4. Overproduction and Inventory

For the sixth waste—*unused employee creativity*—the cook could have used his time more effectively by simultaneously engaging in another activity while waiting for the water to book and spaghetti to cook (Figure 5). Ironically, at the end, the completed spaghetti was discarded since the cook had neglected to first ask his girlfriend for her preferences before embarking on the task (i.e., she was allergic to spices in the spaghetti). This would be considered a *defect* (seventh waste) and was thrown into the trash (Figure 6). All the mentioned wastes comprise the eighth waste, *overprocessing or incorrect processing*, which is represented by redundant tasks that do not add value.

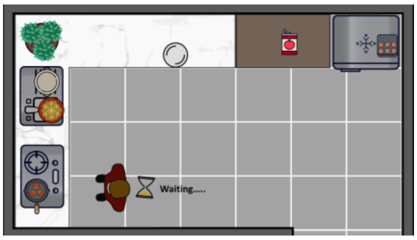

Figure 5. Unused employee creativity

Figure 6. Defect

In his second attempt (Scenario II), the man was able to cook the spaghetti within 2-minutes-32-seconds by removing extra movements and performing activities simultaneously (e.g., cleaning the countertop) during waiting times. Two variables that were changed in Scenario II were replacing the stove and using an electric kettle to expedite the boiling process (Figures 7 & 8).

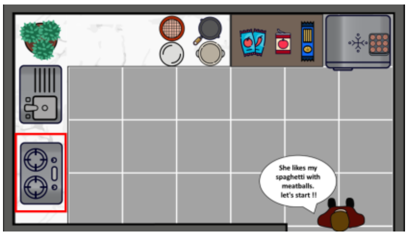

Figure 7. Scenario I Layout

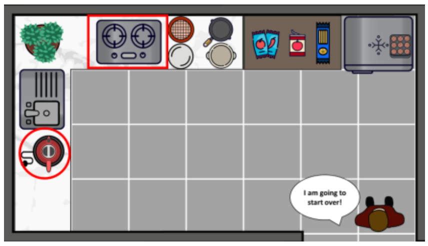

Figure 8. Scenario II Layout

As is apparent by the motion tracking during Scenario II, as shown in Figure 9, the amount of motion and waiting times were reduced by 39.7% compared to Scenario I. Also, overproduction and inventory wastes were removed by preparing the spaghetti only when needed (Figure 10).

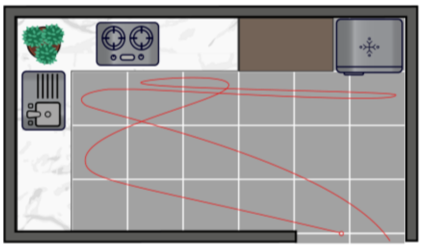

Figure 9. Motion Tracking (Scenario II)

Figure 10. Elimination of Overproduction

In the end, the cook's girlfriend was satisfied since he asked for her opinion about the spaghetti before beginning the process (e.g., conditions of satisfaction). Therefore, the result was satisfying, and no defects emerged during Scenario II. At this point, it is important for the facilitator to discuss with participants the need to define *conditions of satisfaction* at the beginning of any process because a product that is done quickly but that does not satisfy critical, stated needs is ultimately considered to be 100% waste.

Figure 11. Added Productivity

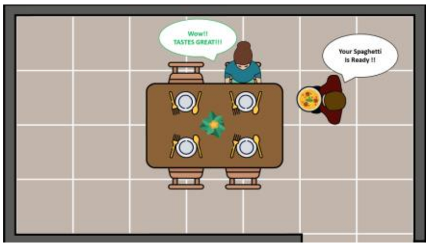

Figure 12. Satisfying Result

FACILITATING THE SIMULATION

To collect feedback from participants in the initial of three first run studies, the video was streamed to student laptops as an assignment a graduate level Advanced Productivity and Lean class in the Department of Construction Science at Texas A&M University. Students were requested to use graph paper, excel, etc., to graphically capture the flow of activities along a timeline: (a) *before* leaning the process, and (b) *after* leaning the process. Participants were then asked to respond to the following questions:

i. Which processes are waste? List them and/or circle them.
ii. What metrics could you use to quantify the improvement?
iii. If you were to design a Scenario III, can you think of any additional actions that could be taken? If so, what are they?

The intent of the assignment was to help students learn to see waste by communicating with simple graphics. The students were given 30 hours to complete this assignment. The authors of this paper discussed during the class some of the most interesting approaches submitted by the students. The authors also briefed the class about Value Stream Mapping, the eight wastes found in Scenario I, and improvements made during Scenario II. The authors of this paper presented opportunities to visually capture the processes in the form of a timeline, Gantt chart, and spaghetti diagram to map both scenarios. Ultimately, the students were asked to individually offer feedback on what they liked about the exercise (i.e., "plus") and what they thought could be improved ("delta"). The plus/deltas were collected anonymously to encourage frank responses.

For two additional first run studies, the authors of this paper ran the simulation during a Zoom meeting with 9 experts from the San Diego Community of Practice, and then later, with 14 Zoom participants during an APLSO (Administering and Playing Lean Simulations On-Line) meeting. Participants were asked to sketch a spaghetti diagram on top of provided kitchen floor plans which were sent out before the meeting and which participants could print. In addition, they were asked to respond to an online survey which asked about their education, current profession, past training regarding VSMs, and perceived effectiveness of Gantt Charts and Spaghetti Diagrams versus the conventional method of VSMs (i.e., ranking effectiveness along a 1-7 Likert scale). Respondents were also invited to share recommended plus/deltas and potential applications to construction.

EVALUATION AND RESULTS

Participants of the primary first run study included 48 graduate students taking an in-person lean construction course with no prior familiarity with the concept of VSM. Students came up with different ways to graphically represent their ideas and value stream map the processes portrayed in the video. They used a combination of tools to present their assignments. Most students used a table listing activities and their durations, a line chart, screenshots from the video, sketches, and bar charts / histograms to represent their observations. Others used color-coding, Gantt charts, and flow charts to visually capture and quantify differences between Scenarios I and II. A few students created spaghetti diagrams, conventional VSMs, AON diagrams, timelines, and other creative graphics (Figure 13). The authors of this paper selected several representative assignments and presented them in class for general discussion. The students discussed whether they would be persuaded by the chosen tool or graphic if they were the manager of a construction company and an analyst presented the visual to them to improve their decision-making.

The students mostly agreed that they could not immediately understand the data presented in the flow charts of conventional VSMs since they require a substantial understanding or prior training in VSM symbols.

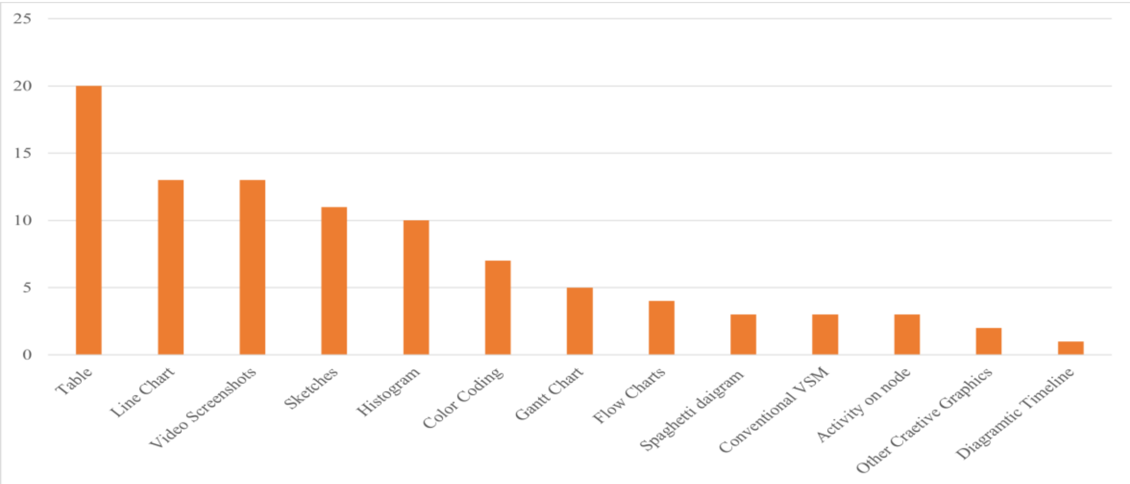

Figure 13. Frequency of the tools utilized by the students

By contrast, assignments that included tools such as tables, bar graphs, Gantt charts, color-coding, and timelines were more successful in being understood by construction management students who were new to the concept of VSMs.

Furthermore, the authors presented their diagnostic tool consisting of a timeline, Gantt chart, and spaghetti diagram for scenarios I and II (Figures 14, 15, and 16). Following class discussions, individual student feedback was collected via an online survey about what they felt worked with the given exercise (i.e., “plus”) and what they thought could be improved (i.e., “delta”; Table 1).

To demonstrate that incremental improvements should be continual, the authors challenged participants to suggest an additional scenario. Based on collective feedback to include an island in the middle of the kitchen, movements were further reduced (Figures 15, 16, & 17), generating Scenario III—and time was further reduced by 10 seconds.

A modified version of the simulation representing Scenario III was then shown via Zoom to a group of 9 construction experts and they were asked to fill out a Google Form™ survey at the end of the session. Demographics from the survey reveal that 54.2% of the participants had a formal education in construction, 20.8% have a formal engineering education, 8.3% were educated in operations management, 8.3% in architecture, and 8.3% in technology and project delivery. Of the participants surveyed, 25% currently work in construction firms, 23.3% work as consultants, 8.4% in architectural and engineering firms, and the remaining are members of academic faculty or students. A large number of the participants (75%) stated that they were given prior training in VSM.

Respondents verbally expressed that the visual simulation was easy to understand. Of those surveyed, 91.7% assigned the proposed Gantt Chart and Spaghetti Diagram a Likert score of five and above (5, 6, &7) while 75% of participants gave the conventional VSM method a score of five and above (5, 6, & 7). Respondents also stated that they preferred the proposed VSM formats (Figure 15, 16, & 17) over the conventional form of VSMs (Figure 14). This is likely because constructors have more experience with Gantt charts.

Table 1. Plus & Delta on the VSM Exercise

Plus	Delta
• Simple / Easy to understand / Straightforward • Good graphical representation • Practical & Generic • Helps in critical thinking and problem solving • Good attention to details • Helps in deep understanding of value-added & non-value-added activities • Lucid and effective way to show continuous improvement • Shows application of learning in real life • Helps in raising a broader perspective / Brainstorm • To the point (Short video while delivering the concept) • Encourages student involvement in the class • Helps present different ideas graphically • Helps to think out-of-the-box • Explains the basics of lean using a simple example • It is a fun and innovative exercise for learning VSM • [It] encourages to learn more about how to better qualify [and] quantify specific metrics	• Commercial setting instead of a private setting • rearrange the kitchen for the optimized scenario • Give more instructions on the exercise • Use construction-oriented example • Use the real time needed for cooking activities • Distances should be calculated in both scenarios

Also, they noted that the Gantt Chart is understood with interrelated and multiple tasks that could have an impact on others. Besides, there was a consensus among the experts that the presented simulation is an excellent tool for teaching the fundamentals of Lean and introducing the concept to individuals unfamiliar with the idea of VSM. Furthermore, they mentioned that Value Stream Mapping could help streamline practices in the concrete construction activities, material delivery to the job site, logistics, area-based scheduling, manufacturing, process document management in the trailer, information management on the jobsite, and any repetitive tasks in construction.

RESEARCH SCOPE AND LIMITATIONS

The developed simulation is intended to help expose students and practitioners to VSM as a means to convey foundational Lean concepts such as waste, value, cycle time, takt time, and flow. The simulation is designed to depict processes and wastes graphically.

IMPLICATIONS

Value Stream Mapping is a tool used to think through a current situation, identify potential wastes in the process, and ultimately develop an improved future state map. The ultimate intended value of this work is to help users improve workflows.

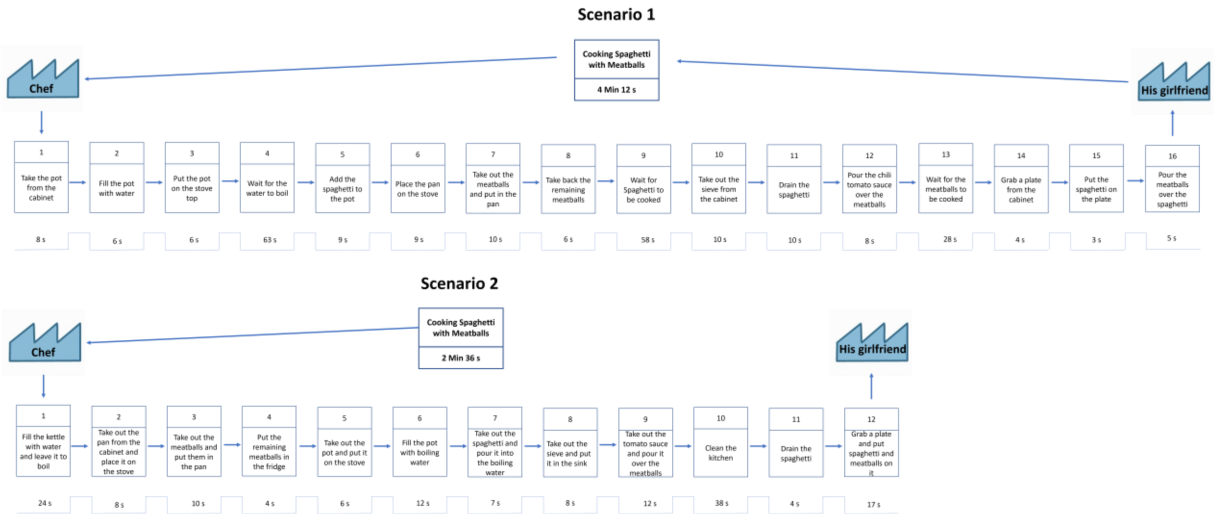

Figure 14. Conventional VSM for Spaghetti Making Process

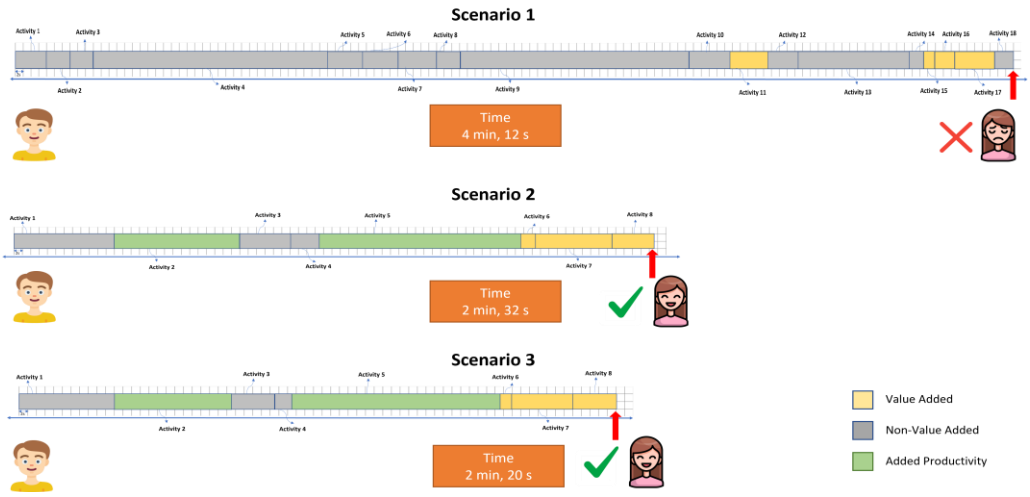

Figure 15. Comparison of Three Scenarios using Timeline

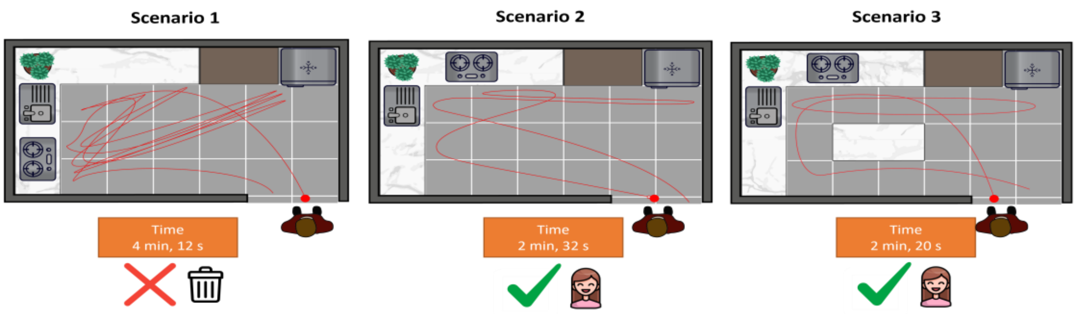

Figure 16. Spaghetti Diagrams for Three Scenarios

Figure 17. Comparison of the Scenarios Using Gantt Chart

CONCLUSION

This paper reports on the development and testing of a novel simulation as a preliminary study to expose participants to the utility of Value Stream Mapping as a means to identify and remove the eight wastes from processes. As part of the simulation, a graphic video was created to depict the process of making spaghetti. As a first run study, the simulation was tested on (i) 48 graduate students taking an advanced productivity and lean course in the Department of Construction Science at Texas A&M University; (ii) 9 experts from San Diego Community of Practice; and (iii) 14 participants at a meeting of the Administering and Playing Lean Simulations Online (APLSO) community.

Results from the first run studies showed that most participants liked the graphics of the videos, and found it simple and easy to understand. Additionally, there seemed to be a consensus that the designed exercise encourages participants to generate innovative ways represent process flow to the construction industry.

There also appeared to be general agreement among experts that the presented simulation is an excellent tool for teaching the fundamentals of lean and introducing the concept of VSM to individuals previously unfamiliar with the concept.

The authors of this paper observed that by sharing the simulation video and by implementing a Gantt chart to represent current and target conditions, students and practitioners trained in construction felt comfortable applying VSM to construction processes. While the conventional VSM format is perhaps well suited for many engineering and manufacturing applications—especially for those with prior VSM training—results from this research suggest there are additional and alternative ways to map construction processes that may be more aligned with the conventions of those trained in the construction industry.

AKNOWLEDGMENTS

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KAIZEN AS AN IMPROVEMENT METHOD FOR CONCRETE WALLS CONSTRUCTION IN SOCIAL HOUSING PROJECT

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ABSTRACT

Making production processes stable is the basis of the Toyota Production System (TPS) for improving processes and consequently of increasing the value of production activities. Hence, the set of tools based on the TPS that can be used within the kaizen approach emerges as an opportunity to seek to optimize processes and to increase productivity. The research points out the possibilities of improving production processes in social housing projects through the implementation of structured kaizen events. This article describes the implementation of kaizen events developed in a Brazilian company that constructs residential buildings with a focus on standardizing and stabilizing the process for producing the structure of buildings with a concrete wall typology. The methodology used to develop this study is action research. Based on a kaizen methodology structured in four stages: Definition and preparation; Execution; Monitoring and standardization; and support, the main steps that form the process of building concrete walls were analyzed. The main results obtained are flow improvements in the main stages that make up the construction process, a reduction in the workload and a contribution to reducing and adhering to the total lead time in the concrete wall stage, in addition, providing a reference for structuring kaizen events in the construction environment.

KEY-WORDS

Kaizen, Stabilization, Concrete Wall, Last Planner System

INTRODUCTION

The construction sector is commonly analyzed and criticized for its performance and for its various problems. The causes of these are the object of studies and research at the levels of product, of the production of projects and of the industry as a whole (Vrijhoef and Koskela, 2005). In an increasingly competitive market, implementing a lean production philosophy focused on reducing stock, optimizing time and process and

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product quality and reducing the price becomes decisive for the success of organizations (Bordin et al. 2018). In its simplest form, lean production is about eliminating waste or efforts without added value in a company and, in the essence of its concepts, this is sought by taking initiatives that prompt the continuous improvement of processes (Ortiz, 2010).

The factors that guide the continuous improvement of processes were introduced based on presenting a scientific model for implementing improvements that are founded on a sequence of questions that focus on identifying, analyzing and solving problems, called the Scientific Thinking Mechanism (STM) (Shingo, 1987; Shingo, 2010). Imai (1986) spread the concepts of continuous improvement in management in the West using the term kaizen, the Japanese word for "continuous improvement". Kaizen involves all employees of a company, who focus on improving processes (Ortiz, 2010).

In the field of civil construction, the institutionalization of a culture of kaizen or the continuous improvement of processes is marked by initiatives such as measuring and monitoring processes, defining the desired objectives clearly, standardizing the best procedural practices and always seeking to improve them, and finally, by delegating responsibility for improvement to all those involved (Koskela, 1992).

Thus, some initiatives regarding structured kaizen practices initiatives have been developed in the construction industry. Rybkowski and Kahler (2014) approach the theme of games and simulations to illustrate the basic concepts of continuous improvement and standardization; Bordin et al. (2018) explore the A3 tool in the kaizen process of a company that assembles metallic structures; Tezel et al. (2018) seek to understand the execution of cells of continuous improvement, with its associated benefits and challenges, in the supply chain of highways in the United Kingdom; Vivan et al. (2016) present a proposal for a model for developing kaizen projects aimed at the construction sector with a focus on housing.

However, as commented on by Berndtsson and Hansson (2000) and Brunet and New (2003), a *kaizen* methodology, and therefore the techniques and tools used in its development, can be adapted and transferred to the circumstances and characteristics of each company or sector.

In this context, this work presents the possibilities of improving processes in civil construction, in social housing works through the approach of structured kaizen events. By conducting action research at a construction site of a Brazilian construction company, this article puts forward the process for making the production of concrete walls more stable by applying a *kaizen* methodology.

LITEARATURE REVIEW

LEAN CONSTRUCTION AND THE LAST PLANNER SYSTEM

The civil construction sector has looked to the manufacturing industry in search of solutions to minimize its problems (Pereira and Cachaldinha, 2011). The Toyota Production System (TPS) in its essence focuses on eliminating waste and increasing value for the customer (Ohno, 1988). In the early 1990s, the concepts and ideas that guide the basis of the TPS were adapted for the construction industry, giving rise to what we know today as Lean Construction.

Lean Construction, the production philosophy for construction proposed by Koskela, is based on principles that serve as a basis for reducing wastes and improving the efficiency of the production system. Complementarily, Ohno (1988) adds that the basis of a production system is to provide stability for carrying out operations.

Thus, the Last Planner System (LPS) has emerged as a technique for controlling production, providing basic stability and generating conditions for introducing advanced lean concepts (Viana et al. 2010).

In this system, long-term planning focuses on global objectives and constraints, contemplating the project as a whole and providing guidance on what should be done. At a lower level, medium-term planning, specifies the means to achieve these objectives, identifying and removing constraints restrictions, looking ahead 6 weeks and ensuring that the necessary materials, information and equipment are available so that the activities can be performed (Ballard, 1994). Finally, the system can improve the reliability of short-term assignments, protecting the planned work from variability and looking for the commitment of the workforce through the actions of the work teams that decide what will be performed (Ballard, 1994).

KAIZEN

The term kaizen is an expression of Japanese origin, formed from "Kai", which means to modify, and "Zen", which means for the better. (Martins and Laugeni, 2005). The essence of kaizen means continuous improvement, involving all team members, including managers and workers of the production system (Imai, 1994).

For Sharma and Moody (2003) the philosophy of kaizen is supported by improvements in work processes by means of initiatives that seek to eliminate wastes by using inexpensive solutions that are supported by the creativity and motivation of work teams.

Kaizen events have often been implemented for targeted improvement actions, carried out with the support of cross-functional teams focused on improving a specific work area, pre-determined objectives, and accelerated deadlines (Farris et al. 2008). In this context, in a short period of time (between 3 and 5 days), teams involved in the kaizen event focus their attention on solving problems by using low-cost tools, to develop and implement improvements in specific areas (Farris et al. 2008).

Therefore, kaizen teams can identify and tackle problems that oblige companies to work with high levels of waste. However, although the methodology is simple, it needs a lot of determination to succeed, as it represents a change in the company's culture (Graelm and Peinado, 2007).

Imai (1996) suggests that for kaizen implementations to result in problem-solving based on evaluating data, to facilitate the communication of problem-solving processes and to keep the kaizen culture active in organizations, the application should be structured in eight steps:

1. Choose the theme/focus of the application (determined according to administrative policies according to priority, importance, urgency or economic situation);
2. Analyze the context;
3. Collect and analyze data 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.

Finally, is shown in the IGLC literature an important contribution from Rybkowski and Kahler (2014) that brings the outcomes for a new simulation that illustrates the productivity potential of collective kaizen and standardization. They investigate how collective kaizen and standardization can be made part of the daily process fabric of lean construction processes bringing new improvement opportunities (Rybkowski and Kahler (2014).

RESEARCH METHOD

DESCRIPTION OF THE METHOD

The development of this study was carried out through an action research, due to the characteristics and contexts presented. This methodology presents an empirical basis associated with the process of solving a collective problem, and researchers and participants of the problem involved in an operative way (Thiollent, 2011). For Tripp (2005) this methodology is defined as any continuous, systematic and empirically based attempt to improve practice. The main features. In addition, aspects related to the participation and intervention of those involved, process documentation, an oriented proactivity and the continuous search for problem solving are observed as characteristics (Tripp, 2005).

Thus, throughout the study, researchers acted in a participatory and active way in the generation, collection and analysis of information. During the stages, data were collected through photographic records, documents and spreadsheets, containing information on the execution flows, number of operators and execution times of activities.

DESCRIPTION OF THE COMPANY AND CONSTRUCTION SITE

The study was carried out in a company in Brazil that was founded in 1979 and that has been working in the residential construction sector, in the construction and incorporation of medium standard projects and projects with a focus on social housing. It operates on the national scene with an average of 230 projects per year. The construction company is certified by ISO 9001/2000 and PBQPH (Programa Brasileiro da Qualidade e Produtividade do Habitat – Brazilian Program of the Quality and Productivity of the Habit), – Level A.

The project analyzed in the study consists of medium standard residential buildings, located in the city of Fortaleza - Ceará. The development consists of two towers, with 224 housing units, distributed in 3 different typologies. The work began in May 2021 and is scheduled to take 25 months to complete.

Figure 1: Illustration of the project and how it will be implemented (provided by the case study company)

THE LEAN APPROACH IN THE CONSTRUCTION COMPANY

The construction company began to implement the Lean Approach in September 2020 by seeking to understand the concepts and carrying out the first implementation at a pilot works. From there, a process of disseminating Lean was initiated within the company, the model being extended to another 20 construction sites.

Currently, implementation has grown and has become a strategic project within the company's production sector. The focus of the project is to implement Lean Construction concepts in a progressive and sustainable way. Hence, planning is developed based on the Last Planner System and on a stable and standardized production rhythm for all activities that take place in the apartments. Thus, the flow and the standard sequence of activities are maintained, and defined to meet a standard takt time.

Having consolidated a structure of long, medium and short-term routines, the project now seeks actions for continuous improvement by holding kaizen events, where the challenge is to reach the production rhythm defined with the structure team.

KAIZEN EVENT STEPS AND RESULTS

To carry out the kaizen event, choosing a construction works was based on the level of maturity of Lean implementation that the company had reached. Figure 2 shows the steps of the Kaizen event implemented in the study.

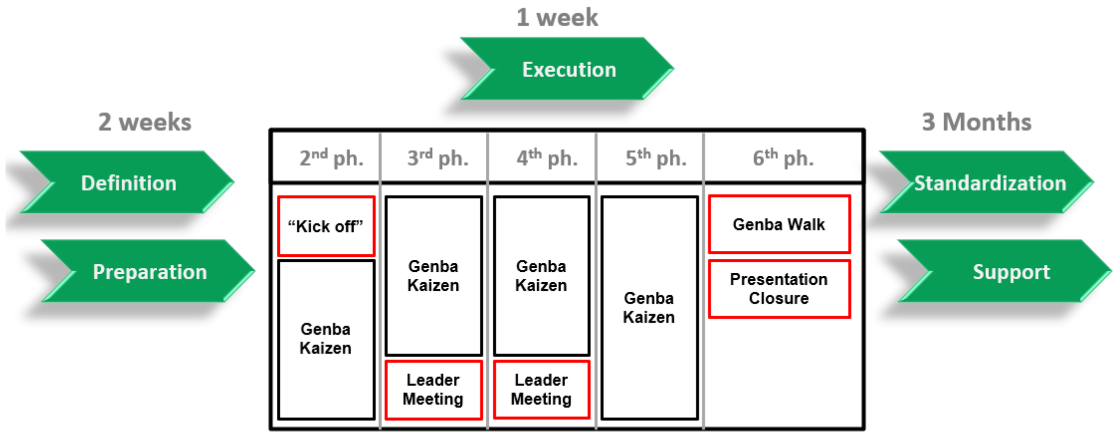


Figure 2: Execution steps of the Kaizen event (the authors)

DESCRIPTION AND PREPARATION

The process chosen to carry out the kaizen event was identified from the information collected by the production team. It was attested that building the concrete wall was not performed as expected by the macroflow that the company had standardized. It expected this step to be carried out in 4 working days, and the work was maintaining an average lead time of 5 working days. In addition, the high impact of the process on the organization's production system was decisive for choosing this process.

Process and information flow

From the definition of the production process, each of the activities that compose it were mapped and a mapping was carried out in a collaborative way with those in charge of each of the stages of producing the concrete wall. The activities of each step were sequenced and the process for doing this was described using a swimlane flow chart.

The sequence of building the concrete wall comprises the stages of marking, scaffolding, installations, formwork and concreting. This comprises a total of 38 activities, carried out by 6 production teams consisting of 54 employees of different functions, bricklayers, unskilled laborers, electricians, plumbers and assemblers.

Current Status (Description of problems) and need for kaizen

The field analysis and the sequencing of activities carried out with the field teams indicated that the main process problems were the interference between service fronts (Operators); interference between product and tooling; difficulties in moving materials, the use of defective tools and wastes being created due to movement, rework and wait-time.

As actions to improve and address the problems presented in the production process, proposals for improvements were defined involving the creation of the following items:

- Process Capability Framework;
- Operator Balancing Chart;
- Standardized Work Diagram;
- Definition of takt time by activity;
- Creation of supply routes/windows;
- Define Supply Standards;
- Management at sight;
- Application of continuous flow;
- Creation of Pull System where necessary.

EXECUTION

The execution stage was marked by holding a kaizen event focused on stabilizing the marking, scaffolding, installation, formwork and concreting processes.

Survey of opportunities

The members of each of the production teams responsible for carrying out the steps were invited to talk about their difficulties in carrying out daily activities and to present possible proposals for improvements to the process as a whole. The information collected in this step was structured by means of a prioritization matrix (impact vs effort). As a result of this stage, 86 improvement actions were proposed in an interactive and collaborative way. These improvement initiatives will be implemented and monitored by the construction management team using a document called the kaizen journal.

Kaizen Journal				***Status***					
Item	*Problem or Fact*	Idea	Who	When	25	50	75	100	Remark
63	Electricity boxes – Narrow Rooms	Define the height of the low box	VERAS	17/11/21					MOLD
64	Concreting materials above the beam	Check exactly what the materials are that lie above the beam and define a fixed place for them	TALYS	17/11/21					SCAFFOLDING
65	Different production between works		LARISSA	12/11/21	OK	OK	OK	OK	SCAFFOLDING
67	Turner	Insist on delivery	LARISSA	19/11/21					SCAFFOLDING
69	Heavy hose	Implement spider	ALEXANDRE	11/11/21	OK	OK	OK	OK	CONCRETING
70	Poor quality of the concrete	Aligned with Polimix	POLIMIX	11/11/21	OK	OK	OK	OK	CONCRETING
71	Hard concrete makes descent difficult	Aligned with Polimix	POLIMIX	11/11/21	OK	OK	OK	OK	CONCRETING
72	Delay of concrete	Definition of 5 trucks	POLIMIX	11/11/21	OK	OK	OK	OK	CONCRETING
73	Truck short	Definition of 5 trucks	POLIMIX	11/11/21	OK	OK	OK	OK	CONCRETING
75	Cleaning more difficult in the part above the façade – vap Position		POLIMIX						CONCRETING
80	Hall lighting	Piu in a mobile reflector	POLIMIX	16/11/21					SCAFFOLDING
83	Priority in the ascent of the climbing mold	Speak with the crane operator	LARISSA	17/11/21					SCAFFOLDING
85	Broken spacer – beam	Abir agilis	LARISSA	17/11/21					SCAFFOLDING

Figure 3: Kaizen journal developed based on workers' suggestion (the authors)

Production process alternatives

The managers involved in each of the 5 stages were divided into working groups to analyze the process. The Seven Ways scenario and layout analysis tool was used to simulate and propose different execution flows of the production stages. The alternatives proposed by the work teams were presented and evaluated in a collaborative way, giving rise to new process flows for each of the stages of building the concrete wall. The groups were divided to meet the standard macroflow following the main macro steps: Marking, Scaffolding, Installations, Formwork and Concreting.

STANDARDIZATION AND SUPPORT

In this stage, the objective is to apply the improvements developed during the kaizen event so that they can be implemented gradually, focusing on improving processes, reducing lead time, optimizing teams and on the consequent stabilization of conducting the stage of building a concrete wall.

Hence, proposed improvements are in the phases of implementation and evaluation so that then new standards can be established for the execution process. However, from the first data collected, indications of good results can be detected when analyzing the activities.

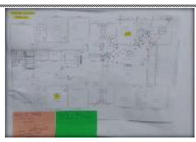
Step	Current Layout	Current situation	Problem	Actions / Impact	Proposed layout
 Marking out		Activities being performed sequentially	Carrying out marking activity takes a long time	The activity of fixing the spacers will be done in parallel with the witness, thus reducing the total time by 40 minutes	
 Framing		The activities are done in large batches of production.	It takes a long time to assemble the framing	Application of the principle of continuous flow in the activities of fixing the screens, corner screens, reinforcement and spacer. 40 minutes reduction in time. Making it possible to reduce the total time of the framing + installations by 4 hours	
 Installations		The activities are carried out in large production batches.	High turnaround time for installation.	Application of the principle of continuous flow	
 Mold (Assembly)		Activities being carried out non-sequentially	High amount of time taken to do the activity of mounting the mold	Creation of work teams by block of activities with the crew working in line (disassembly, transport and assembly of the mold)	 
 Concreting		The activities are carried out in excess	High amount of time taken to do concreting	Concreting points changed from 13 points to 9 points. And total time reduced by 2 hours	

Figure 4: Scenario analysis using the Seven Ways tool (the authors)

Process benefits, reduction in cycle time and teams optimization

Table 1 presents the partial results collected from the improvements proposed during the kaizen event. With regard to the processes, changes in the personnel responsible for conducting some activities, changes in the sequencing and reducing production batches provided a better integration between the work fronts, thereby reducing waiting time losses and prompting flow improvements in the process.

The reflection of the process improvements has been translated into reducing the cycle time of various activities in the construction process. On the day before the concreting stage, activities such as axis transfer and marking had a cycle time reduction of at least 50% in their execution process. In the formwork assembly stage, activities considered critical, such as assembling the outer part of the formwork, achieved an average reduction of 30% in cycle time.

For the steps carried out in the concreting, the impacts on the cycle times were mainly reflected in the activities related to the framing stages and the 2nd stage of the formwork, respectively, with reductions of 14% and 32% in the average execution time performed previously. In addition, activities related to the installation and concreting stage also obtained time gains after the proposed changes.

The impact of these cycle time reductions resulted in reducing the average lead time for executing the process for building the concrete wall as a whole. Although the results are still initial, the number of the last 10 concretings reveal that the average lead time fell from 4,8 days to 3,9 days, approaching the ideal lead time of 4 working days.

PLANNING THE STEPS OF BUILDING A CONCRETE WALL			
1 DAY BEFORE CONCRETING	**STEP**	**AVERAGE REDUCTION OF THE TIME CYCLE (%)**	**GAINS IN THE PROCESS**
	TRANSFER OF AXIS	**-67%**	BEFORE: Activity was done by the marking team. NOW: Activity done by the topography team.
	MARKING OUT	**-50%**	NOW: Marking team transports the materials from 07:30 until the liberation of the topograph. BEFORE: A lot of materials present at the work station (beam) generated losses by waiting, thus increasing the time to do the work.
	INTERNAL MOLD - 1ST PHASE	**-**	-
	EXTERNAL MOLD	**-30%**	NOW: Starting with the alignment of the crane, there was a reduction in the transport time from the facade.
DIAY OF CONCRETING	**ACTIVITY**		**GAINS IN THE PROCESS**
	FRAMING	**-14%**	The Flow of activities improved and the sequencing of the framing with the installer was observed with the real gain. The sequencing of the framing with the installer was the real gain.
	INSTALLATIONS	**-10%**	
	INTERNAL FORM - 2nd PHASE	**-32%**	Prioritizing the facade of the twinned apartments reduces the number of closure activities for the following day.
	CONCRETING	**-36%**	When the number of conctete-mixer trucks is adequate and the concrete is within the receipt criteria, concreting flows rapidly.

OBSERVATIONS
1) THE IRONWORK TEAM AND INSTALLER INTERRUPT THE CAGE TO START THE FRAMING AND INSTALLATIONS OF THE BEAMS WHILE THE SERVICE IS BEING LIBERATED.
2) RAISE THE CLIMBING SCAFFOLD ON THE SAME DAY AS THE FACADE.
3) CHECK POSSIBILITY OF THE PRODUCTION BEING BY AREA.

Table 1: Impact by stage on the cycle time of the improvements implemented (the authors)

Finally, the improvements implemented made it possible to reduce the number of teams performing the framing and formwork stages, causing a decrease of five skilled workers in these teams as its presented on Table 2. In addition, a rearrangement of the concreting team could be carried out, thus replacing a skilled with an unskilled worker. These changes were reflected in the scaffolding, formwork and concreting teams and generated savings opportunities of approximately 18% in the labor costs of the process of building concrete walls.

The next steps in this stage are to formalize the actions proposed in the kaizen that result in process improvements due to structuring clear work instructions, and that enable each activity of the steps involved in the process of building concrete walls to be better understood. In addition, support initiatives such as feedback from the kaizen journal, training, and the presentation of changes after the kaizen is carried out, must be developed so that the teams involved in the event maintain the culture of continuous improvement in the company and can replicate the process improvements in the company's other production units.

ACTIVITY	POST-KAIZEN FUNCTION			MODIFICATIONS
	SKILLED	SEMI-SKILLED	UNSKILLED	
SCAFFOLDING	-18%	-	-	REDUCTION OF 2 SCAFFOLDERS
INTERNAL FORM	-11%	-	-	REDUCTION OF 3 ASSEMBLERS
CONCRETING	-50%	-	50%	REPLACE ONE SKILLED WORKER WITH ONE

Table 2: Impact by stage on the production teams (the authors)

DISCUSSION

The implementation of the kaizen event related in the study took place over 5 days with the involvement of a multidisciplinary team responsible for executing the selected process, which corroborates what Farris et al. al. (2008), about the process of implementing kaizen events requiring a concentrated effort in a short space of time.

However, it is essential to highlight that the result the kaizen event is the result of a structured process initiated previously before the execution of the event itself, and involves the selection of the topic studied, the analysis of the context in which the problem is inserted and finally the data collection and evaluation (Imai, 1996). In this sense, the preparation stage was developed over two weeks prior to the event, where the theme of stabilization of the concrete wall process was defined based on the lead time data collected and the high relevance of the process for the work.

In a complementary way, another fundamental point for the success of the event is that the essence of continuous improvement proposed by kaizen is based on the involvement of everyone on the team (Imai, 1994). Sharma and Moody, (2003); Farris et al., (2008) point out that the implementation of kaizen events is marked by the identification of waste and problem solving based on the involvement of teams and low-cost creative solutions. From this, as shown in Figure 3, the demands raised by the production teams were structured by evaluating not only their impact within the production process, but the level of effort spent on implementing the actions.

Following the steps proposed by Imai (1996) throughout the event, several countermeasures or improvement actions were proposed, proposed through the seven ways tool, implemented by the production teams and validated or rejected by the kaizen team. As shown in tables 1 and 2, the first data point to good results in terms of time, cost and workload indicators (18% reduction for scaffolgind, 11% reduction for internal form, and 50% reduction for concreting) . However, it is necessary to continuously monitor the actions and validate the improvements developed in order to define new process standards, avoiding the recurrence of the listed problems and establishing together with the work teams behaviors that provide a change of culture in the organization (Imai, 1996; Graelm and Peinado, 2007).

In addition, in the context of Lean implementation in which the company is inserted, the problem solving culture and the concepts of continuous improvement stimulated from the implementation of kaizen events prove to be strong allies in the consolidation of the implementation of the lean construction philosophy (Rybkowski and Kahler, 2014).

Finally, the literature suggests several paths and routes for the realization of kaizen events, however it is important that these implementations take into account the scenario of the organizations in which they will be inserted. In this way, understanding the context and developing an event structure suitable for each situation can be decisive for the consolidation of the concepts of continuous improvement. As Rybkowski and Kahler (2014) concluded that collective kaizen events can bring the improvement outcomes and place for standardization, the current kaizen event shown the Company a new way to improve production process trough lean methodologies.

CONCLUSIONS

The current implementation was effective as it managed to promote a culture of improvement based on the engagement of all team members involved in carrying out the stages of the process studied. The participation of the production teams provided a detailed understanding of the activities and generated future opportunities for further improvements. Therefore, it is important to highlight the importance of the support of managers and coordinators, in addition to the commitment of the workers involved in the event.

The preliminary results indicate that the proposed improvement actions are contributing to stabilizing the process for producing concrete walls, to the extent that process flow improvements, reductions in activity cycle times and the rearrangement of teams are reflected in matching the lead time taken to what the company desired.

The next steps of the study are to develop a standardized working procedure for the concrete wall process comprising the steps covered in this study. Furthermore, considering that a research action where the researchers are involved in the implementation of the full Lean Construction project, and since the kaizen methodology is part of the implementation path of this project developed by the company, the structuring of a methodology for carrying out standard kaizen events, focusing on the stabilization of construction processes, is addressed and will be conduced as pilot implementation. Activities performed at the event can serve as a reference for implementing a new kaizen focused on stabilizing other production processes carried out by the company, such as: ceramics, painting, and roofing.

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USING PULL PLANNING AS A METHOD FOR THE CERTIFICATE OF OCCUPANCY PROCESS

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ABSTRACT

In Brazil, the procedure for obtaining a Certificate of Occupancy is bureaucratic, time-consuming and dependent on decisions that should have been taken in the early execution phases or even during design approval phases. Considering that fit for occupancy legalization is an important milestone in the life cycle of a real estate construction project, this research describes how the Pull Planning approach has been used to ensure that construction planning could reach the whole construction life cycle: since the design phase until customer hand over.

The Pull Planning workshops were part of a larger project considering Lean Construction implementation in a large construction company in Brazil. Nine Pull Planning Workshops were applied when mapping the life cycle of a real estate construction company. This research will describe how the Lean Philosophy was applied and what benefits the Pull Planning workshops brought to the whole project planning perspective in terms of communication, collaboration and decision-making process clearer. A survey was conducted with the workshop participants to understand which benefits were perceived and which improvements could be implemented in the method.

The results are that the Company succeeded in standardizing a new Planning tool that clarifies the whole life cycle of projects. The main benefits that the workshop participants highlighted are: Collaboration and multidisciplinary involvement in the Workshops, Clarity of information, View of the whole project and View of sequence.

KEYWORDS

Lean construction, Pull Planning, Certificate of Occupancy, Collaboration.

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INTRODUCTION

Pull Planning is an important component of the Last Planner System (LPS). It helps define how work will be handed over from one project actor (owners, designers, contractors, suppliers, construction company) to the next (Tsao et al., 2014). It is important to state that that the Last Planner System was initially focused on production control. In other words, it set out to improve the link between "should" and "can", "can" and "will", and "will" and "did". (Ballard and Vaagen, 2017). In 1999, the specification of "should" was introduced into the practice of Last Planner considering the implementation of pull planning and phase-scheduling (Ballard 1999). The next phase for the Last Planner System is the planning of Master Schedules and the strategy for conducting the whole project, which takes into account risks and opportunities that have arisen since its early phases (Ballard and Vaagen, 2017). Pull planning also brings a new perspective about workflow, considering that the collaborative approach may focus on what can be done and not what should be done, given the current situation of the project.

Tvedt (2020) describes how pull planning is used to increase productivity in the design phase. The main goal is to establish a reliable flow in the iterative work performed by designers by bringing them together to engage collaboratively with each other to work out the best possible plan for the design phase and thereby to reduce waste. (Tvedt, 2020). These pull planning workshops should lead to a commitment to the production plan (Freeman and Seppänen, 2014). Tsao et al. (2014) describe pull planning as a process that encourages the actors in the project to collaborate from an early stage on design solutions.

Tsao et al., (2014) list some recommendations regarding how best to implement Pull Planning. Some of those were applied in the current implementation, namely:

- Distribute an agenda one week or more in advance to Pull Planning meeting attendees considering all the participants that could collaborate;
- Identify the start and end milestones as well as initial ideas for breaking up the project into modules or phases that support the planning;
- Have project drawings, master plans or details, readily available for referral during the meeting either in paper or electronic format.
- Tsao et al., (2014) suggest that a single pull plan could cover approximately three months of work. The current research aims to cover the whole project life cycle, which can last for up to 20 months. But we followed the recommendation that the workshop take place at least one month if not two months in advance of when work begins;
- Explain to attendees that the meeting will proceed in three phases: (1) the "backward step" which focuses on the main milestone, (2) the "forward step" will check the workflow logic and add any other activities that are required to support the end milestone, and (3) the "tightening step" will strive to manage work in smaller batches and balance work flow to enable the overall duration to be shorter.
- Clarify the agenda for the meeting. Attendees will become less resistant to working backwards because they have been assured that they will be allowed to work forwards during the next part of the meeting.

Understanding the main features identified by Tsao et al., (2014) in how involve an collaborate with construction crew; and considering the characteristics of the Certificate of Occupancy in Brazil can achieve very complex phases, Pull Planning Workshop could be considered as a Method for better project planning.

Even though the criteria and deadlines for obtaining a Certificate Occupancy (CO) can vary from city to city. In general, the process for doing so is long and bureaucratic, considering different city councils and long flows of analysis and approval in the different public sectors, i.e. water and energy supply, environmental approval, firefighting inspections. The major phases for obtaining the CO are better described on Table 1. These tend to lead to deadlines having to be extended. Moreover, some decisions, if anticipated, can provide greater agility in undertaking activities on the site and in adhering to legalization processes, such as evaluating the possibility of obtaining a certificate that declares fitness for partial occupancy (or by phases of the works). Such an option depends even more on well-executed prior planning to obtain approval from the fire brigade service and city hall for projects and the environmental processes, which are duly organized for this purpose.

In view of the above, the company which is the focus of this study identified that the efficiency obtained in reducing the deadlines for executing works, obtained as a result of a broad project to implement Lean Construction, was not being reflected in the deadline for final delivery to the client. This occurs precisely because the Certificate of Occupancy process does not keep in step with the improvements that the teams on the construction site have started to benefit from the Lean Construction implementation.

Thus, what became a complementary objective of the project mentioned above was to seek to bring together the multiple processes and teams that work and participate in the CO process, in a collaborative way, so as to map the schedule in the initial stages of the project. Doing so ensure greater predictability of the process and of action on deviations in the initial stages of execution of the works, with sufficient time to correct deviations, which in this case tend to take longer to resolve.

It also important do highlight that there is a knowledge gap considering Certificate of Occupancy process and also, how lean tools and methods could be applied to improve this process. Thus, the objective of this research is to understand the benefits of using Lean Construction Tools to define, in a collaborative and efficient manner, the schedule for the entire life cycle of residential projects. Secondary objectives are defined as: (i) identify the characteristics of Pull Planning applicable to operational and indirect processes of the works; (ii) to identify work packages and milestones for the entire cycle of the site works; (iii) to identify how to connect the Certificate Occupancy Process to the production process; and (iv) to identify which benefits were perceived when using Pull Planning as a method for Certificate of Occupancy process. Hence, a tool was developed, based on pull planning, that had the goal to plan and monitor this critical stage for the works and the Company`s strategy as the Certificate Occupancy is a key factor for the final client delivery and also for the construction funding process and has a big impact in the company cash flow.

The current research will be presented as follow: (a) literature Review and in practical cases of the possible planning tools defined by Lean; (b) methodology used and definition of a pilot roadmap for the implementation of Pull Planning to map the Certificate of Occupancy; (c) assessment of the perception of the use of Pull Planning as a tool for sizing the Certificate of Occupancy schedule; and (d) standardization and criteria for the use of the methodology.

METHODOLOGY

The investigation was based on a consultancy project in a construction company in Brazil, named Company A. Considering that the authors of this research are consultants and Company`s A Improvement Group members the methodological approach adopted in this investigation was the Action research (AR) strategy. AR focuses on solving real problems (O'Brien, 1998) and contributing to the development of the organization, the emphasis being on simultaneous action and undertaking research in a collaborative manner (Coghlan, Brannick, 2001). Based on "learning by doing" as a primary aspect of the research process, AR turns the clients involved into researchers in order that they learn better and that they more willingly apply what they have learned (O'Brien, 1998).

The company focused on this research, presented as Company A, has been in existence for more than 40 years as a construction and real state company. It is present in more than 160 towns and cities and is the leader in the civil construction market in the residential real estate segment in Brazil and South America. The company has been constantly investing in improving the quality of its products, using the best market practices, while always prioritizing customers' needs. Its focus is operational efficiency, and, corroborating this with market data, which demonstrate the stagnation of the evolution of civil construction productivity in relation to other sectors of the economy. In response to this, it saw an opportunity, supported by the lean philosophy, to foster a change in efficiency within the company.

Considering we have an AR as a methodologic approach, in which testing and improving are characteristics, three pilot cases were conducted in different projects of Company A to reach the first model. After a first reference model of the Pull Planning Workshops, the researchers applied the CO Pull Planning Workshop in more nine projects of Company A in the cities of Ribeirão Preto, Campinas, Goiânia, Porto Alegre, Fortaleza and Belo Horizonte. To address objective of the current research, a questionnaire was conducted with the pull planning workshops participants. The questionnaire was structure on Google forms platform, with 11 questions considering a scale from 1(very low benefit) to 5 (very good benefit).

SCRIPT AND APPLICATION OF PULL PLANNING

The initial strategy for applying the methodology developed was to carry out pilot Pull Planning workshops. In order to facilitate holding these workshops, strategic and key people were summoned to solve problems related to the themes for obtaining the CO. These included: the project engineer, the engineering coordinator, responsible for the legalization process, the installations responsible (electrical and hydraulic networks), and the responsible for planning and for the regional implementation of the lean philosophy. The initial step was to analyze and group by common discipline "work package" all milestones considered as prerequisites for the company to obtain the CO. In summary, a work package is understood to be the set of activities that lead to the conclusion of a common milestone that is a prerequisite for the CO process. After carrying out three events of pilot workshops, the project team arrived at a configuration of work packages as shown in Table 1.

Based on Tsao et al., (2014) the following steps were applied in the three pilot workshops: Definition of Milestones and Project handover: As the beginning of the process, it is necessary, with the engineering and planning team, to define, by analyzing the enterprise's budget, the deadline of the project and, therefore, the date scheduled for handing over the residential project to the final clients.

Definition of work packages: This definition was carried out, while mapping the main services related to the CO and, in general, the packages mentioned above in Table 1 will be the main packages in the mapping, regardless of the town/city in which the works are located. In parallel with these pre-defined packages, the engineering sector must analyze whether there are specific activities for each city/town, state or region in order to include new packages. At this stage, it is understood that, with the evolution of the regional maturity in the execution of the methodology, more packages will be refined and standardized, reaching the point where there is a “catalog” of packages that will be combined according to the needs of the works.

Definition of the milestone dates for each package: Within the long-term planning of the works, the milestone dates are those that will directly influence the flow of the CO and, therefore, must be scored at the beginning of the pull planning process. Earthwork, foundation, structure completion and finishing completion dates are examples of milestones that directly affect the deadline for the works and these must be mapped.

Table 1. Work Packages for the proposed study

Work Packages	Description
Energy	Package with activities mapped for the process by which the concessionaire turns on the energy supply
Water and sewage	Package with activities mapped for the process of turning on the water supply and connecting to the sewage system
Drainage network	Package with activities mapped for the process of connecting to the drainage system
Report on the Inspection by the Fire Brigade Service (AVCB, in Portuguese)	Package with activities mapped for the process of inspection and acceptance of the guidelines for anti-fire installations made by the Fire Brigade Service.
Environment Certificate	Package with activities mapped for the process of inspection and acceptance of the environmental guidelines.
Town Hall Certificate	Package with activities mapped for the process of inspection and acceptance by the Municipal Secretary of Public Works.

Pull Planning: With the aforementioned points raised, with the definitions of the project's delivery date and main milestone activities, the pull planning process is started. This is when all the long-term planning of the construction will be analyzed, including all the work activities to be carried out as well as everything to do with regularizing the documentation so that it is possible to have the CO within the deadline set for the works.

Constraints Analysis: After finalizing the planning with all the mapping of packages, all the constraints, risks and potential new strategies that may contribute to the outcome of the enterprise must be reviewed by the engineering team. That is, all possible impacts that will affect the established planning must be mapped.

Action Plan: Having constraints, risks and potential new strategies identified and analyzed, an action plan can be carried out by the team, defining deadlines and responsibilities for dealing with all the impacts raised.

Figure 01 illustrates one of those workshops held with different engineering teams to use the methodology described above. We highlight the collaboration involved during the Pull Planning workshop.

Figure 1. Pull planning meeting for the CO of works in Ribeirão Preto.

ASSESSING THE USE OF PULL PLANNING FOR CO

This section is dedicated to the presentation of the results obtained by collecting feedback regarding the perception of the benefits and opportunities for improvement related to the use of the Pull Planning methodology for the detailing of the CO schedule. The questionnaire was developed using Google Forms and its main objective was to verify the participants' perception according to the following possible attributes:

- Collaboration and multidisciplinary involvement in the Workshop: the involvement of different areas contributes to a more complete analysis of the process of the enterprise as a whole, from project approvals to final handover to the clients;
- Clarity of Information: Analogously, as mentioned in the previous item, the participants come to understand the operationalization of the processes of all those involved, thus making the mapping of planning and restrictions clearer for everyone;
- Holistic view - ability to identify milestones: Looking at the "back to front" assembly of the planning, what becomes clearer for the participants is the possibility of identifying the necessary milestones throughout the duration of the project;

- Sequence view - ability to visualize the dependence between the stages: As the planning takes place throughout the entire enterprise, and involves the site activities and auxiliary sectors (projects, documentation, supplies, etc.), the vision of interdependence of work packages is evident at the time of assembly, allowing for discussion among participants about interference between activities;

- Vision of rhythm - possibility of identifying "rhythmable" stages: With a view of the "whole" it is possible to see, within the documentary and works processes, those that can be rhythmic, thus maintaining a scheduled delivery plan;
- Possibility of anticipation of deadline: With the analysis of all interferences, and the multidisciplinary participation, the possibilities of gain begin to appear and, thus, the ability to anticipate activities is evident for the entire team;
- Possibility of managing constraints: The management of restrictions is very visible and palpable, since the survey is carried out in a multidisciplinary way with the different sectors alerting to the “locks” existing in each of the processes;
- Possibility of altering indirect and executive processes: Due to the analysis being carried out in a collaborative way, participants have the possibility to see the processes that interfere both directly in the CO (such as project approvals, processes and execution activities of the works), and indirectly (such as contracting a supplier to perform a certain service);
- Help chain - ability to involve leadership in the management of constraints: with the format of the execution of the practice, the employees involved are those who are relevant within the processes and, therefore, when carrying out the analysis with all the leaders involved, the ability to evaluate planning and constraints is made simpler as is and sharing responsibilities;
- Duration of the Workshop - time dedicated to the CO Line: the duration is linked to the time for assembling and discussing the planning processes and restrictions; and;
- Prior knowledge of the teams: this topic is directly linked to what information each employee has in the process of obtaining CO for the enterprise. Therefore, it is necessary that, in order to carry out the practice, everyone has at hand the essential information to fulfill the requirements of the packages.

RESULTS AND DISCUSSION

In the research carried out, each of the aforementioned attributes could be classified by the respondents at the following levels: “Very good”, “Good”, “Indifferent”, “Bad” and “Very bad”. In the total of the nine Pull Planning Workshops, 52 people participated in the events, but only 27 participated in the applied research. When analyzing the results, by questions addressed in the research, the representation in percentage of the answers, is evidenced in Figure 02.

Multidisciplinary collaboration and involvement (89%), Clarity of Information (93%), Ability to Identify Milestones (93%), Sequence Vision and ability to visualize dependence between steps (93%), were topics that highlighted the relevance of the results and made it possible to relevant gains such as:

- With the multidisciplinary involvement, the possibility of optimizing projects was identified so that the approval in the competent Organs could be done more quickly and in stages;
- With the optimization mentioned above and the visualization of the sequencing of the work, the possibility of obtaining a partial CO was seen, which, therefore, would generate an early delivery to the clients;
- With the clearer identification of milestones and information shared, the interdependence between work activities and project approvals became more evident and, as a result, strategies for prior assessment at the time of approval were raised;
- Regarding the sequencing vision, the need to comply with both administrative and operational milestones was evident to the teams, as well as the impact of one milestone on the others and generated a learning effect for future projects.

On the other hand, the results that the respondents received with lower indices are linked to attributes of the methodology's operation, which, throughout the process of the rollout of the tool were adjusted:

- Workshop duration (81%) and Help Chain (82%) were items that, over the course of the pilots, were adjusted. The initial duration, for example, was 2 days and, with the development of the practice, it became 1 day, with a more intense and collaborative multidisciplinary work. The help chain, on the other hand, was adjusted with the vision of the need for punctual collaborators who would need to be present during the practice;
- Possibility of Managing Restrictions (78%) was an item for which, initially in the operation, it was not very clear how the feedback of this process would happen. However, during the rollout, a practice of managing restrictions online was developed in order to facilitate management follow-up.

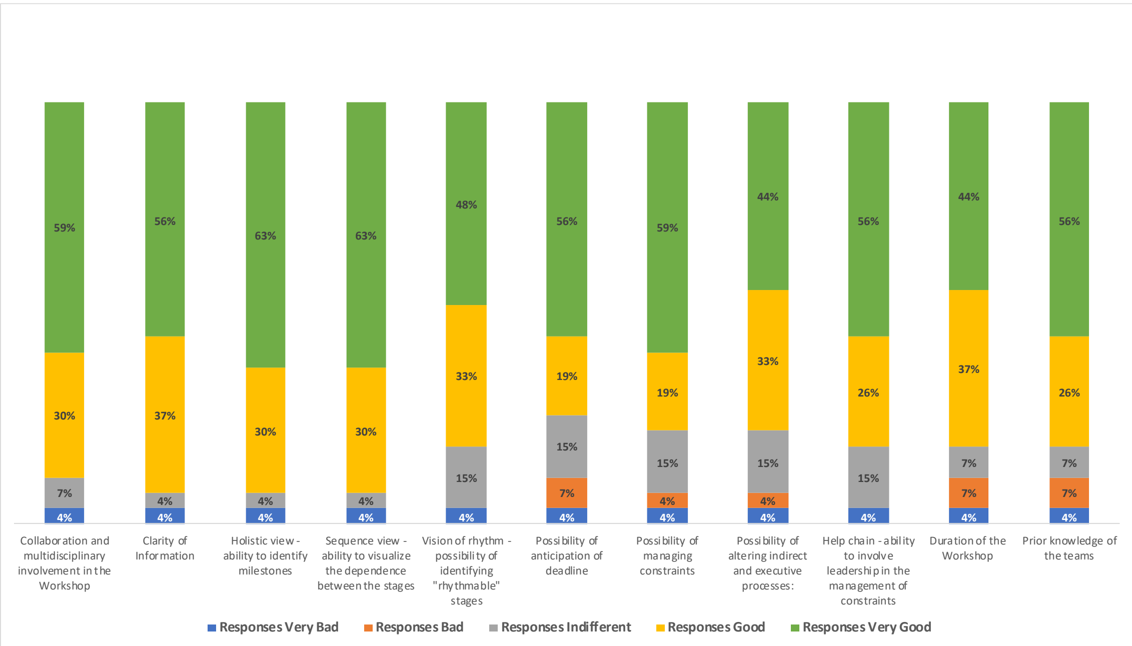

Figure 2. Analysis of the results of the questions applied

Another interesting analysis found that the audience that was most involved in the research carried out was the construction engineer. About 40% of respondents have this function and the average participation of this audience in workshops is 1.45, compared to a general average of 1.7 participations. Of the 27 responses collected, 66% reported that the person responsible for the lean implementation in the region was the one who conducted the workshop. This is normal, since these people were trained in the methodology for applying pilot projects. The audience with the highest participation in the workshops, an average of 4.2, was related to the team that started the implementation of the methodology. Considering the answers of the engineers, the following points are highlighted:

- Rhythm view - possibility of identifying "rhythmable" steps, with 100% of the answers being "very good"; and
- Collaboration - multidisciplinary involvement in the Workshop, also with 100% “very good” responses.

The item with the least relevance for this audience was: clarity of information, with 4 responses “very good” and 3 “good”. Analyzing the responses of those responsible for implementing lean in the region, what stands out is that they had a less “optimistic” perception than that of the engineers. For this audience, the most relevant factor was the clarity of information, with none of the others being considered important to highlight.

STANDARDIZATION AND ROADMAP OF IMPLEMENTATION

At the end of the nine pilots, the Pull Planning model for CO was standardized in an Implementation Manual and a schedule and Roadmap were defined for expansion to the other construction sites of Company A. In this document, the prerequisites for implementing the tool were defined. These include: (a) the work must be in the initial stages, prior to mobilization, in mobilization or in a phase prior to the start of the structure; (b) the construction site and the engineering team must have previously implemented the set of Lean Construction tools, rituals and training defined by the company; (c) the construction must have a team that is familiar with the CO process in their region; (d) the master plan for must be completed and the legal projects approved.

Finally, the Roadmap for the next year includes all the new projects to be launched by Company A, which totals approximately 100 construction sites that must go through the approach described in this study.

CONCLUSIONS

Considering our main objective to understand the benefits of using Lean Construction Tools to define, in a collaborative and efficient manner, the schedule for the entire life cycle of residential projects, with the results obtained, it is possible to highlight the relevance of using the pull planning methodology to obtain a CO for vertical residential works. It was clear that using the methodology led to a pull planning view with obtaining the milestone dates that were “key points” in the analysis of restrictions and interferences between the processes. Such evaluations took place by means of discussion between the different sectors, evaluating the interdependencies between the execution of the constructions sites, project approvals and inspections and the process of final handover to the clients.

In the same way, the practice made it clear to those involved that the deadlines for the execution of the services are directly linked to the need for approval of stages in the concessionaires and city halls for the release of the CO. With this, the need to anticipate documental processes was seen, so that approvals could occur respecting the deadlines in a more planned way and making the "link" with the partial deliveries of internal packages of the works, such as the end of a block and the end of activities related to AVCB (the Fire Brigade Report).

The involvement of the entire management body of the enterprise and support areas, made it clear to everyone that the multidisciplinary collaboration at the time of pull planning was of paramount importance for everyone to see the interdependence that exists between the activities of each one. Therefore, this made it perceptible that group work (with the prior information of each package in hand) has become essential for putting the planning together.

Therefore, the promotion of practices such as the pull planning methodology for mapping the CO process of an enterprise, proved to be essential for meeting the deadlines for the construction site and for public bodies, thereby showing that, with its use, it becomes clearer for the entire management of the construction what steps have to be followed for a good fulfillment of the planning of works.

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CONTINUOUS IMPROVEMENT OF TAKT PRODUCTION WITH DATA-DRIVEN KNOWLEDGE MANAGEMENT APPROACH

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ABSTRACT

This study investigates how data-based continuous improvement could be applied in construction projects utilizing takt production. The purpose is to define a process model that will guide how such a continuous improvement system can be created in an organization utilizing takt production methods, and how the system can then be improved.

This research follows design science approach to highlight the practicality of the solution. Research consists of diagnosis, process model creation, validation of the process model, discussion, and conclusion. Diagnosis is performed with a literature review and empirical research, including interviews and observations of current practices in a case company. Validation is performed by collecting external feedback and by organizing internal interviews.

The findings indicate that the created process model provides a system that can be used to improve the takt production process with data, and that the process can be supported by also handling tacit knowledge. A defined learning system will help in tackling the current barriers facing the construction industry related to inefficient data processing and unclear knowledge management. As the system utilizes the terminology and theory of takt production, it is proposed that the system can be expanded to other projects and construction functions with further research.

KEYWORDS

Lean construction, takt planning, continuous improvement, knowledge management.

INTRODUCTION

The ideology and actions of continuous improvement have already been seen beneficial in several other fields, such as shipbuilding (Liker and Lamb, 2001); it could be similarly assumed that continuous improvement could be implemented in the construction industry as both the construction and shipbuilding industries are mostly project-based, local, and highly volatile (Segerstedt and Olofsson, 2010). However, improving the operations and

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productivity of the construction field in general has faced an issue: companies are very independent on their development actions (Henderson et al., 2013.) Additionally, a case-by-case approach to plan and control projects often ignores the lessons learned in earlier projects, which limits the continuous improvement of construction projects (Lehtovaara et al., 2020). This, combined with the habit of mostly tackling issues when they arise, restricts the development of knowledge management in construction compared to other industries (Ruikar et al., 2007).

Continuous improvement can be supported by having structured information and an efficient production system. However, while data is widely collected in construction projects, the inadequate quality of this data restrict its usage in continuous improvement (Bilal et al., 2016). Henderson et al. (2013) state that creating a system that effectively collects and implements lessons learned in past projects helps organizations gain increasing benefits from learning. Structured information and production systems in construction could potentially be achieved with takt production (Dlouhy et al., 2016; Binninger et al., 2016).

Takt production is a well-functioning method that improves the production phase of construction projects in terms of productivity and project lead time (Frandson et al., 2013; Dlouhy et al., 2016; Lehtovaara et al., 2019). Takt production provides definitions and guidelines to describe unique construction projects in a systematic manner (Dlouhy et al., 2016; Binninger et al., 2016), which facilitates the collection and addressment of data and information systematically throughout projects. The application of the learning system described by Henderson et al. (2013) could potentially enable benefits from takt production to reliably increase over time in an organization.

Based on the aforementioned research gap, the goal of this paper is to create a data-based process model for the continuous improvement of takt production. the process model is approached with a design science approach to combine practical knowledge into theory.

RESEARCH DESIGN

This study follows a design science approach and aims to find a theory-based solution to solve a practical issue (Holmström et al., 2009). According to Holmström et al. (2009), the design science approach is formed by four steps: 1) diagnosis to define the issue, 2) development of a solution, 3) testing and validating the solutions, and 4) generalization of the defined solution and justification of the used theory. To emphasize the practicality of the created solution, this study implements an action research approach to support the design science steps. In action research, practice and theory are combined throughout the study to steer the solution with continuous reflection regarding the decisions made during the research process (Azhar et al., 2010). A practical view is brought to this study by creating a process model in the context of an infrastructure segment of a large Finnish case company. The research steps of this study are presented in Figure 1.

Diagnosis is performed through a literature review and empirical research. The literature review focuses on takt production, which is supported with lean construction and knowledge management. The empirical research focuses on observing operations and interviewing personnel of the case company. Company interviews are semi-structured and include people from parking center projects and specialists working in the infrastructure segment and corporation. The findings of the interviews are placed in tables to categorize the responses, which are then induced into general conclusions to present the main results of the interviews. The interviews are then accompanied by investigation of data handling system, which is used to collect and address the information of projects. The findings and conclusions of these steps are developed into a process model that is placed into the company's project business, especially the construction of on earth parking centers. Creation of the process model is performed by listing the development propositions found during the empirical research and solving them by adapting the methods presented in the literature review. The parking center is a suitable case example due to the company's experience in takt production on that specific product. Utilizing the experience of implementing takt production in this specific product type serves the needs of the company, while simultaneously providing an opportunity to learn about the continuous improvement of takt production in general, to later excel in a wider scope.

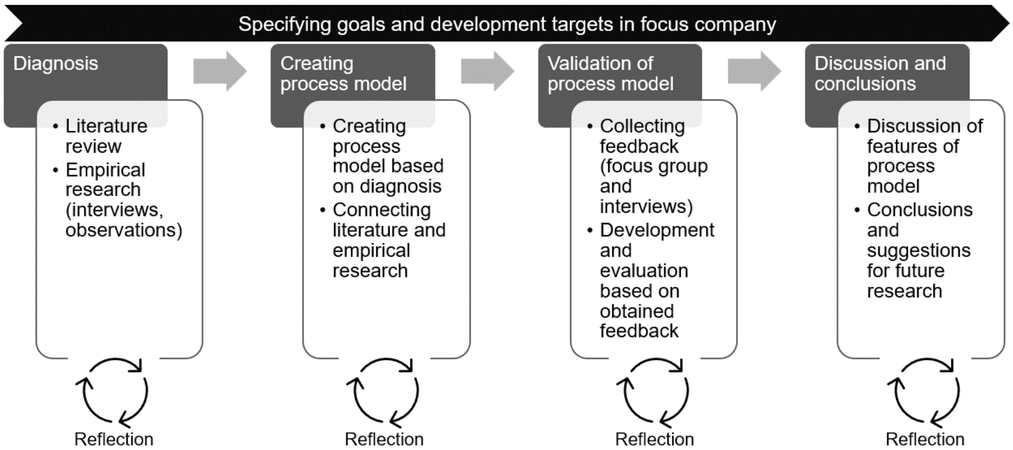

Figure 1: Structure of the research steps.

The testing and further development of the process model is performed by interviewing personnel of the case company (internal validation) and with an external focus group meeting with representatives from 20 architecture, engineering, and construction companies seeking feedback regarding the solution and its suitability. The feedback is obtained as responses to questionnaires, and those responses are then categorized to identify the required modifications to the process model to ensure successful implementation. Finally, the process model is evaluated by considering its potential in a variety of construction product types, and other functions of construction operations, to confirm its practical value. In discussion, scientific contribution is evaluated by examining how presented theories are applied in the proposed process model. The conclusions and suggestions for future research are presented last to ensure practicality and to expand the scope of the model. The suggestions account for the limitation that there is no test case project in this research to validate the success of practical implementation of the created process model.

DIAGNOSIS

FROM LEAN CONSTRUCTION TO TAKT PRODUCTION

Takt production is based on lean thinking, where the main target is to optimize the value creation of production while reducing waste (Koskela, 2000; Liker, 2003; Binninger et al., 2016; Linnik et al., 2013). Optimization is performed by pursuing perfection in production planning and operations (Womack et al., 2007). Improvement of production focuses on the flow of the entire production chain, which can be pursued with an even work pace that is defined by customer requirements to meet the deadlines (Liker, 2003).

Plans will always face deflections during production execution (Koskela, 2000), leading to the need of an effective production control system. One method used to control production in construction is the Last Planner System™, which highlights the need for a detailed short-term production plan that helps detect deflections before they lead to delays (Ballard, 2000). Having a detailed production plan with requirements for performing upcoming work will cure the issue of solving deflections reactively (Ballard, 2000).

Implementing a lean ideology has also led to the consideration of the implementation of continuous improvement and standardization in construction processes. A standardized production process functions as a starting point for continuous improvement (Liker, 2003) and reduces variations in the process (Koskela, 2000). By encouraging innovation, the production process can also be increasingly improved, which can lead to a more optimized standard process via trial and error (Liker, 2003).

To adapt lean methods and ideologies, various studies have developed a takt planning and production system to describe the construction process and products in a creative manner (Linnik et al., 2013; Binninger et al., 2016; Dlouhy et al., 2016). Takt production presents the construction process in a new manner, one that includes work packages, work sequences, and takt areas (Haghsheno et al., 2016; Dlouhy et al., 2016). Work packages and sequences depict the production process in a manner that allows for the transfer of deeper knowledge between projects, as more information can be easily tied to certain tasks while adapting to customer requirements (Dlouhy et al., 2016).

Takt production enables an even workflow with the help of work packages that are planned for closely aligned lengths (Linnik et al., 2013). By emphasizing process flow instead of solely maximizing labor efficiency, takt production allows for the development of overall flow, particularly when production flow is supported with the well-planned use of buffers, especially favoring capacity buffers instead of large time and space buffers (Lehtovaara et al., 2021).

KNOWLEDGE MANAGEMENT IN TAKT PRODUCTION

Knowledge management highlights the systematic management of knowledge and data leading to knowledge-based improvement. According to Lehtovaara et al. (2019), the learning process of a project-based organization can be described with three concrete steps: 1) acquisition of the information and data created in projects, 2) filtering and analyzing the collected information and data, and 3) storing and implementing the collected information and data. Implementing these three steps in construction can lead to increased learning and development in individual projects. However, the collected data from construction projects has been problematic due to a lack of cohesion and quality (Bilal et al., 2016). Therefore, there is a need to define a process that guides how construction project data should be collected to create knowledge.

Blackler (1995) proposes that there are five types of knowledge (embrained, embodied, encultured, embedded, and encoded) with different features that affect how they should be addressed to gain benefits. Following this categorization there is a need for a method to structure information in construction so that knowledge is not lost during the learning process. In this study, information is structured by applying the methods and terms of takt production.

As it is central in takt production to standardize the production process (Dlouhy et al., 2016), it is also possible to utilize the standardized process to achieve continuous improvement by adding new information to it with lean principles (Binninger et al., 2016; Liker, 2003). Earlier, the problem with the standardized construction process has been the fact that unique features of projects and the information collected therein could not be directly utilized in another project. One possible solution to tackle this problem is the use of takt production's work packages, which tie explicit knowledge (Nonaka and Takeuchi, 1995) to standard units, which can be applied to various projects.

If explicit knowledge can be processed with methods of takt production, there is still a need to find a solution regarding the management of tacit knowledge (Nonaka and Takeuchi, 1995) alongside takt production, as tacit knowledge is found to be remarkably important in construction (Carrillo and Chinowsky, 2006).

INVESTIGATION OF THE CURRENT STATE OF TAKT PRODUCTION AND LEARNING IN A CASE COMPANY

The target of diagnosing the current state of the case company was to identify how the process model can adapt to fit into the specific needs of the company. At the start of this study, the infrastructure segment of the company had run a couple parking center projects with takt production methods. The execution relied on expertise of a takt specialist, who was responsible for creating and supporting the new production system. The following three observations were found to be successful during the diagnosis of the current takt production implementation:

1. Takt production helped the task crews work in more locations simultaneously.
2. The production plan can be prepared further ahead, which helped detect deflections before they occurred.
3. Takt production provided project personnel with an experience of more comprehensive control over daily work on site.

As a result, the implementation of takt production led to less remarkable schedule overruns in tasks during project execution. This has come as a by-product when project personnel understand that takt production seeks to improve the control of production leading to less deflections, not that the takt schedule itself would lead to actual benefits.

However, during interviews and observations, a few drawbacks were noticed that currently limit the continuous improvement of takt production. First, the experiences are not wide enough to form a standardized production process that fits into every takt project in a certain segment. It was noticed that there is a need to simplify construction methods in a manner that narrows down the variation between the execution of projects to speed up the standardization process. When there are more projects performed with similar construction methods and features, the organization can develop work package and sequence structures, as proposed by Dlouhy et al. (2016), which will then begin to develop a standardized construction process. After formation of a standardized construction process, improving information content tied to its work packages functions as a basis for continuous improvement of takt production.

To develop work packages and sequences, it is important that the organization collects data and information accordingly, so that gained knowledge can be easily connected to the actual construction actions performed on site. According to interviews and Bilal et al. (2016), construction data is currently collected through various methods and systems that lead to fragmentation and difficulty in the automatization of data processing. Consequently, when handling data and information requires vast amounts of manual work, there are no resources to perform analysis and learning during or after a project when needed. When the data collection system is tied to structures of takt production, however, it becomes evident what information is beneficial to the actual construction operation, which was mentioned as being important in the interviews. This can help judge, in the future, what information organization needs to simultaneously serve the needs of sites and management, leading to a learning system with less non-necessary work.

When tacit knowledge is concerned, a learning system cannot entirely rely on the collection of data and written information directly from projects. There is a need for a defined system pertaining to how feedback is collected and how innovation is ensured. Currently, innovation has mostly relied on active individuals to mention their ideas, which implies that there are numerous ideas left unshared. Commonly, in construction, various post-project reviews are used to collect lessons learned from recent projects and their personnel; however, the benefits from these reviews are limited by the lack of time that key personnel have and the lack of a systematic process to address content (Carrillo, 2011).

Construction projects always consider their many stakeholders, so it is relevant to also include subcontractors in their consideration when the main contractor is willing to implement a new production system. A challenge faced with takt production, according to interviews, is that it is a new system for many subcontractors, which often leads to resistance, arguing that the system is unsuitable for their tasks. However, according to interviews, this thought has proved to be faulty, and conversely, implementing takt into new tasks has led to subcontractors finding new benefits and appreciating the accurate production plans that perform well in practice. Still, contracts that may be conflicted with the takt production system are currently limiting subcontractors' benefits regarding the implementation of takt production (Lehtovaara et al., 2019). For example, instalments may be aligned so that working against takt production plans may benefit subcontractors' cash flow, which can lead to issues with total flow at the work site.

To conclude, there are four topics to be covered in the process model to ensure the continuous improvement of takt production:

1. There is yet no standardized production process to be improved systematically.
2. Data collection must be aligned with takt production structure, which simultaneously provides the required information to site operations and management.
3. The learning process is not clearly delineated and improvement relies on active individuals.
4. Subcontractors' contracts need to be aligned so that their interests meet the requirements of takt production.

PROCESS MODEL FOR THE CONTINUOUS IMPROVEMENT OF TAKT PRODUCTION

The continuous improvement of takt production is guided by a cyclic process model (Figure 2), which describes and supports institutionalized knowledge sharing and functions as a clear guide on how to address data and tacit knowledge as a part of the learning process. The process model proposes that, in the production phase, data is collected with the structure of work packages and work content is defined by takt production. While new data and information is collected, the project simultaneously benefits from using old knowledge tied to the work packages. This system provides a standardized production process over time that can be systematically developed.

One centric element of the process model is the division of information and data types based on whether it can be tied directly to work packages or not. This system directs explicit knowledge directly into work packages. Simultaneously, tacit knowledge from projects is collected with a defined system that creates fewer barriers for personnel to participate; the current procedures are evaluated based on monitoring project records. This allows for updates to procedures based on knowledge justified by data, and the categorization simplifies the presentation, addressment, and implementation of new information in an organization (Rezgui, 2001; Dalkir, 2017). To handle information based on this categorization, two already known solutions in the company (updating the database and expert sharing knowledge) are used as main methods to implement new information, and to connect the new system to familiar methods of the organization (Barber et al., 2006; Moffett et al., 2004).

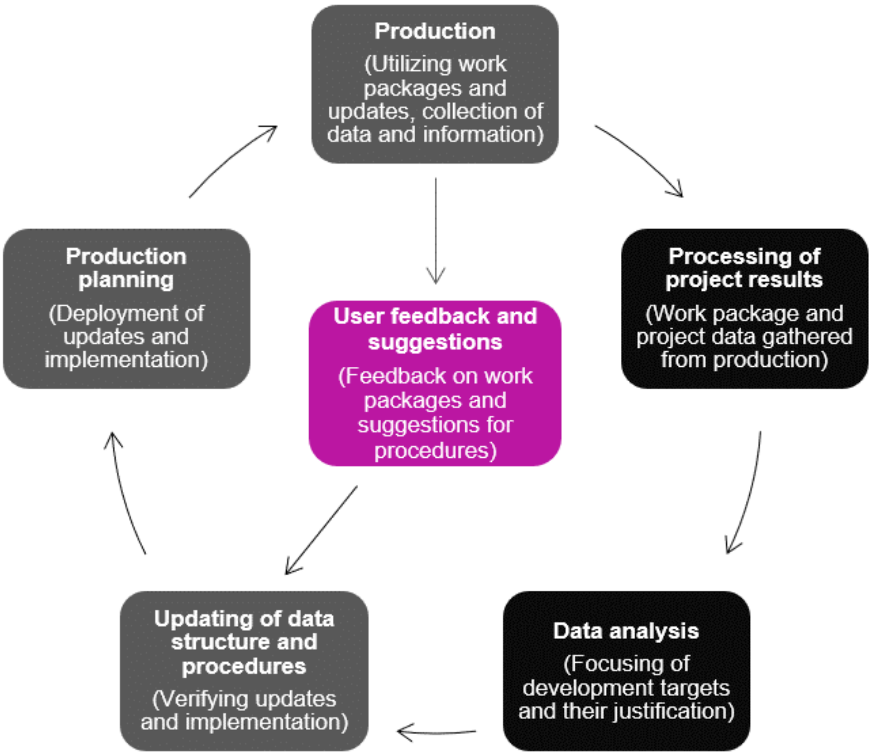

Figure 2: Process model of the continuous improvement of takt production presented in a project environment.

According to the categorization of information and data, there are four different types of processes that address information from the collection to the implementation stage. All four processes follow the three-step-structure proposed by Lehtovaara et al. (2019): collecting information and data, addressing information, and implementation. The content of these steps is formed to all processes (Table 1) by applying the idea of knowledge types (Nonaka and Takeuchi, 1995), filtering and analyzing of knowledge (Crossan et al., 1999), and categories of preserved information (Blackler, 1995). The processes shown in Table 1 are tied to the process model so that user feedback and suggestions follow the pink (middle) path, and analysis processes follow the black (circle) path, while both are connected to project execution with the grey steps (Figure 2).

After each project obtained feedback, and data are addressed to recognize potential development targets in the current production process. Additionally, data can be run through automated analysis to obtain analytics to support decision making if data is collected according to the defined methods with adequate quality. Having structured information and analyzed data will enable extensive root-cause analysis to support continuous improvement. The continuous improvement process can be roughly described in a hypothetic takt project as follows:

1. Production planning: creation of takt plan by using work packages of the organization, so that the familiar work packages can be applied in takt planning of a project constructing a relatively known product, simplifying the task of defining takt areas and work sequences.
2. Production: utilization of the familiar work packages that are continuously adjusted to fit the current project, while simultaneously enabling improvement.
3. Processing of results and data analysis: learning from information gained in a project to ensure that the creation of the next takt plan will account for the lessons learned in the previous project of constructing a relatively similar product.

Table 1: Content of the steps required to handle information to guide the categorized information processes.

Information process	Step 1: Collecting data and information (Worksite personnel)	Step 2: Addressing information (Development organization)	Step 3: Implementation (Development organization and worksite personnel)
Update based on user feedback	Current work package as initial data. Update based on simple modification to content of package.	Update is edited to content of work package with basic information of project and reason for update.	Person in charge for work package checks and agrees to modification, after which users can see the update. (Updated work package.)
Update based on analysis of data	Work package specific data collected as initial data, supported with memos and results of project.	Inspection of data to search improvement targets, with methods such as statistics and data mining.	Update of instructions of work package or editing current work packages. Information sharing ensured with info or trainings. (Updated work package.)
Update based on user's suggestion	Solution found in community of practice or suggested development by individual.	Adapting solution to current procedure and forming instructions to implementation.	Information sharing with info or handouts, supported with specialist implementation if necessary. (New or updated procedure of working.)
Update based on analysis of operations	Work package specific data collected as initial data, supported with memos and results of project. Root cause analysis is encouraged.	Assembled analysis of data and memos to justify and explain the need of update, formed into procedure. Root cause analysis is encouraged.	Project-specific implementation to ensure adequate support and correct interpretation of new or updated procedure. Supported with info and training. (New or updated procedure of working.)

VALIDATION AND DEVELOPMENT OF THE MODEL

REVIEW OF FEEDBACK

The external focus group responded to a questionnaire about the proposed requirements of the data and the development targets of the continuous improvement of takt production in construction. The responses to the requirements of data express that there is clearly a need to focus on the quality of data collection, since the requirements are currently not widely fulfilled. The respondents mostly agreed to present development targets that were used to form the process model, which can be interpreted so that the focus of the process model is suitable for practical needs.

The most upstanding development targets of external feedback were the lack of a standardized takt production process, and the fact that data collection and processing are not sufficiently guided to support development. During the discussion about the presented process model, the focus group brought up observations of two main challenges that may occur in the implementation: 1) the encouragement of personnel to provide feedback to the current production process, as updates following the feedback will often be visible only after the project is finished, and, 2) disunity of the used takt production terms could lead to misunderstandings if the terms vary inside the organization.

The feedback from the case company focused on the implementation of, and how to ensure success of the implementation of the process model. The most critical remark was that the steps of the process model must be comprehensible to ensure that site personnel understand the content as intended and that the actual development benefits are grasped on site. In total, it was found that the ongoing development system required clarification for site personnel, and that the process model seeks to solve this issue.

REMARKS FOR FUTURE IMPLEMENTATION

There was no evident need to make modifications to the structure or content of the process model according to the obtained feedback. However, there were a few remarks introduced that must be considered during the implementation and possible expansion to other functions, apart from the construction production process:

1. Agreeing on mutual takt production terminology across the organization (or industry). (External feedback.)
2. Defining persons in charge for work packages to monitor updates and viability. (Internal feedback.)
3. Creating a quick and easy-to-use feedback system and guiding the use of it. (External and internal feedback.)
4. Encouraging feedback and development ideas to create an ethos of improvement. (External and internal feedback.)
5. Defining a schedule for handling feedback and updating the content of the data structure (work packages). (Internal feedback.)
6. Harmonization of other operations (such as procurement) with the takt production structure and work packages. (External and internal feedback.)
7. Verifying that each update or modification to the production process is implemented with adequate support from specialists responsible for change. (Internal feedback.)

DISCUSSION

The goal of connecting takt production and knowledge management was approached in this study by creating a process model that utilizes the terminology and methods of takt production, while seeking to develop this system with guidelines from knowledge management. Although the process model was created to serve the needs of building a parking center, the same principles can be applied to improve production processes of other construction product types. Considering on earth construction, roughly the same guidelines for the creation of a takt plan can be applied and improved through information handling to enhance the knowledge tied to work packages and sequences. When subterranean construction is considered, there is a need to define the takt production guidelines for such projects that do not follow the same restrictions of constructability. However, when a takt production system is created for subterranean projects, there is no apparent reason why the same guidelines of continuous improvement would not apply.

Apart from the production process planning and control, other construction companies' functions are currently working with the project information as it is provided to them. Currently, cooperation between site and other functions is very project specific, which causes work to be defined by the form of information provided. If the project information is provided in a standard form defined by a takt plan, there is a possibility that other functions, such as procurement, could develop their operations around the work package information as well. Work packages would have definitions of work that include more information other than quantities and rough verbal estimates of work difficulty, which will lead to more precise estimations of work hours and costs in general.

While the idea of takt production enabling continuous improvement was presented by Dlouhy et al. (2016), there was no sufficient presentation of how data and information should be managed in practice (Bilal et al., 2016) to accomplish continuous improvement. This study presented one verified method on how this improvement could be achieved in practice. However, it requires long-term verification to ensure that the presented model is eligible due to the limited scope and material in this study alone.

Using the work packages and sequences of takt production to address explicit knowledge is presented in this study with depth and can be applied in practice to form a standardized production process for continuous improvement (Liker, 2003). However, the model's current presentation of tacit knowledge categorization is not as accurate as what is presented in the literature (Blackler, 1995; Nonaka and Takeuchi, 1995). The methods surrounding the handling of tacit knowledge proposed in the process model should be sufficient to start the improvement process in practice, but should be further studied to form a complete knowledge management strategy.

CONCLUSIONS

The management of information and data can be organized by following the methods presented in knowledge management literature. Management of information alongside the terminology and methods of takt production can be used to create a standard production process so that collected information and data can be directly tied to production processes. Describing a continuous improvement system with a process model helps spread knowledge to the personnel of an organization, which reduces the threshold to participate in learning. By utilizing familiar, well-functioning implementation methods, the model can be tied to current practices and, thus, the model is easier to adapt to various projects. Updates of work packages make improvement visible to project personnel, thereby encouraging people to submit more feedback for continuous improvement.

Further research is suggested to verify the presented process model's long-term success in practice. After proving functionality to the process model, it is possible to further research the model's adaptive ability in other construction functions. When construction operations are run with well-defined takt production processes, it is easier to improve cooperation with stakeholders, such as subcontractors, by utilizing information provided by the work packages.

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MANAGING PRODUCT INFORMATION FOR LEAN CONSTRUCTION: USE CASES AND A PROPOSED PROCESS

Antti Peltokorpi[1], and Olli Seppänen[2]

ABSTRACT

This paper explores how the flow and management of product information could enable lean construction operations. Recent research has underlined the need and possibilities to integrate product information with building information modelling (BIM). This research extends that knowledge by investigating more thoroughly (1) what are the use cases in construction project life cycle for product information management (PIM)?, and (2) what kind of solutions and processes would support these use cases in lean and BIM-based building projects? Design science approach was used to identify six common use cases for PIM and to identify sub-solutions. In total 36 representatives from Finnish Architectural, Engineering and Construction (AEC) companies are used as informants and participants in workshops. Finally, a process for the PIM was proposed based on the use cases and the identified sub-solutions. The process helps construction practitioners in their efforts towards smoother product information flow which finally contributes on better operations flow in building projects.

KEYWORDS

Lean construction, Supply Chain management (SCM), Logistics, Product information management, BIM

INTRODUCTION

Product information is important for improving flow and maximising value, and thus better access to timely and accurate product information is aligned with the goals of lean construction (Koskela, 2000). In particular, owners, users and administrators are interested in the traceability of the building's products and materials: what products are installed in the building and how they should be maintained and used (Cavka et al., 2017; Watson et al., 2019; Wang et al., 2020)? This information adds value to them because climate targets require that the carbon footprint of buildings can be calculated accurately based on environmental data of the manufactured products (e.g., European Commission, 2021). The safety and health of buildings is also becoming increasingly important to owners. More will be required of the materials and their properties, and manufacturers have to demonstrate the safety of the products. In addition to increased value, improved product information can play an important role in ensuring that requirements are passed

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down from the designers to the installer, optimizing logistics, and ensuring quality by having access to up-to-date instructions specific to a certain product.

Recent research has underlined the need to integrate product information with BIM (Berard and Karlshoej, 2012). The focus is shifting from BIM technology to BIM-based processes. Nummelin et al. (2011) developed a BIM-based PIM procedure for the supply chains in industrialized construction. They envision how BIM-based supply chain management between a contractor and product suppliers should enable identification of construction products and building parts digitally in various systems, utilization of BIM in cost estimation and tendering process, access to accurate product and quantity information to site staff, improving logistics of incoming materials on site, and recording as-built-data into BIM or database. Later, Palos et al. (2014) presented a BIM compatible product library process, which indicates how native models could function as a platform from which the required information is extracted by different applications in procurement, construction, and maintenance. Latest research by Lucky et al. (2019) focused on defining a common data structure for product information and using existing technologies to share this data. Data templates are suggested to foster mutual understanding and efficiency in information management at product type level (Meda et al., 2020).

The previous studies on PIM mostly focus on defining data content, BIM process or key areas for product data use. This research extends this knowledge by investigating (1) what are the use cases in construction project life cycle for product information?, and (2) what kind of sub-solutions and processes would support these use cases in building projects which utilize BIM, and aim at smooth flow of product information? Lean is used as a lense in the analysis by aiming at smooth flow (Phelps, 2012) of enriching and linked product information throughout the project lifecycle. Previous research suggests that poor design information flow causes significant waste for the following activities in the construction process (Al Hattab and Hamzeh, 2017). Similarly, this research hypothesizes that poor product information flow leads to remarkable manual work and waste in construction operations, and practitioners would benefit from knowledge on thorough processes on lean management of such product information in their building projects.

This paper explores how the flow of product information could be improved during a construction project. Product refers to a permanent building component, structure, or an accessory, or device integral to the construction site. The building consists of different products, which are mostly Make-To-Stock (MTS) standard products or Engineered-To-Order (ETO) products which could be variants modified from commercial products or unique building components designed separately for the project.

Information related to products can be divided into a) standard information, b) instance information, and c) process information (see, e.g., Lucky et al., 2019). Standard information includes e.g., product dimensions (e.g., length, weight), performance characteristics, and material and packaging information. The usability of standard information depends on how it is enriched with instance and process information. Instance information refers to the unique identifier of a particular product individual and the specific information of that individual. Process information, in turn, refers to e.g., timestamps, location codes, and employee information, related to the processing, distribution, location, and use of a product individual.

RESEARCH METHOD

The design science approach was chosen because it enables designing an artifact as a solution (process) to the identified problem (use cases) that practitioners face in a proper context (Pfeffers et al., 2007). In practice, the management of product information was investigated with the help of two sub-objectives. The first objective was to identify use cases for product information flow, enrichment and utilization in the design and construction process. The second objective was to develop a process with embedded solutions for the effective management of product information, including standard, process and instance information, to meet the above needs. Here, the solution refers to partial components of the overall PIM process, including existing commercial solutions as well as new type of solutions enabled by existing technologies.

The research methods included expert interviews, documentary analysis of existing solutions, and four focus group discussions (FGDs) conducted in Finland (Figure 1). As an output of the first FGD, six construction products representing various construction product classes (Finnish Talo 2000 system) were selected for further investigation: recessed ceiling light (P1), window (P2), ready-mixed concrete (P3), partition wall (P4), interior paint (P5), and wood product (P6). The selected products are different in size, technology, material and design process. The window and partition wall are designed for the project while others are standard MTS or MTO (Make-to-Order) products.

For each product, expert interviews were conducted to explore: 1) what are product information use cases in this product? 2) what information is needed? 3) who needs the information and for which purpose? 4) what are the current challenges in PIM with that product? and 5) what opportunities exist for proper PIM with that product? In total 36 professionals, representing designers, general and trade contractors, logistics operators, project management services, IT companies and hardware stores, were interviewed. Based on the interviews, six common use cases were identified and then elaborated and validated in the second FGD. Next, separated interviews and document analysis (mostly web documents) were utilized to determine which existing partial solutions, including commercial solutions and technologies, would support PIM in each use case. The relevance of the solutions was validated in the third FGD. Finally, a proposed process of the PIM was formulated as a synthesis of the use cases and the identified solutions. The process was validated in the fourth FGD. Participants in the four FGDs overlapped. The expert interviews included mostly informants who were not present in the FGDs.

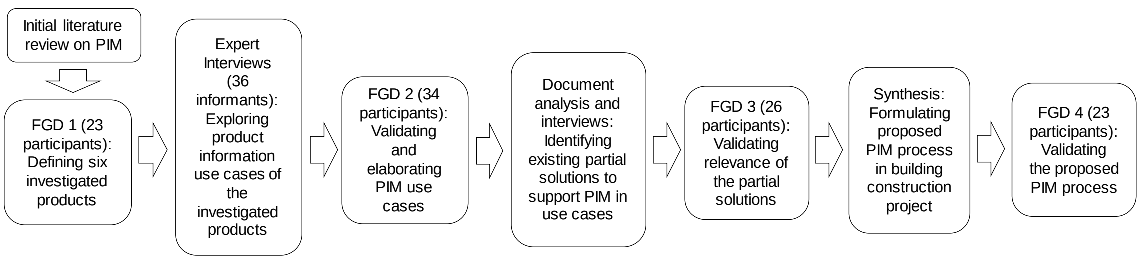

Figure 1 The research process

RESULTS

USE CASES FOR PRODUCT INFORMATION

Table 1 provides a summary of the challenges and opportunities of managing product information for the six products under review. In some products, different actors should have access to product information because the product is affecting several tasks around the product. For example, recessed ceiling lamp affects the work of ceiling designer and installer. On the other hand, windows have many different requirements, but their information can be handled separately from other products and actors as interface between the window and building is rather clear.

Table 1 Product-specific notes on product information

Product	Challenges	Opportunities
P1. Recessed ceiling lamp	Related to many other products and factors, e.g., suspended ceiling designer and installer	Basic and easy access to basic product information
P2. Window	Several different requirements and features	The interface of the product to the rest of the building is quite clear
P3. Ready-mixed concrete	The final location of the deliveries in the structure is usually unclear	A lot of information is already being collected on manufacturing, transportation, and casting
P4. Partition wall	Consists of several sub-products; associated with Mechanical, Electrical and Plumbing (MEP) systems and furniture; deliveries often in bulk	Management of product data of by-products by means of a cost structure; room-specific material deliveries (kits)
P5. Interior paint	The product consists of a standard product and additives; storage and condition information critical	National painting classifications indicating possible combinations of standard products and additives
P6. Wood product	The origin often difficult to determine; products from different suppliers mixed in the supply chain	Product similarity, the number of suppliers quite limited

Ready-mix concrete differs significantly from the recessed ceiling lamp and window, as it is purchased in loads and typically from a standard supplier. If quality problems occur, the exact disposal location of concrete is practically impossible to determine which makes it impossible to connect defects with a particular load after casting.

The partition wall is an ETO product, consisting of standardized MTS products, such as frames, gypsum boards and insulation, and the product information of all of these. Interior paint, on the other hand, differs from others as it consists typically of two components, namely a primer and a tint, and the information of these both components.

Wood products cover several variants from simple lumber to the Cross-laminated timber (CLT) element. In all wooden products, there is a need to know the origin of the wooden material. This will be emphasized in the future as traceability needs and environmental certification become more widespread.

GENERAL USE CASES OF PRODUCT INFORMATION

Based on the interviews and workshops, six key recurring use cases of product information were identified. Table 2 describes these use cases and for which products they are relevant (P1-P6), the users involved, and the possible solutions for PIM.

Table 2 Generic use cases

Use case (associated products)	Users	Possible solutions
Structured design information for efficient procurement and cost estimation (P1-P6)	Procurement, cost estimating	Standardized data templates for design and commercial products → tools for product search and comparison
Efficient process to suggest and approve substitute products (P1, P5, P6)	Contractors, procurement, designer, client	Process software; use of data templates for product types, product libraries

Calculating environmental footprint for building (P1-P6)	Designers, procurement, site managers	Environmental Product Declarations (EPD), Carbon budgeting tools
Coordinating material deliveries on site (what, whose, where) (P1-P6)	Logistic, site management, sub-contractors	Identification codes (products, batches, individuals); readers/trackers (bar code readers, RFID, crane cameras); links to product libraries and project data
Access on site to space- and element-specific products and instructions (P1-P6)	Workers, site managers	Codes and tracking technologies; products linked to BIM models; user interface from building model to product information
Access to as-built product information in maintenance and use phase (P1-P6)	Maintenance, user, owner	Products (individuals) linked to as-built BIM models; user interface from maintenance model to product information (Virtual Reality etc.)

Structured design information for efficient procurement and cost estimation

Based on the data provided by the designer, the procurement of the contractor selects a suitable product for the project. The problem is often that the design information is not structured and comprehensive, and finding suitable commercial products requires a lot of manual work. A structured and product type-specific standardized presentation of design information would enable the streamlining of procurement and cost estimating processes.

Efficient process to suggest and approve substitute products

When the contract includes both products and their installation, the contractor often has an opportunity to propose a replacement product alongside the product specified by the designer. The analysis showed that the process is not transparent and efficient, and the designer's consultation and supervisor approval can take a long time. Also missing information about the product will be completed along the way. The acceptance process would be enhanced by a process tool built on structures and standardized product information. In the tool, the contractor can propose a replacement product and the approval processing proceeds automatically from one project party to another, for example in the form of task requests and links to e-mail.

Calculating environmental footprint for building

The third use case is related to the calculation of the environmental footprint based on product information. Three phases to determine a carbon footprint were identified: 1) planned, 2) procured, and 3) constructed carbon footprint. The planned footprint must be calculated based on design information; quantities of building components and materials derived from them. In that phase, the calculation should be based on product benchmarks or average data. The procured commercial product must obtain the carbon footprint provided by its manufacturer for the implementation of the carbon budgeting defined in the design. The environmental statements of the products and their data on the carbon footprint is the key information to be used. The constructed footprint verifies that the delivered and installed products lead to the carbon footprint defined in the procurement. The built carbon footprint also considers site functions, such as the use of energy and transportation, which are not directly related to any commercial product.

Coordinating material deliveries on site

After the final selection of the product, the identified key use case was related to the management of product delivery from the supplier to the construction site and to the installation within the site. In that activity, it is central to identify a physical product or batch and to associate that with a specific contractor and installation location. Access to packaging information and storage instructions may be essential for logistics. A key part of the solution in coordinating material deliveries is machine-readable product and batch identification codes. Technological solutions, e.g., using QR and RFID codes in physical product and batches, could play a key role in identifying products on the job site.

Access on site to space- and element-specific products and instructions

From the various site actors' point of views, access to the information of the products to be installed on the site, especially their installation instructions, technical dimensions, and other features, are essential. This use case can be divided into two: first, there may be a need to find out the information and features of the product to be installed in a particular space of building before the product is physically on site. This requires a user interface to a space or building object model from which there is an easy access to the selected products and their features. On the other hand, there is often a need at the site to find out more detailed information about the product on the construction site, for example regarding installation instructions.

Access to as-built product information in maintenance and use phase

The sixth use case identified in the study concerned access to as-built product information during the operation and maintenance phase. Although this research was mainly limited to the design and construction phases, it is appropriate to consider the needs for operation and maintenance, as the starting points for the usability of the information are often created already in the project phase. Access to the product information is important both through the building's data model and the machine-readable identifier of the physical installed product.

SOLUTIONS FOR PRODUCT DATA FLOW

This chapter delves into the identified and validated sub-solutions to manage and utilize product information. The use cases were connected to several existing solutions and technologies. Figure 2 shows the partial solutions in a way that solutions shown on the left create the basis for the development and implementation of the solutions on the right.

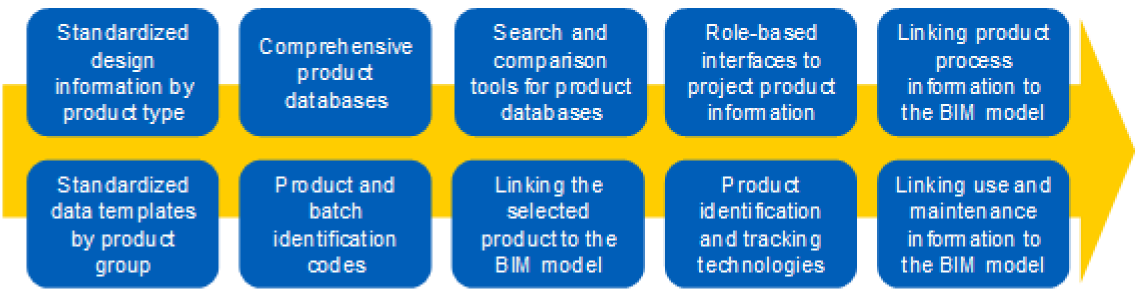

Figure 2 Partial solutions for product information management

Standardized design information and data templates by product group mean that it is defined at the product group level what information should be presented in the design information and what corresponding information should be provided by the manufacturer for its products. This means jointly agreed data templates for the information content (Meda et al., 2020). International classification standards, such as ETIM (international classification standard for technical products), should be favoured. The definition work requires cooperation between designers and manufacturers.

Standardized information is a prerequisite for the comprehensive product databases. Comprehensive information on all products on the market should be found in open databases. If the content of information is not structured, quantified and comprehensive, the benefits of the database will be reduced, especially at the procurement phase.

Comprehensive and structured databases enable the development of search and comparison tools to review products and facilitate selection. Some tools are already available, e.g., in Finland for electrical products. The tools can also be used when contractor proposes a substitute product. Transparent and usable tools also increase pressure on better and more comprehensive product information.

A key feature of product databases is the identification code assigned to each commercial product. The study suggests the use of international identification codes, such as GS1 GTINs, which allows developed systems to operate in international business and flexible addition of new products to supply chains. Use of a particular code system enables investing in applications to manage product information and logistics processes. The unique identifier of the delivery batch SSCC is also useful in construction. With help of SSCC the received materials and products can be read on site, and a stock balance can be maintained. The serialized GTIN could be used to identify which product instance was installed in certain space or element. This way, in problematic situations, it is possible to trace all the way back to the product and the production batch.

International standards also support the development of identification systems for logistics management. Technologies, whether based on RFID, QR barcodes, or image recognition, enable product flow tracking as well as machine-readable access to product information. Through codes it is possible to access all the information of the product.

To truly benefit project management, the FGD suggested that the identification codes must be linked to other information of the project, such as BIM objects, plans and scheduled tasks. Previous research (Berard and Karlshoej, 2012) suggested using product-specific objects developed and maintained by the manufacturers, instead of using generic objects. However, this study indicated that the links from generic BIM objects to product-specific information could be an efficient solution. Linking selected products to the project's 3D-5D model is essential, especially when the builder's standard products guide the design. Additional tools have been developed on top of the modelling programs, with which product information from the databases can be linked to the building and space objects. In one case, the builder developed an own database between the general product database and the design program, including the products approved in their projects.

Role-based user interfaces help access to the BIM-linked product information. Design software is intended for design and designers, and therefore product information should be accessible separately, e.g., from a browser-based tool. The FGD also highlighted the need for role-based data filtering tools. A filter could form compact product information packages for needs of different roles, both for procurement and site personnel.

For utilization of product information, it is also central that process information related to the status of the product (who did what and when?) is linked to the BIM elements. Using integration between the product tracking and the BIM objects, the BIM could be enriched by process information. Through a unique product identifier, all information related to the product supply chain can also be linked to the BIM. After the project, the information model can be further enriched with operation and maintenance data. Linking the process information of project and operation phases to the model generates the information content needed in the digital twin of the building.

PROCESS FOR PRODUCT INFORMATION FLOW

Based on the validated partial solutions, the process which combines the results and visualizes the possibilities of enriching and smooth flow of product information, was defined. Separate versions for MTS and ETO products were described, however, due to space limitations, this paper presents only the validated process for MTS products (Figure 3). The embedded BIM process in the overall process represents the enrichment of the building information from product requirements to selected products and their standard information, and finally including also process and instance information of each individual product assembled into the building.

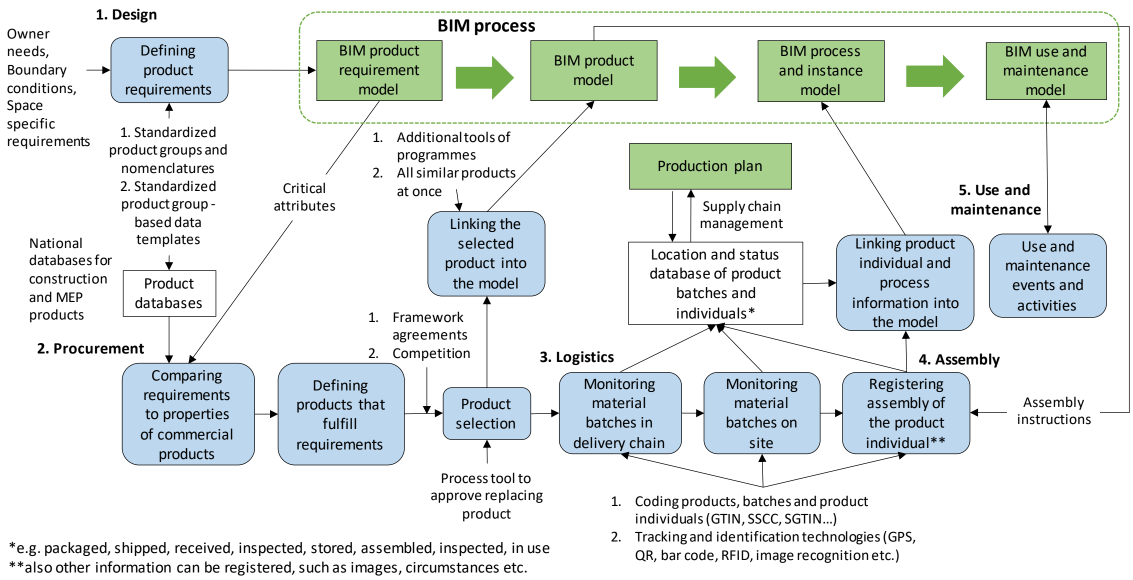

Figure 3 Proposed process for product information management of MTS products

The process begins with the design phase, in which requirements for the products are defined based on customer needs, the project's boundary conditions, and the space-specific requirements. The requirements are defined based on standardized product groupings, nomenclatures, and data templates. The requirements are presented in the same way as the corresponding information in the product databases. A BIM product requirements model presents the building with design information and product requirements related to its sub-products.

Product requirements are then used in procurement. The purchaser uses critical characteristics defined by the designer to determine which products in databases are possible to this project. The final selection among products is made based on framework agreements or a call for tenders. If the original procurement covers both labor and materials, the selected contractor may propose a replacement product using a process tool that utilizes existing product databases.

Once the product is selected, the BIM model is enriched to a BIM product model by linking the commercial product to that design object. Now, the project parties have access through the BIM to products' all standard information. Next, the product information is enriched with process information from logistics and installation. The product, delivery batch and product individual codes will be used to track the progress of the product in the supply chain and on the construction site and to record the installation time on site. The status information and batch can be compared to production plans, and based on this, the supply chain can be controlled by responding to problems and delays or by updating the plans. It is essential that site storages are also tracked by utilizing the codes. Since similar standard products can be installed in different locations, it makes sense to maintain a separate location and status database for delivery items and product instances and link the unique product code to the model object only after installation.

Finally, the process information complements the model into a BIM process and instance model, including also supply chain and installation information. Process information can also include images, storage and installation condition information, pre-installation precision measurements, and tolerances. After the project, the data model is supplemented with operation and maintenance events and measures. At all stages, the parties should have access to the enriched product information.

DISCUSSION

This research extends the existing knowledge on PIM in construction (Nummelin et al., 2011; Berard and Karlshoej, 2012; Palos et al., 2014; Cavka et al., 2017; Lucky et al., 2019) by proposing a comprehensive PIM process for BIM-based building projects. The process presents a justified vision for utilizing product information in projects to achieve better value for the customer and to streamline construction flow in many ways. The individual solutions presented in the process are already used in advanced companies, however, the novelty of this research is in its way to present these solutions and technologies in a comprehensive manner to support smooth flow in construction project.

The study shows that the proposed process leads to many benefits for the project actors. By using a product database and data templates work of designers and procurement is systematized, and routine tasks can be automatized. Product information is better available on site, which improves flow by speeding up installation work and improves quality.

The results also indicate that by connecting product standard information with instance and process information, logistics flows become more efficient. This requires, that the deliveries are planned, and location of product is known in real time: Site production control improves when real time product delivery information can be compared to plans. Overall, enriching process and instance information increases the transparency of the construction process and enables identification of root causes for deviations during the operation and maintenance phases.

The study suggests that linking product information with BIM objects through product identification codes is a cost-efficient way to integrate product information with design models. Previous research suggested integrating producers BIM objects into the design model (Berard and Karlshoej, 2012). Our analysis indicates that linked data would make the integration easier and require less efforts both from manufacturers and project actors.

Despite of the many benefits of the streamlined and BIM-linked PIM process, the process is partly theoretical and faces practical challenges in projects. First, BIM is still not used in all projects. In those projects, some use cases, such as structured design information for procurement and access on site to space- and element-specific products, may not be possible. Without BIM, projects could still benefit from many use cases, including tools to manage product substitutes and to track material deliveries.

Secondly, to fully utilize the PIM process, material delivery plans must be complete, and efficient solutions are needed to link products to the BIM. It can be hard to decide to which object product information should be linked because all sub-components are not modelled. For example, the reinforcement and pumped concrete of wall elements are usually not modelled. In those cases, cost accounting may provide a more detailed breakdown of the final product into which to link the code of the trade product. In addition, adding products to individual objects is time consuming. Therefore, tools are needed to link all similar products at once to all the elements in the model.

The development of the comprehensive databases is also challenging. Currently, databases are often separated for MEP and other products, and they do not cover all the commercial products. Producers do not have sufficient incentives to add product information to open databases. Therefore, aligned efforts and industry-wide statements are needed to increase urgency among producers to openly provide their product information. At the same time, international standards and databased should be favoured so that global producers can publish their information in one shared database.

CONCLUSIONS

In this research, six common use cases of product information were identified during the life cycle of the construction project. In addition, solutions to enrich and import product information in the usable form for the project parties were identified. Finally, the research suggested a process model for PIM in construction projects.

The most important sub-solutions of the process are related to harmonization of product group-specific information in design, and to the product databases built according to these. Based on comprehensive and harmonized information, other solutions can be implemented, such as linking standard product information to BIM, using product and batch identification codes, and linking product process information to the BIM model.

The results and their validation with the construction professionals showed that product information is valuable not only for building owners and users, but already during the project from design to site installation. Designers could benefit from standardized ways to present product requirements. Contractors could streamline sourcing and procurement processes with use of product databases which fit with the requirements presented in the designs. Logistics and site managers can build real-time situation picture of the operations by utilizing machine-readable product information and the links between product information, delivery batches, task schedules, and designs. Overall, the enriching, linked, and real-time product information enables construction project actors to lean their operations by reducing manual work and better decision-making.

The research highlighted that systematic PIM is an essential part in the effort for lean construction. However, this research is limited to concept development and validation in FGDs. More practical research is needed to test the process and integration of the solutions. Future research could focus on the following topics:

- How to streamline procurement by standard design information and product templates?
- How to apply international product and delivery batch codes in supply chains of various construction products, including make-to-stock and project-specific products?
- How to efficiently link product standard, instance, and process information with BIM?

Further research could validate the proposed process from global product provider point of view. In addition, as information contents vary between the products, instead of project approach, it could be useful to take supply chain perspective to PIM. The supply chain perspective could reveal possibilities to learn from product information which is used, enriched and linked in the providers overall client portfolio.

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IS CONSTRUCTION INDUSTRY STILL PERFORMING WORSE THAN OTHER INDUSTRIES?

Jan A. Elfving[1] and Olli Seppänen[2]

ABSTRACT

It is difficult to find a cross-industry comparison where the construction industry is not one of the worst performing industries. Countless studies demonstrates that the industry is lacking other industries in productivity development and safety. But are we actually comparing apples-to-apples, or, moreover, are there areas where construction industry is performing better than most industries? It is easy to show what does not work but it seems to be harder to show what works. This paper presents some early results of performance measures that large number of leading engineering and construction companies have agreed to measure performance on in the Finnish construction industry. We compare reliability, user experience, sustainability, productivity, and customer satisfaction. Based on this baseline progress in the industry will be followed and also compared to other industries. There are already some interesting points to be lifted, like schedule reliability in Finland seems to be higher than in studies in other countries. Another interesting observation is customer satisfaction and Net Promotor score, where construction industry scores higher than most other industries. Based on the performance measures the paper discusses about industry performance in general.

KEYWORDS

benefits realization, continuous improvement, lean construction, waste.

INTRODUCTION

Construction industry often scores poorly in cross-industry benchmarks. Particularly, the productivity growth shows a depressing picture of the industry. Productivity growth has been flat for many decades, and construction industry has been one of the worst performing industries (Pekuri et al. 2011). At the same time, the lean construction movement, which started three decades ago has produced a vast amount of research, tools and methods and increased our knowledge how to drive improvement. Very successful cases have been reported related to lean methods and in several countries, like Finland, these methods are starting to be mainstream. A new generation of construction managers and engineers are entering the industry, and they have been educated to lean straight from the beginning. So, do we see the impact on industry level?

It is likely that our industry level measurement requires improvement, and we need industry-level progress metrics. Except for some measurements such as financial

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measures and safety, it has been challenging to compare performance improvement among companies within the industry. Lean and digital tools and methods have not moved the productivity needle yet. Are they moving some other needle that we did not find yet?

To answer this question, the paper has two goals. First, the main aim is to introduce a set of measurements that the industry and academia have agreed to measure and follow in Finnish construction industry. Second, is to review other available metrics which could be used to measure progress, especially those related to customer satisfaction. Many performance measurement methods tend to be waste and productivity driven and less value driven, such as customer satisfaction and Net Promotor Score (NPS). With these metrics, the construction industry scores better than most other industries, and even performs on the best level in some surveys.

The authors intend to report annually the progress of the industry in Finland and want to understand:

- Is the construction industry improving performance in Finland?
- Is construction industry performing worse than other industries?
- Why is the industry scoring high on customer satisfaction, even if it scores low in many other cross-industry performance measurements?
- What is different from other countries

The paper starts with a literature review on existing work on performance metrics, followed by a chapter of typical industry metrics, then presenting the new metrics Building 2030 metrics developed by key players of the Finnish construction industry. We will end this paper with a discussion attempting to partially answer the questions above.

LITERATURE REVIEW

BENCHMARKING INITIATIVES

Previous research includes information on several benchmarking initiatives in different countries. Many studies focus on benchmarking management practices, for example, by comparing companies to their competitors using surveys on project level (Kim 2014; Cha and Kim 2018; Bonilla and Castillo 2020). These initiatives are important because they can be used to convince other companies to do more. The challenge is that they do not represent a sample of all projects but rather those projects which participants have contributed. Therefore, they do not help to answer the question of this study: can we see improvement on industry-level metrics?

Several initiatives have been developed in different countries to come up with holistic performance measurement systems. Costa et al. (2004) described four different performance measurement systems in Brazil, Chile, the UK and the USA. These systems all shared the same aims as our study and aimed to measure construction sector performance. Typical approach was to have a group of companies who agreed to share project-level information and agreed on KPI's which would be reported. Then companies could compare their results with those of their peers. The challenge of these systems included that data could be time-consuming to collect, might not be available in every project (Costa et al. 2004), and restricted membership means that a large part of the industry is left out from the measurement.

One of the largest construction industry based performance metrics database has been collected by Construction Industry Institute, they have since 1996 collect systematically performance metrics. In 2002 published summary report (CII 2002) the database included already 1037 projects with a total installed value of $54.2 billion. However, some of the data shows that the performance of the industry has actually worsened between 1998-2018. The drawback of this method is that it relies on contributed projects and the companies contributing data are not stable. Less mature companies joining the benchmarking initiative could result in seemingly decreased performance.

INDUSTRY LEVEL METRICS

Industry level macroeconomic labor productivity data show declining productivity. National statistics bureaus are reporting productivity by sector by dividing construction Gross Value Added (GVA) with labor hours. According to Neve et al. (2020), these data are reported slightly differently between countries. Regardless of the actual way of measurement, these industry-level figures have not shown any improvement. Part of the problem is that prefabricated elements are often reported in another industry, so any increase in prefabrication will move both GVA and hours to another more productive industry and just the less productive work remains. (Lehto 2020).

In recent years, net promotor score (NPS) has become popular to benchmark companies mainly within the same industry. It is a widely used market research metric that typically takes the form of a single survey question asking customers' willingness to recommend a product or service to someone else (Reichheld 2003). NPS measurement in construction industry is interesting for several reasons. First, in lean construction literature, there is a good amount of waste related measurement, such Percentage Plan Completed (PPC), inventory, and waiting time but less value [3] related performance measures, like customer satisfaction that could be used on industry and even cross-industry level. Second, NPS is easy to collect and to compare companies within the same industry. Third, construction industry scores high compared to other industries. This is unusual, because often in cross-industry comparison of various performance measurements construction industry scores below the average, e.g., safety (TVK 2021) and productivity (Lehto 2020).

A study by Retently (2021), a consulting company, evaluated 35 industries, and construction scored the fifth highest score, NPS 52. In another survey conducted by Pendo (2019), a consulting company, construction industry scored third highest, NPS 27, among 9 other industries. A survey study performed by EPSI, a Swedish based consulting company, shows that new residential construction sector has scored highest rating the last three years over 6 other industries (EPSI 2022). In their latest survey 2021, new residential construction scored 40, and the next highest sector insurance scored 9. Many companies provide NPS measurements, and the above surveys are just randomly selected NPS surveys. It certainly requires more data collection and understanding why construction industry scores higher than other industries.

NPS has been praised for being simple, providing timely data and easy to act on the findings. Traditional customer surveys are complex to process, take too long time before the frontline employees and managers can act on the findings and expensive (Reichheld 2003).

[3] See Koskela (2000) for conceptualization of value as the ratio of satisfaction of needs and use of resources.

NPS has can been critized for that it cannot be used as a standalone metric for measuring customer loyalty and customer satisfaction needs to be measured with more than one questions (Keiningham et al. 2007, Zaki et al. 2016). As all surveys-based metrics, also NPS is challenging because organizations rely on the respondents' memory of a service process or a transaction, which may not always be a correct representation of the actual occurrence (Kristensen and Eskildsen 2014).

EPSI has developed its own customer satisfaction rating. This rating considers many other aspects than just NPS, and even this rating ranks the new residential building highest of all other measured industry sectors (Figure 1).

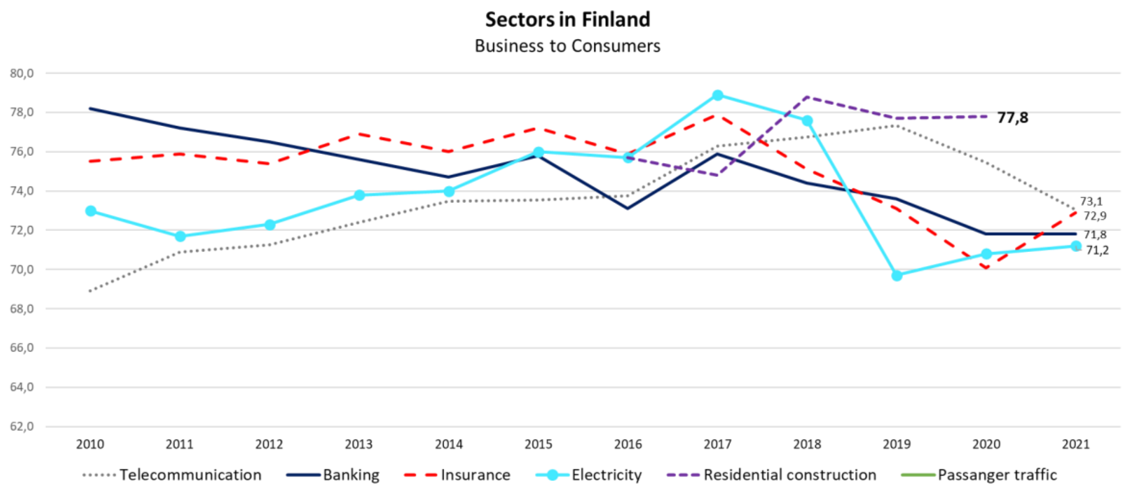

Figure 1. Customer satisfaction in various sectors in Finland (EPSI 2022)

METHOD

To come up with metrics acceptable for Finnish construction industry, a design science approach was used. Design science leads to artifacts which help solve real-life problems in their context and can be applied in daily practice (Voordijk and Adriaanse, 2016). The first step was to review industry metrics typically collected in Finland. Then a group of companies co-created the performance metrics in collaboration with the researchers. The developed metrics were validated by collecting data from construction sites.

Building 2030 is a consortium of 21 companies and Aalto University which has developed a vision for the Finnish construction sector in 2030 and works towards implementing it. Tthe CEO's of participating companies agreed to benchmark industry performance by sharing project data which Aalto University compiles and uses to calculate industry metrics which are not available in other, publicly collected industry data sources. The metrics were defined based on the five themes of the published vision of the companies. Construction companies should be seen as highly reliable partners, buildings should be user-centric, all decisions should be guided by sustainable development, construction sector should generate value for the customer and construction employers should be seen as inspiring (aalto.fi/en/building-2030, accessed 11.2.2022). Some of the themes already had publicly collected information but especially project-level information was lacking.

The metric development started by reviewing the data companies had available on project level and by making proposals to the CEO's of companies. The metrics were

iterated with the CEO's of companies in four quarterly meetings until the companies agreed on the metrics and were ready to provide data for the study.
The metrics were developed so that companies had data available in their internal records on project level and could be used to measure project-level performance and its improvement from year to year. The approach is similar to earlier initiatives in other countries, but the focus on setting measurable targets and aligning the KPI's with the vision of the group is novel. The group represents a large part of construction volume in Finland, including 6 of the 10 largest companies.

RESULTS

INDUSTRY METRICS TYPICALLY COLLECTED IN FINLAND

In Finland, general contractors typically measure performance on project and company level. On project level typical measurements are cost, profit, schedule, changes in scope, quality, safety, environment, and stakeholder satisfaction. On company level, there is a large range of both leading and lagging measurements that take place. However, most of them are for internal use and company specific and are thus never made public. Therefore, it is challenging to compare cross-companies or industries how well the company or industry is performing.

Relatively few measurements are made public. These are mainly financial related performance measurements such as revenue, changes in revenue, profit, changes in profit, and various other financial KPIs. Besides financial performance some companies report safety, e.g., Lost time accident rate, and environmental performance, e.g., climate impact or carbon reduction. Also, NPS has increased its popularity. The simplicity and easiness to collect are probably the reasons why so many companies have chosen to report the NPS score instead of a broader customer survey results with multiple questions. "One question" is easier to communicate, to compare and to report to the stakeholders than a large set of questions. Even in "standard" customer satisfaction surveys every company tend to tweak the standard set of questions with company specific questions, making them incomparable. However, as the literature review indicates, regardless, whether a single question is asked (such as NPS) or a larger set of customer satisfaction questions, construction industry seems to score higher than other industries in Finland.

METRICS DEVELOPED BY THE BUILDING 2030 CONSORTIUM

Table 1 shows the metrics developed by the consortium. Defect related data and accidents are reported on company level but the share of projects with zero defects and zero accidents could be an even more important metric because it was a generic observation by the participants that quality defects and accidents tend to focus on certain projects and when lean implementation spreads, the projects with zero defects and zero accidents should get more common. The share of collaborative contract forms was considered a good indicator of more user-centric design and construction. Sustainability metrics readily available on project level include the recycling rate and which energy and environmental certification is applied by the project. Related to productivity, construction duration measured from top of foundations to commissioning was considered a stable enough metric by project type that it could be used as an estimate of process flow improvements, and share of direct work by workers could be used to measure the improvements in operations flow. Electrical and plumbing tasks were selected for analysis because they are tightly connected to other tasks and there are often disputes about productivity of these trades. All the other metrics can be reported by participating companies except the share of direct work which requires additional studies to evaluate improvement. When systems such as indoor positioning get more common, the share of direct work could be replaced by uninterrupted presence in work locations (Zhao et al. 2019) which could be scalable measured.

Table 1: Metrics agreed by Building 2030 consortium

Theme	Metric	Notes
Reliability	Zero defects at commissioning	Zero defects (0/1) (all punchlist items fixed before commissioning)
	Zero accidents	Zero accidents (0/1)
	Finished on schedule	Original internal schedule + any time extensions
	Finished on budget	Original internal budget + any change order adjustments
User centric	Collaborative contract form	IPD, Alliance, collaborative project management contract etc.
Sustainability	Recycling rate	% of waste recycled (= not burned or taken to disposal area)
	Energy classification A or B	A & B are the best classifications in Finland
	Environmental certification	Leed, BREEAM, Joutsenmerkki, RTS
Productivity	Construction duration	From top of foundations to commissioning (excluding earthworks and foundations). Correlated with project type and construction budget
	Share of direct work	Measured with time-and-motion studies / work sampling of electrical and plumbing tasks (mandatory breaks removed)

The baseline performance of Building 2030 companies was evaluated based on projects completed in 2020. Companies were asked to supply details of a sample of their projects that finished in 2020, separately for residential, commercial and infrastructure projects. 58 projects with a total value of 1,1 billion EUR were supplied by five different construction companies. The average size of projects were 10,2 MEUR for residential projects, 26,2 MEUR for commercial and 0,5M for infrastructure projects. The researchers instructed the companies to take a random sample of completed projects but could not ensure that sampling guidelines were followed. There were so few infrastructure projects supplied that their results are not included in the results below.

The results are shown separately for residential and commercial projects below. Commercial projects turned out to be a too heterogeneous group and will be subdivided to several project types such as offices, retail, hospitals etc. in the next rounds of data collection. The need to do this can be seen when correlating project budget with project durations. Figure 1 shows the scatterplot for residential and Figure 2 for commercial buildings. There is no correlation with commercial buildings and a very strong correlation for residential buildings.

Table 2: The first measurement in 2020

Metric	Residential	Commercial
Zero defects at commissioning	41,7%	25,8%
Zero accidents	70,8%	35,5%
Finished on schedule	83,3%	80,6%
Finished on budget	50%	51,6%
Collaborative contract form	16,7%	51,6%
Recycling rate	70,3%	74,5%
Energy classification A or B	63%	48%
Environmental certification	0%	19%
Construction duration	Average 66,1 weeks (strong correlation to project size, see Figure 1)	Average 66,8 weeks (no correlation to project size)
Share of direct work	21% (electrical and plumbing tasks based on a time-motion study of 2 projects)	20% (electrical and plumbing tasks based on a time-motion study of 2 projects)

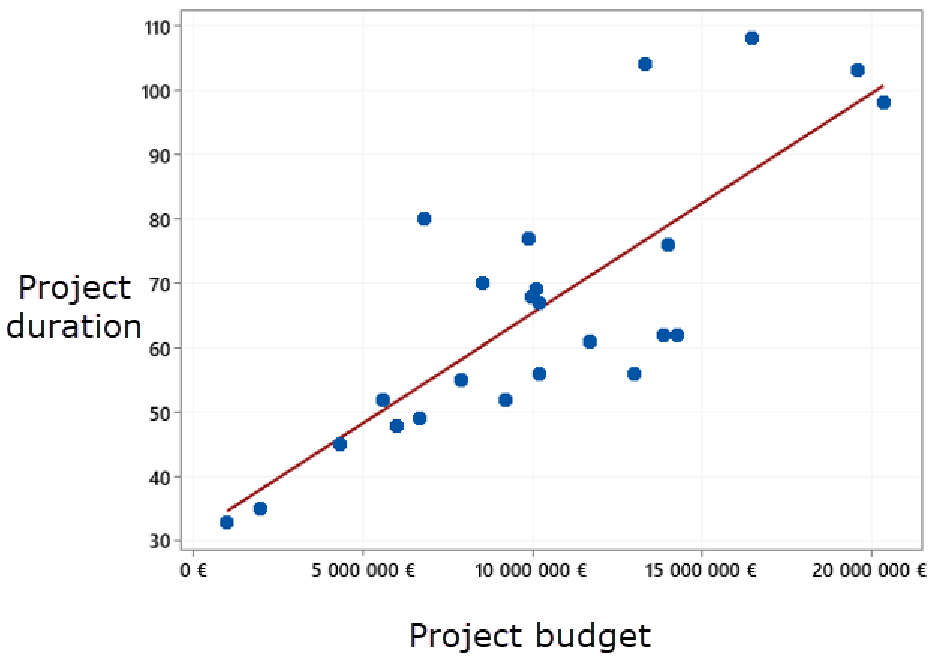

Figure 1: Project duration vs. budget for residential projects

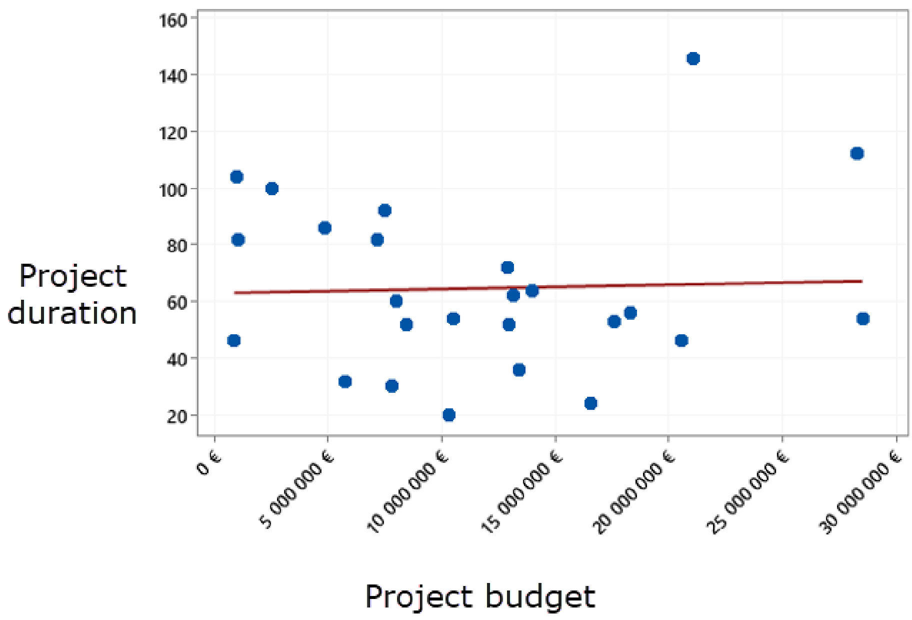

Figure 2: project duration vs. budget for commercial projects

Based on the results of the 2020 projects, the group set targets for the industry for 2030. All reliability measures should improve towards 100%. The share of collaborative contract forms in complex commercial projects should reach 80% by 2030. The target for recycling rate was set at 90%, which is better than car manufacturing today (at 87%). Energy classifications A and B should reach 80% of all projects and at least 50% of projects should be environmentally certified. Project durations should be decreased by eliminating waste in the process. The target for an average residential project was set to be 40 weeks (currently 66 weeks), adjusted by project budget. In other words, the target is to move the regression line of Figure 1 down. The target for commercial projects will be set after more detailed measurements in 2021. The share of direct work of electrical and plumbing tasks should increase to 40% (with mandatory breaks removed from data). The next round of measurement is ongoing and the participating companies have committed to implementing lean and digital methods to keep improving project-level performance consistently.

DISCUSSION

IS CONSTRUCTION INDUSTRY IMPROVING IN FINLAND?

Koskela and Koskenvesa (2003) introduced Last Planner to Finnish construction industry already in 2002, since that several companies have reported (e.g., Elfving 2021) about company specific lean deployment. Lean Construction Institute (LCI) Finland was founded 2008, it has active members widely from owners, engineering firms to contractors. Since 2015, Aalto University have significantly invested in lean construction research and education, spearheading with the Building 2030 program, where members represent about 40% of the Finnish construction market. There is no doubt that the awareness and knowledge of lean in construction has significantly increased just measured by how many people have been trained in internal company trainings, through

LCI Finland and the academia. Another indicator of the maturity of industry can be the shift of contract models, from transactional to relational. The use of alliance or integrated project delivery contract model was over 10% of the total building volume in 2020, being only few pilot projects 10 years ago (LIPS and Lean Construction Congress 2021). However, the question is, has the construction industry improved performance in Finland? Short answer, probably but except for safety, there is lack of data to show results.

In order to take the industry to the next level, we need to have fact-based information to evaluate whether we are progressing as an industry. It would have been interesting to see how the industry performed 20 years ago against Building 2030 performance metrics. Unfortunately, there is no data available. The base line is currently set, now it is important to annually continue with the measurement and follow the development. Even more, to act on the measurement results and help companies to improve. The commitment of the CEO's of participating companies to participate and direct the benchmarking effort and implement actions that move the needle is key.

The authors believe that the construction industry is improving performance, and through collaboration with industry and academia and successful anecdotal case studies, there is enough knowledge to get to the next level. The authors intent to report annually the performance indicators for the Finnish construction industry to see whether the performance improvement is limited to few projects or can we observe effects on industry level.

IS CONSTRUCTION INDUSTRY PERFORMING WORSE THAN OTHER INDUSTRIES?

It has taken a long time to establish comparable performance metrics within the construction industry, and it is even harder to measure the construction industry against other industries. Financial measures are not as simple as they may look like, because the risk profile of the industry and companies needs to be also considered. In productivity and safety, we are clearly below average. On the other hand, as earlier mentioned, some of the productivity improvement may not be seen in the statistics because they are recorded elsewhere. Customer satisfaction, and particularly NPS sticks out. Why is construction industry performing so well in NPS? Are we more customer focused than we tend to believe? Does the nature of our industry enable us to understand customer needs better than in many other industries? Or are the expectations so low for our customers that it is easy to meet and exceed them? These would be interesting future research questions to explore and in the best case other industries could learn from us. It is evident that industry must improve productivity and there is plenty of opportunity. The industry needs to also bring up and talk about customer satisfaction; how it captures the requirements, generates the value and how it measures the value (Koskela 2000). Here we may perform better than others.

WHAT IS DIFFERENT FROM OTHER COUNTRIES

Finland is an interesting test bed for industry level studies, because the market is fairly small, thus it is possible to reach a critical mass. The industry players are relatively keen to collaborate within research and development and are used to work together. Finally, there is already 20-years of experimenting with lean in the industry, which gives a good knowledge base to spring off. The other Nordic countries may have similar characteristics, however, the larger the industry becomes, the more challenging it may be to reach the critical mass and common performance indicators.

One metric that immediately raises questions is the schedule performance measured by the consortium. Over 80% of projects finished on time (adjusted for any time extensions). This is much higher than typically reported in international studies. Finland has a long history of implementing location-based management, focusing on the risk management angle, where time buffers are used to prevent cascading delays (Kenley & Seppänen 2010). Are the time buffers too large? How do the Finnish projects compare to other projects of similar scope? There is a large effort to shorten cycle times and eliminate time buffers in Finland through takt production. Will the high reliability of schedules suffer or stay the same? Or are there tradeoffs that are made in Finland with respect to budget, safety or quality? The proposed metrics attempt to capture and evaluate these trade-offs on industry level.

CONCLUSIONS

Lean methods were introduced two decades ago to the Finnish construction industry, during the years the pace has gradually increased and the last six years it has been hard to find a mid or a large sized project that does not apply some of the lean concepts. However, it has been difficult to evaluate if the industry has improved. The research set out to introduce a set of benchmarking measurements that the industry and academia have agreed to report annually in Finland and to review other industry-level metrics in use. The first measurement results highlighted that the project types generally used in reporting are not granular enough for comparisons to be made. In future, more detailed project types will be used. Even if the reporting was not enough granular, the CEO's of companies were able to use the results to set goals for 2030 and commit to annual measurement and scrutiny of results. Some early insights include the high share of Finnish projects that are completed on time. An interesting finding was also that the customer satisfaction of construction industry is on the same or higher level than other industries. For other metrics more data will be needed to understand if the Finnish construction industry is performing better or worse than others. The data collection of 2022 metrics is in progress, and it looks promising. Yet, it is too early to say if the industry has improved compared to previous year. The real success of the measurement will be tested in the future if the industry and academia together can learn and improve the baseline results. Therefore, it is vital to continue collecting and sharing as comparable as possible data for a longer period. Also, to perform industry-level comparisons to other industries and other countries using similar metrics.

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LOCATION-BASED PLANNING TO PROMOTE SAFE DISTANCING DURING CONSTRUCTION ACTIVITIES

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ABSTRACT

Brazil has been harshly affected by COVID-19. Several decrees applicable at a national and local level have been emitted with general and specific protocols for construction activities aiming at social distancing. Location-Based Planning (LBP) is a valuable technique to size and allocate crews considering space availability; thus, there is an opportunity to test this production planning and control approach to support social distance at construction sites. This work proposes using LBP to verify and measure crews' conflicts at the construction site to keep social distance as part of the COVID-19 measurement. The research was designed into two phases: (1) characterization of the scenario regarding the implementation of social distancing measures based on surveys, and (2) identification of crews' conflicts in location-based planning and implementation of actions against Covid-19 based on a case study. The results indicated that the proposed LBP and the Minimum Distance Indicator (MDI) could help identify and reduce total and unsafe crew conflicts. The main contribution of this work is a practical implementation to verify the possibility and effectiveness of using LBP associated with indicators to promote social distancing at construction sites.

KEYWORDS

Location-based Plan (LBP), Indicator, Safe Distancing, Workers, Covid-19.

INTRODUCTION

Since the pandemic's beginning, Brazil has been severely affected by Covid-19, with many cases and deaths. Intense disease peaks occurred mainly from May to August/2020 and March to April/21. Aiming to contain the spread of virus dissemination, the Supreme Court decided on the autonomy of states and municipalities to determine measures to control the spread of Covid-19 (Supreme Federal Court of Brazil, 2020).

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Therefore, despite recommendations at the national level, including specific guidelines for the construction industry (Official letter SEI No. 1247/2020/ME of April 14, 2020, and by Joint ordinance nº 20, of June 18, 2020) in Salvador city-Brazil, and several decrees applicable to the local context were issued. The regulations determined general and specific protocols for construction activities. There were also recommendations from local sectorial entities, such as Sinduscon-BA (Construction Industry Chamber of the State of Bahia) and SESI Saúde-BA (Industry Social Service Institution- Bahia).

One of the effective ways to reduce the chances of infection and spread of the disease is adherence to physical/social distancing policies and personal protective equipment (WHO, 2020). However, in some construction sites, it was difficult to comply with the social distancing measures because part of the activities requires the proximity of workers for the effective execution of the task (Amoah and Simpeh, 2021). Also, to improve productivity, project managers and supervisors often assign different crews of workers to the same work area (Afkhamiaghda and Elwakil, 2020). Thus, it is essential to plan and control with proper management of the physical space available to execute the work packages.

Location-based planning (LBP) can make the workflow explicit, allow the simulation of alternatives to the sequencing of activities, and simultaneously provide information on when and where each activity should be carried out across production units (Kenley and Seppänen, 2010). Due to the uniqueness of the Covid19 pandemic and its impacts on construction, it is crucial to understand how this planning tool, already used by construction companies, can contribute to physical space and conflict management. This work aims to identify social distance measures applied in the construction sites as part of the COVID-19 measurement and use LBP to assess and measure crew conflicts to support social distance. For that, two indicators were proposed. The first one aimed to keep the size and allocation of crews considering space availability and verifying crew conflicts that could pose a risk to the worker. The second indicator proposed aimed to assess the effectiveness of the actions implemented during the planning.

RESEARCH METHOD

This study was developed in two phases: (1) characterization of the scenario regarding the implementation of social distancing measures based on secondary and primary data collection and (2) identification of crews' conflicts in location-based planning and implementation of actions against Covid-19 in a construction project. Figure 1 presents the research design.

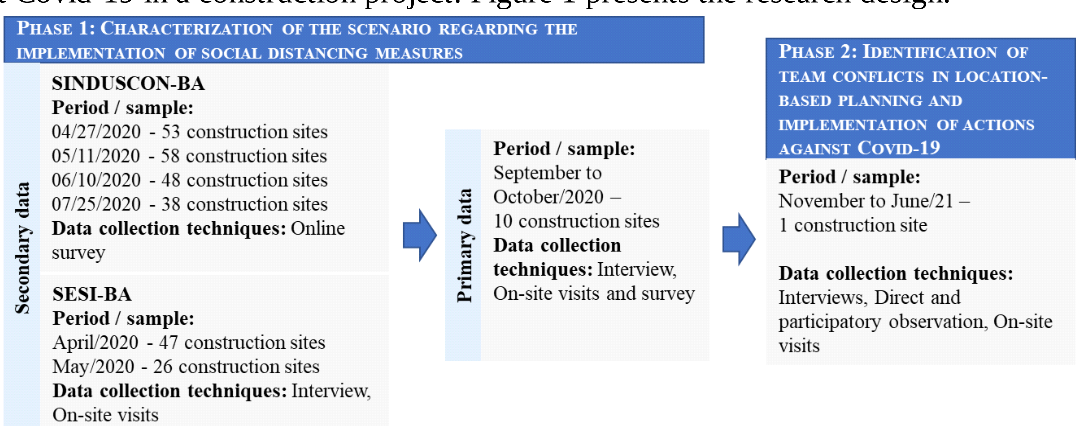


Figure 1: Characterization of the data collected

Phase 1: Characterization of the scenario regarding the implementation of social distancing measures

Secondary data

Secondary data collection was carried out from reports developed by industry entities in Salvador, such as Sinduscon-BA and SESI-BA. Most of the data from Sinduscon-BA was in bar graph format, and it was necessary to infer some answers through interpretation. The data from SESI-BA were made available in spreadsheets with questions, answers (yes or no), and, in some cases, a brief report on the sources of evidence that supported the participant's response. These reports were grouped by similar evidence to assist in interpreting the sources of evidence in each question when possible.

Primary data

Primary data was also collected from local construction companies. The Sinduscon-BA provided a contact list of 23 companies in the Metropolitan Region of Salvador with construction projects in progress. Ten of these companies agreed to participate in the data collection. In each company, a project was selected; if there was more than one project, the interviewees chose the participating construction site. Table 1 shows the profile of the ten construction sites studied.

Table 1: Profile of the construction sites studied

No. of sites	Buildings type	No. of sites	Building system	Area (M²)	No. of sites	Construction phase	Workers
8	Residential	**5**	Reinforced concrete masonry and drywall	Min. 2.000	**7**	Infra / Supra structure	Minimal 15
1	Hospital	**2**	Concrete wall		**6**	Fences / Coatings	
1	Mixed	**1**	Reinforced concrete and masonry	Max. 64.992	**6**	Installations/ Finishes	Maximum 280
		1	Structural masonry				
		1	Reform				

At each construction site, interviews were carried out with construction managers about the projects' characteristics and changes in production planning and control due to Covid-19. In addition, ten safety personnel (safety technicians or engineers) were interviewed about the safe distancing measures embraced and their main implementation difficulties. Moreover, visits occurred in six of the ten construction sites to collect data through photographic records and interviews with workers. During the six visits, questionnaires with closed questions were applied to workers asking about their perception of the health and safety measures adopted in their work environment. Two workers were interviewed per visit, totaling 12 workers interviewed. The profile of all respondents is shown in Table 2.

Table 2: Profile of Respondents and time of interviews per construction project visited

Project	Safety personnel	Time (min)	Construction Managers	Time (min)	Project - Worker A	Project - Worker B
#1	Technician	26	Civil Eng. – Site Manager	15	Inspection	Bricklayer
#2	Technician	18	Civil Eng. - Site Manager	6	Electrical installations	General foreman
#3	Engineer	16	Civil Eng. - Site Manager	18	-	-

Project	Safety personnel	Time (min)	Construction Managers	Time (min)	Project - Worker A	Project - Worker B
#4	Engineer	45	Civil Eng. - Site Manager	9	Signalman	Quality Control
#5	Technician	17	Civil Eng. - Site Manager	6	-	-
#6	Technician	27	Civil Eng. - Site Manager	12	Pipeline Anchoring	Gas Installation
#7	Technician	25	Civil Eng. - Site Manager	4	Carpenter	General foreman
#8	Technician	12	Coordinator	17	Air-conditioning installation	Facade plastering
#9	Technician	23	Coordinator	22	-	-
#10	Technician	20	Construction Director	7	-	-

Phase 2: Identification of crew conflicts in location-based planning and implementation of actions against Covid-19

The LBP implementation was carried out at Project 1 (Table 3) of Construction Company A, which is a medium-sized Brazilian company with around 34 years of market experience and more than 30 thousand housing units delivered. The case study at Construction Site 1 took place from January 2021 to June 2021.

Table 3: Characterization of the construction site

Project 1 Description
Built Area: 22.585 m²
Total 220 units - 1 Tower - 27 Floors
Construction Deadline: 22 months
Constructive Technologies: Concrete wall structure

The case study involved the analysis of available documents (designs, spreadsheets, and planning files) related to the production planning and control of Project 1. Moreover, it involved participation in the ten weekly work planning (WWP) and three lookahead planning meetings with an average of 1.5h.

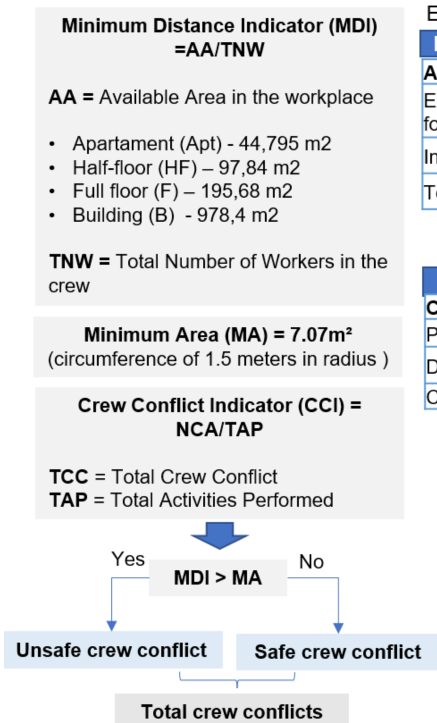
Based on a preliminary data analysis, it was identified the need to understand, considering the information from the master plan that already exists for Project 1, if the sizing of the crews was according to the space where the activity would be carried out. That means if the space of the work environment allowed the minimum social distancing adequate for the number of workers allocated in the crews assigned.

Considering the minimum distance recommended by the WHO (1.5 meters), it was calculated what would be the Minimum Area (MA) needed available in the environment for each employee, considering a circumference of 1.5 meters in radius (MA = 7.07 square meters). Thus, a Minimum Distance Indicator (MDI) was created to compare with MA, where: MDI=AA/TNW (AA = Available Area in the workplace; and TNW = Total Number of Workers in the crew). In practical terms, the result of this indicator informs the area available for each employee, which necessarily needs to be a value greater than the calculated MA.

First, the MDI was defined for each activity based on the workplace area (apartment, half-floor, or full floor), the list of activities from the master plan to be carried out, and the number of workers required for each activity. Based on these indicators, the crew's conflict was analyzed in terms of unsafe and safe crew conflict. So, if MDI >MA, it was a safe conflict; otherwise it was an unsafe conflict.

Then, during the WWP, the MDI was calculated for activities executed in the same place and time. For this, when there were conflicts, the sum of the TNW of each activity in the same AA was used to calculate the MDI. One of the limitations of the MDI is that it does not consider the movements of workers in the workplace, assuming that they would be careful not to crowd, as they would have enough workspace.

A second indicator was developed to understand whether the actions against COVID-19 implemented in this study (rescheduling of activities, resizing crews, raising awareness, etc.) were effective. This indicator is named Crew Conflict Indicator (CCI), where: CCI=TCC/TAP (TCC = Total Crew Conflicts; and TAP = Total Activities Performed). The Total Crew Conflicts was the sum of safe and unsafe conflicts regardless of whether the workers were on the same crew. This indicator provided information about the historical activities percentage with crew conflict compared to the total number of activities. Figure 2 shows a summary and example of MDI and CCI calculations.



Example — Master plan

MDI FOR EACH ACTIVITY – SAME CREW

Activities	AA	TNW	MDI	Status
Execution of metallic formwork and the removal of formwork from walls and slabs	HF	18	5,44	Unsafe
Installation of sewer boxes and grease trap	B	4	48,92	Safe
Test of Hydro-sanitary installations	F	2	97,84	Safe

Weekly work planning (WWP)

MDI FOR ACTIVITIES IN THE SAME PLACE AND TIME – DIFFERENT CREWS

Conflicting activities	AA	TNW	MDI	Status
Plastering on walls	HF	8	12,23	Safe
Drywall lining	HF	7	13,98	Safe
Conflict (sum TNW to calculate MDI)	HF	15	6,52	Unsafe

CCI CALCULATION FOR THE MONTH

Local	TCC	TAP	CCI
Apartments	5	110	4.55
Full floors	30	509	5.89
Half-floors	6	129	4.65
Total	41	748	5.48

Figure 2: Summary and example of MDI and CCI calculation

RESULTS

This section presents the results obtained in the two main stages of the research.

Phase 1: Characterization of the scenario regarding the implementation of social distancing measures

Construction companies adopted several measures when the pandemic began in Brazil in 2020 to promote social distancing. From April to June / 2020, the Sinduscon-BA identified social distancing practices at the construction sites, such as removing the risk group, specific training for the workforce, and shift work schedules.

The social distance concern is also perceived in the data provided by SESI-BA, wherein the period from April to May/2020, the percentage of construction companies adopting administrative measures for workers in the risk group remained around 85%, and the prioritization of the home office was about 77% in both months. Furthermore, all construction companies advised their workers to maintain a distance of at least one meter and used resources such as signaling, posters, and training to reinforce these actions to promote social distancing through isolation. According to Figure 3, the main practices to avoid agglomerations were the staggering work start and finish, changing rooms and dining hall (April – 50%, May – 62%), holding meetings in open space with social distance (April – 15%, May – 31%), and the absence or reduction of face-to-face meetings (April – 12%, May – 19%).

According to primary data collected with ten construction projects from September to October 2020, the safety specialists interviewed reported that the main measures adopted to promote social distancing were: Staggering work start and finish times, dining hall and changing rooms (100%), Changes in the site layout (90%), Removal of an employee from the risk group (60%) and social distancing signaling (50%).

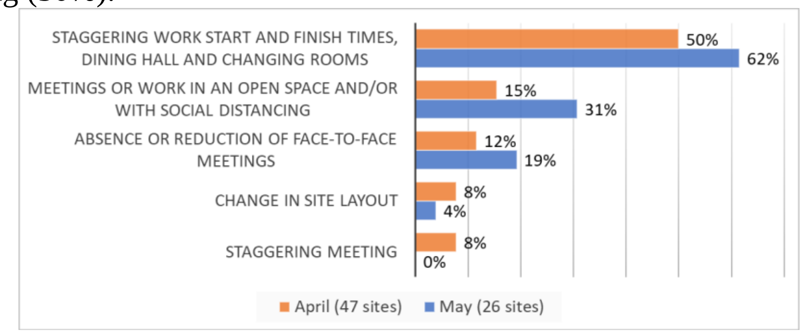


Figure 3: Actions to avoid agglomerations at the construction sites. Source: SESI-BA

Despite implementing the actions mentioned above, safety specialists reported some problems regarding combating the proliferation of COVID-19 in construction sites were still recurring. It was observed that half of these respondents reported having difficulties with maintaining social distance, mostly in activities, such as transporting materials (50%) and concreting (20%), because they still implied a space less than recommended.

Due to the pandemic, the ten constructions sites interviewed highlighted the main changes in the activities schedule, as follows: Reduction of working hours (30%), Reduction of crews or the number of employees (30%), Execution of activities with a safe distance (30%), Redistribution of crews in different shifts (20%), and Redistribution of crews in different zones (20%). Furthermore, according to the interviewees, the planning meetings were mostly held in open, large, or ventilated places (50%). These meetings could also be held to maintain social distancing (20%) or reduce the duration or number of participants (10%). Another possibility was not to have the meetings at the construction sites and deliver the schedule to those in charge (20%).

In addition, according to 92% of the workers interviewed in the six construction sites, there was a precaution to maintain social distancing during planning meetings at the construction site. Half of the workers interviewed also reported changes in the execution of their activities to maintain a safe distance. However, most of them said that these changes did not affect their crew production (58%) or did not create difficulties for the services to be executed (92%). Due to the changes, the crews were distributed in different workplaces (33%), services were taking longer to be performed (17%) or there was a delay for the service to start (8%).

Phase 2: Identification of crew conflicts in location-based planning and implementation of actions against Covid-19

Figure 4 shows Total and Unsafe conflicts by different crews occupying the same workplace simultaneously in Project 1. In November and December/2020, 41 and 33 activities were executed with real Total crew conflicts, respectively. To verify if it was a problem in terms of safe distance among workers, the Minimum Distance Indicator (MDI) was used to check the availability of space and the severity of these conflicts regarding social distance.

To understand if each activity represents a risk by itself, firstly, on January/21, the MDI was calculated using the master plan information. This indicator ranged from 5.44 to 782.72 m^2/worker, and the only activity that had the MDI below MA recommended was the execution of metallic formwork and removal of formwork from walls and slabs (MDI = 5,44). From January/2021 to June/2021 was verified the Total Crew Conflicts and Unsafe crew conflicts to activities in the same place and time, both the real conflict (during the execution of activities) and the one planned according to the WWP, as can be seen in Figure 4.

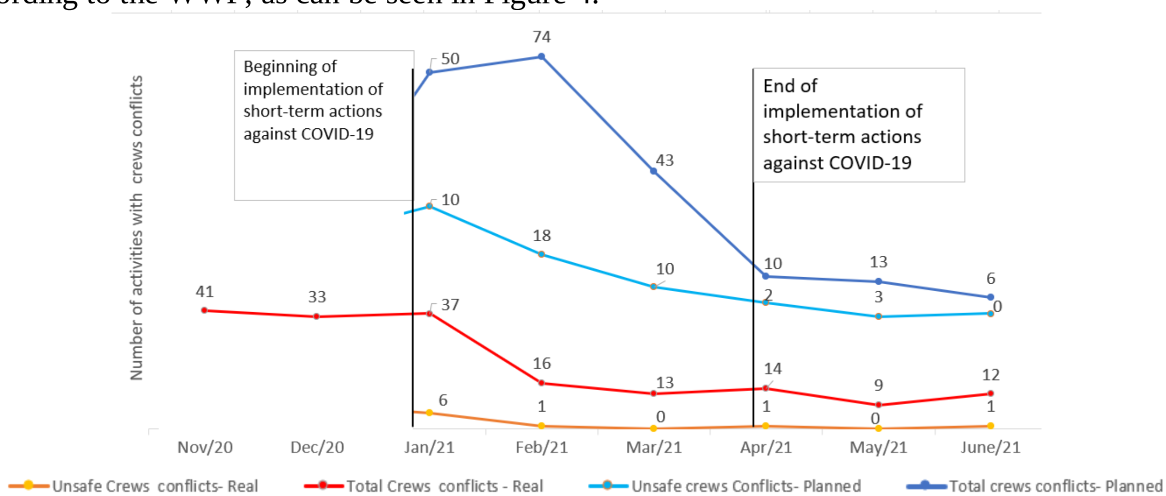


Figure 4: Crew conflicts before and after implementing actions against COVID-19

Therefore, due to the identification of Unsafe crew conflicts from January to March/2021, daily inspections and training of the crews was carried out, in addition to signaling the environments already occupied by crews to promote social distancing during the execution of activities at the construction site. These actions took place weekly and sought to outline strategies to reduce the contact between workers from different crews through the rescheduling of activities, resizing crews, and raising awareness of the planning team. During this period, a high incidence of Total and Unsafe crew conflicts was observed during WWP, but these were reduced when the workers carried out the planned activities. Figure 5 shows the frequency and month that these strategies were implemented.

From April to June/2021, the monitoring of the actions was monthly. It was observed that after implementing measures to promote social distancing, there was a significant drop in the number of real and planned Total crew conflicts and Unsafe crew conflicts. The success of implemented actions is reflected in the reasons for schedule delay (Figure 6), which shows a slight reduction in the number of activities not performed as planned from November/2020 to June/2021. However, except for March month, there was a peak in activities not performed on time due to the increase in Covid-19 sick notes in the Metropolitan Region of Salvador.

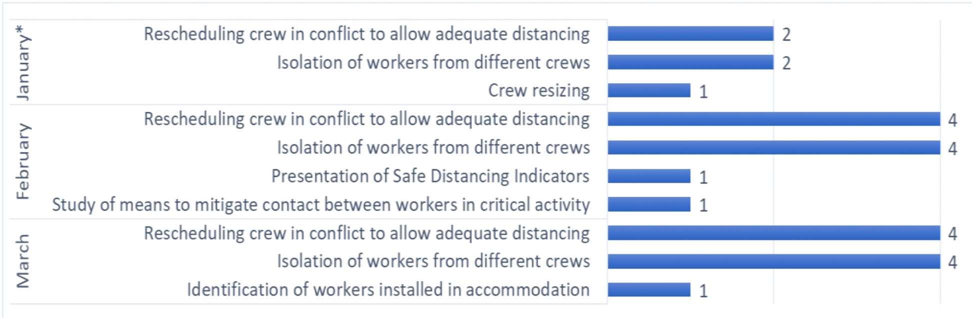


Figure 5: Actions to promote social distancing among workers

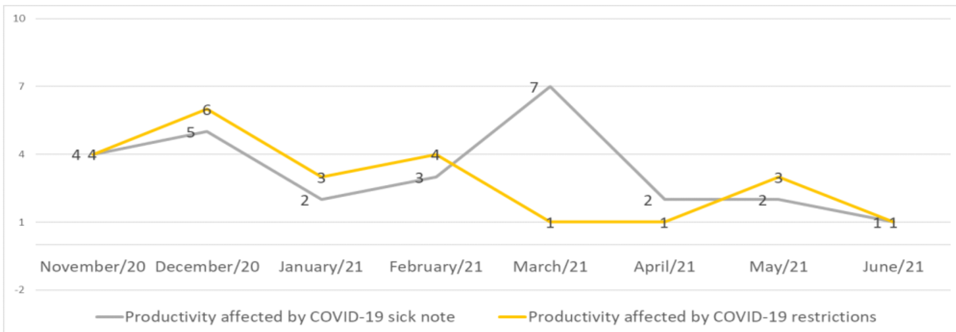


Figure 6: Activities not performed as planned and their causes

The positive effect of the implemented actions can be seen through the Crew Conflict Indicator (CCI), which has been decreasing over the months (Table 5). This means that the percentage of activities with real crew conflict when compared to the total number of planned activities was decreasing, regardless of whether they were unsafe or not.

Table 5 - Results of the Crew Conflict Indicator from Nov/2020 to Jun/2021

Months	Number of Conflicting Activity	Total Activities Performed	CCI (%)
November/2020	41	748	5.48%
December/2020	33	699	4.72%
January/2021	37	958	3.86%
February/2021	16	751	2.13%
March/2021	13	884	1.47%
April/2021	14	658	2.13%
May/2021	9	899	1.00%
June/2021	12	774	1.55%

DISCUSSION

The study shows the most implemented Covid-19 measures to social distance during the execution of construction activities in construction projects in Salvador Metropolitan Area -Brazil. In the face of nonconformities, corrective measures were taken. Nevertheless, it was still challenging to maintain the distance between the workers during the work performance in some activities. This problem was also highlighted by Olukolajo, Oyetunji, and Oluleye (2022). Thus, there was a need to implement other actions that involved changes in the crew's planning to minimize contact between workers.

According to Zakaria and Singh (2021), construction companies needed to ensure that the mobility and logistics of workers allowed safe movement in the execution of their tasks. These authors identified that some companies are limited to a maximum of fifty percent compared to regular days. This study identified the implementation of actions regarding the redistribution of crews in different zones and reducing crews or the number of employees. Besides reducing working hours and the redistribution of crews in different shifts.

Although there were recommendations for prioritizing online meetings and limiting the interaction to the minimum necessary time (Olukolajo, Oyetunji, and Oluleye, 2022), some construction sites' presential meetings were conducted to inform the planning the workers. However, this study identified that care was taken to minimize the interaction between workers, such as holding meetings in open and ventilated places, safe distancing, and reducing the duration and the number of participants.

The LBP (Location-Based planning) provides information on when and where each activity should be carried out (Kenley and Seppänen, 2010). According to Jones, Gibb, and Chow (2022), during the pandemic, there was an increase in the time spent planning jobs and tasks to ensure that there were not too many workers in each area. Besides that, lookahead meetings were held about the work order and the times when different workers would have access to a specific work zone. This management of work zones was also possible using LBP in this work. However, despite the changes in how tasks were performed or in the distribution of the workforce in different areas, it was observed that most workers reported there was no change in their productivity, or the changes did not make it difficult to carry out their work.

Jones, Gibb, and Chow (2022) also found that planning to manage work zones brought positive results, and some respondents reported that planning led to smoother tasks, as problems were addressed in advance. Therefore, the use of LBP in this study also allows to identify and reprogram in advance situations in which different crews would be working in the same place, avoiding conflicts between them. For this, the following actions were taken: (a) rescheduling crews in conflict to allow adequate distancing, (b) isolation of workers from different crews, (c) crew resizing, and (d) study of means to mitigate contact between workers in critical activity, that is, a simultaneous study of the teams to identify solutions to improve social distancing. These actions led to a significant drop in Total and Unsafe crew conflicts. This drop continued even after the end of weekly meetings, indicating a progressive learning effect by construction managers in developing WWP considering the restrictions of Covid-19. Moreover, the number of Total and Unsafe conflicts that existed during the execution of the activities was lower than those programmed in the weekly planning, indicating that the construction managers still managed the crews during the execution of the activities to improve social distancing.

Amoah and Simpeh (2021) highlighted that the execution of some tasks, such as erecting scaffolding on site, loading materials, loading and unloading materials cannot be implemented without probably having contact between workers. In this work, the critical activity was the execution of metallic formwork and the removal of formwork from walls and slabs, due to the heavy material transportation and assembling required.

LPB contributed to structuring the construction site in well-defined locations (Kenley and Seppänen, 2010). The amount of work of each activity in each location made it possible to define more clearly the size of the crew needed for its execution, including the minimum distance analysis. In addition, to allowing the extraction of relevant information (such as area data and location) for Covid-19 restrictions, the LPB brought the opportunity to think about the productivity of activities. That is if having several employees working in the same place can have a negative or positive effect on productivity as it can make it more disorganized and less efficient. One change in the actual practice in the face of a delay in the schedule solves it by increasing the worker amount (Jones, Gibb, and Chow, 2022).

The resizing of the crews did not impact the productivity of the activities. There was no need for a reduction in worker number in the crews, except for the metallic formwork activity. However, this activity was not modified due to crew members residing in the same location. On the other hand, it was thought that scheduling the activities in a way that did not allow two crews in the same place would delay the project deadline. In practice, the buffers were sufficient to accommodate this new constraint added to the schedule, and the productivity was only affected by absenteeism related to Covid-19.

Using the LBP to identify critical activities conflicts made it possible to alert the management of the construction site and seek actions to mitigate the impacts of the high number of crew members per location. LBP also promoted an increase in transparency and communication (Lucko *et al*., 2014) by clearly explaining workplaces and identifying and visualizing conflicts between crews. In addition, it can make the workflow explicit, allow the simulation of alternatives for the sequencing of activities, and, simultaneously, bring information about when and where each activity should be performed along with the production units (Kenley and Seppänen, 2010).

As Project 1 studied already used the LBP, in this study was only necessary to include the analysis related to Covid-19 in the planning routines. At first, there was some resistance from the construction management team in using that information to modify the planning, since the project deadline was already being affected by other factors (such as late materials delivery) and to reduce crew conflicts, in some cases, the expanding of the crews' schedule was needed. Due to the support of top management, it was possible to implement the LBP to manage Covid-19 restrictions.

CONCLUSIONS

This work aimed to identify social distance measures applied in the construction sites as part of the COVID-19 measurement and use LBP to assess and measure crew conflicts to support social distance. First was presented a characterization of the scenario regarding implementing social distancing measures in a sample of a construction site in the Metropolitan Region of Salvador in Brazil. It was observed that the primary measures by frequency of adoption were: (1) Specific training for the workforce, (2) Staggering work start and finish times, dining hall and changing rooms, (3) Removal of the risk group, (4) Changes in the site layout, (5) Prioritization of the home office, (6) shift work schedules, (7) Social distancing signaling, (8) Holding meetings in open space, and (9) Reduction of face-to-face meetings. Furthermore, all these measures had increasing adoption over the studied periods.

Location-based planning was implemented at one of these construction sites to help identify the crew conflicts. It also implemented actions against Covid-19 for conflicts with an MDI below the MA. These actions have resulted in a reduction in both Total and Unsafe conflicts crews and a reduction in activities not completed on time due to sick notes and restrictions from Covid-19. As for recommendations for future studies, it is suggested to use digital technologies with LBP to help monitor safe distancing and automatize the identification and verification of conflicts between crews.

ACKNOWLEDGMENTS

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HYBRID SIMULATION FOR VALUE STREAM MAPPING TO IMPROVE THE ENVIRONMENTAL PERFORMANCE OF THE CONSTRUCTION PHASE

Danh Toan Nguyen[1] and Walter Sharmak[2]

ABSTRACT

The environmental impact assessment of the construction phase is often not fully considered compared to other phases of the project life cycle. Previous studies on environmental impact reduction have often focused on technical aspects rather than organisational aspects. The value stream mapping (VSM) method has been extended to capture and improve environmental performance by systematically adopting lean methods in the manufacturing process. However, in the construction field, this approach encounters difficulties establishing state maps and considering the interrelationships between different processes in an uncertain and dynamic environment. This study proposes a hybrid approach combining Multi-Agent Systems (MAS) and System Dynamics (SD) based on process patterns to overcome these obstacles. First, process patterns, including activity packages, are developed to assist the VSM in creating state maps and identifying environmental impact sources. Then, construction operations with their state maps and needed resources are modelled as autonomous agents containing causal-effect loops (SD modules) in a MAS model. These agents interact with each other to describe the construction operating mechanism. Finally, different lean methods are analysed to find opportunities to improve environmental performance.

KEYWORDS

Lean construction, value stream, process, environmental assessment, hybrid simulation.

INTRODUCTION

The construction industry has been identified as one of the leading causes of global warming due to its remarkable consumption of resources and energy, and the generation of harmful emissions. According to a report from the International Energy Agency, building construction and operations accounted for the largest share of both global final energy use (36%) and energy-related greenhouse gas (GHG) emissions (39%) (IEA, 2019). However, the Intergovernmental Panel on Climate Change forecasted that the construction field has the largest potential for decreasing GHG emissions compared to

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other sectors (IPCC, 2014). Previous studies on the environmental impact assessment (EIA) of buildings have mainly focused on the product phase (modules A1 to A3 per BS EN 15978: 2011) and use phase (modules B1 to B7), while the construction phase (modules A4 to A5) is often overlooked or incompletely considered (Slosharek et al., 2021). Compared to other phases, construction is a short-term phase and is believed to emit lower emissions, so it has not attracted much research (H. J. Wu et al., 2012). Besides, the uniqueness and uncertainties of construction projects make it difficult to standardise the analysis process. Thus, estimating the environmental impacts of the construction phase is perceived as too burdensome and tedious, especially considering the overall benefits. However, disregarding the construction phase in the EIA leads to a gap in fully understanding the possible sources of environmental impacts of the construction project life cycle.

Value stream mapping (VSM), a commonly used lean method, has been developed to uncover environmental impact sources and identify opportunities to improve environmental performance for production processes. For example, Faulkner & Badurdeen (2014) proposed a sustainable VSM by adding a set of environmental metrics such as raw material usage, energy consumption, and process water consumption. Their developed methodology can apply across various industry sectors by customising and selecting different metrics. The US Environmental Protection Agency (US EPA, 2007) recommends applying VSM to record environmental performance data to develop a future state vision for the production process. Rosenbaum et al. (2014) conducted a case study of the VSM application as a green-lean approach to the construction phase of a hospital. This research confirmed VSM’s ability to detect the sources of environmental and production waste, quantify them, and suggest reduction strategies.

Fundamentally, VSM is a method used for the manufacturing industry, which is very different from the construction industry. Therefore, the application of VSM for construction faces the following challenges. First, one of the prerequisites for implementing VSM is the repeatability of processes. In industrial manufacturing, VSM describes the state of a process, which is usually repetitive in an active production system, based on statistical data collected from production lines. In contrast, a construction project presents a unique design and specifications and must be constructed uniquely. Moreover, tracking the construction process is complex and tedious as most of the construction steps are lengthy with the involvement of different stakeholders (Yu et al., 2009). Especially in the execution planning stage, it is impossible to establish the state map because construction activities have not been carried out yet.

Second, VSM relies on static inventory data, so they can not consider the effect of uncertainties and dynamic factors of the construction phase. In addition, the positive effects of implementing lean methods on environmental performance are usually indirect and difficult to evaluate in advance. Many studies combined simulation methods with VSM to overcome these obstacles. For example, the discrete event simulation (DES) method is often applied to enhance VSM in understanding and estimating the impact of randomness and the effect of lean methods on a system (Jarkko et al., 2013; Zahraee et al., 2020). However, previous combinations of VSM and simulation in the construction sector focused only on single processes such as earthwork (Nguyen, 2019), concrete pouring (Zahraee et al., 2020), and steel building erection (Ramani & KSD, 2019). For EIA purposes, all main processes of the construction phase have to be mapped and analysed simultaneously because these processes constantly interact with each other. These process interactions are usually non-random based on rules, terms, and conditions that they meet in explicitly defined networks. Although DES can effectively support VSM in analysing single processes at an operational level, it encounters difficulties when simulating many concurrent processes and capturing causal-effect relations at a holistic level. In contrast, the multi-agent systems method is more appropriate for simulating heterogeneous populations, or agents' networks and their interactions among them and their environment. Besides, system dynamics is a powerful method to complement MAS in modelling feedback processes, demonstrating the interrelationships between project elements at the holistic level (Nguyen & Sharmak, 2021; Swinerd & McNaught, 2012).

This paper proposes a hybrid approach combining MAS and SD based on process patterns to enhance VSM in establishing state maps, identifying environmental impacts and analysing the effects of lean methods implementation on the environmental performance of the construction phase. The paper is organised as follows: The next section describes the VSM application for EIA of the construction phase based on process patterns containing activity packages. Then, the development of a MAS-SD hybrid simulation model and its use to consider the effect of some lean methods on environmental performance are presented. The subsequent section introduces a simulation example of the construction phase of a highrise building to test the developed model. Some conclusions about the contributions of this study are put forth in the end.

PROCESS PATTERNS FOR VSM APPLICATION

Typically, construction projects are unique, differing in architecture, location, function, and structure. However, they can be considered a combination of typical construction processes iteratively. Therefore, several authors suggest that predefined process patterns can conveniently generate the process components for analysis during the planning and scheduling phases (Nguyen & Sharmak, 2020b; I. Wu et al., 2009). A process pattern describes the logic of how a construction operation is organised and performed. Using process patterns can support the VSM method by shortening the mapping time of processes because the practitioner selects only the appropriate method, after which subsequent components are automatically generated.

To apply the VSM for EIA, selecting the appropriate detailed level of mapping plays an important role. Traditionally, the granularity of process patterns used in the construction phase has often been in situ operations such as reinforcement installation, formwork erection, or concrete pouring (Rosenbaum & Toledo, 2014) (level 2 in Figure 1a). However, these processes should be broken down into more granular levels to uncover all activities that affect the environment. For example, the reinforcement should be divided into rebar transport (offsite and onsite), processing (cutting, bending), and installation (level 3 in Figure 1a). In this research, process patterns of the cast-in-place concrete construction process are proposed to facilitate VSM in generating state maps of processes at the "activity" detailed level (level 3 in Figure 1c). The activities of the state maps play an essential role in the identification and assessment of environmental impacts because they are at the atomic level and directly perform specific construction tasks. Activity packages are introduced to minimise the possibility of making errors and omissions in the activity description (Figure 1b). Activity packages depict atomic activities of process patterns with all corresponding data such as constraints, required resources, and environmental impact indicators based on norms and experience. Process patterns and activity packages are stored in databases, which will be queried to generate state maps for VSM. Figure 1 shows value stream maps of construction processes producing vertical components using the cast-in-place concrete method. Each activity can affect the environment in different ways. For example, offsite transport from plant to construction site using trailers or trucks consumes fuel and emits GHGs. Processing activities (cutting, bending) and onsite transport activities from yard to erection site (using cranes, lifts) consume electricity. Installation activities need auxiliary materials such as iron wire, nails, and water (Figure 1c).

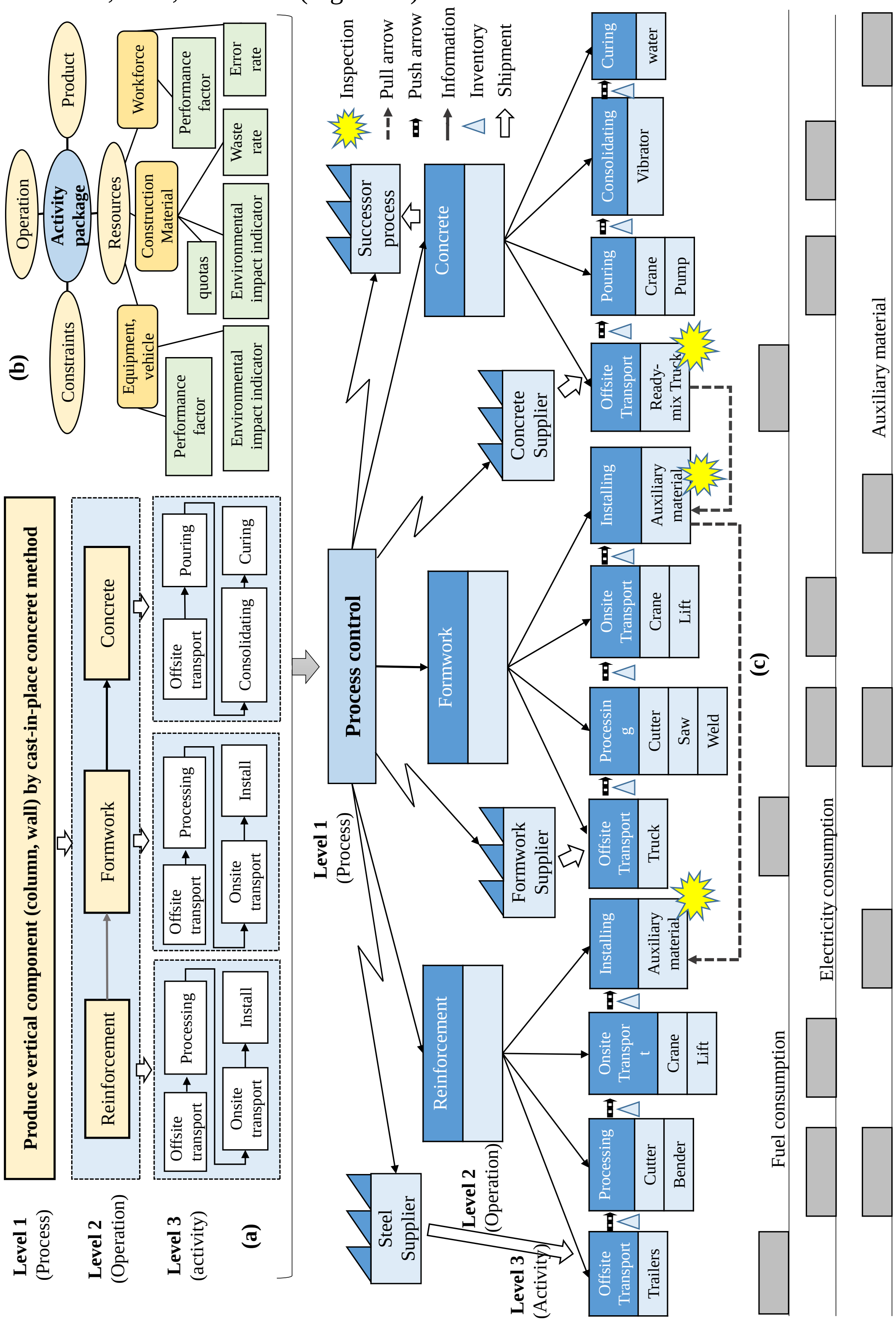

Figure 1: A state map of the construction process using the cast-in-place concrete method.

HYBRID SIMULATION-BASED VSM

HYBRID SIMULATION FRAMEWORK

Since no construction activities have been performed on site during the execution planning stage, planners can conduct the VSM analysis of construction processes based on process patterns and activity packages. First, state maps are established by retrieving needed parts from the process pattern and activity package databases and modelled as statecharts of operation agents of processes in a MAS model. Besides, SD modules are embedded in operation agents to depict the causal-effect loops. In addition, planned resources are also modelled as resource agents in the MAS model (Figure 2). Finally, construction processes are operated through the interaction between operation agents and resource agents according to different organisational and management strategies.

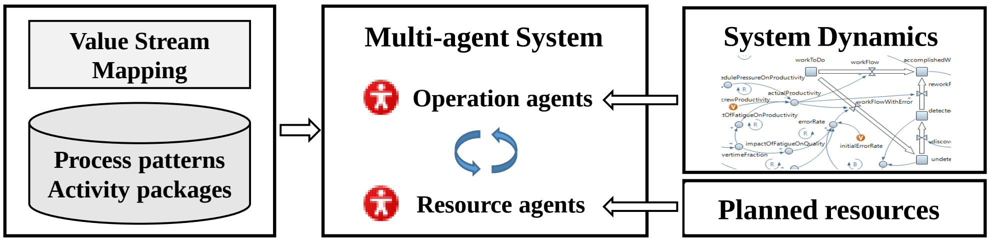

Figure 2: The hybrid simulation framework

MULTI-AGENT SYSTEM

MAS models are based on the bottom-up approach that suits correctly modelling complex systems. The agent-based method is proven helpful in mimicking the system behaviour with autonomous and interactive abilities of agents in a dynamic environment. MAS is defined as intelligent autonomic agents representing real-world parties without global control and unified objectives (Ren and Anumba, 2004). In this paper, both construction operations and construction resources are represented by agents using the AnyLogic simulation engine (Anylogic, 2022).

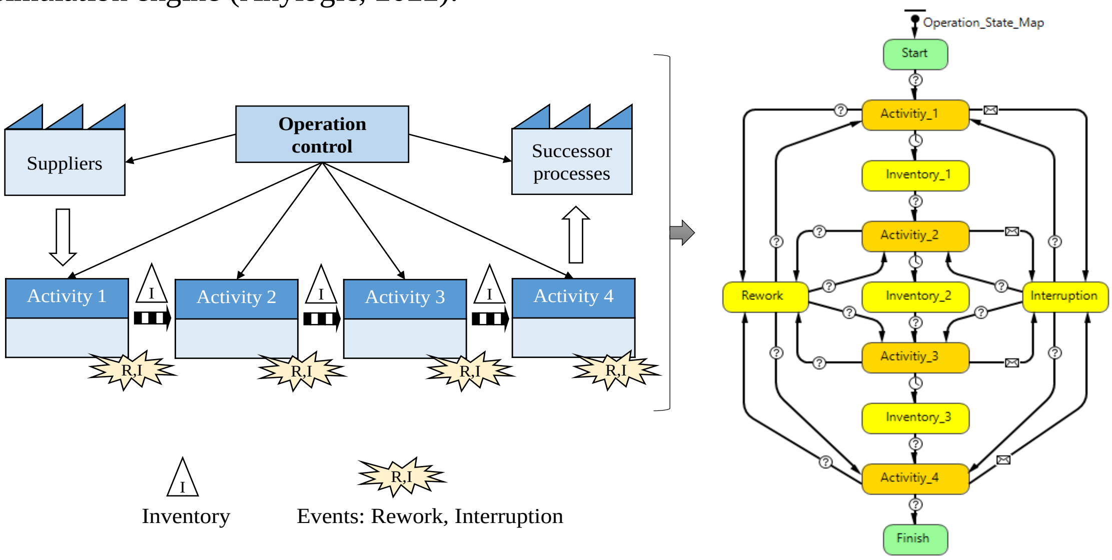

Figure 3: Example of transferring a state map into a state chart in the simulation model

Operation agent

Operations of a construction process are represented by agents containing statecharts to depict all activities of the operation following the VSM method. Figure 3 shows an example of transferring a state map of an operation with four activities into a statechart in the simulation model. According to the flow view of lean principles, processes can be improved by achieving a continuous flow without any interruptions and errors. Therefore, two states, "rework" and "interruption", are added to illustrate the situation when any activity of this flow has a defect leading to rework or is interrupted by external factors. Operation agents contain various attributes such as workload, duration, and due dates. Furthermore, operation agents can self-define their predecessors, successors and needed resources based on process patterns and activity packages. A central control mechanism coordinates communication and interactions between agents that relay information to the respective targets. Each agent process this information on its own, be aware of its state, and behave accordingly.

Resource agent

There are various resources with different functions and variables in the construction phase. Resources are considered autonomous and intelligent agents that can change their state and actively interact with operation agents. For EIA purposes, construction resources should be differentiated into renewable (e.g. machinery, workforce) and non-renewable (e.g. material, water). The consumption of non-renewable resources and the operating time of renewable resources are aggregated to convert into emissions values based on the environmental datasets. Since each resource agent is an instance of a renewable or non-renewable resource, they differ in their attributes and the operations that can be involved. Figure 4 shows state maps of five primary construction resources: workforce, material, offsite transport vehicle, onsite transport equipment, and processing machines.

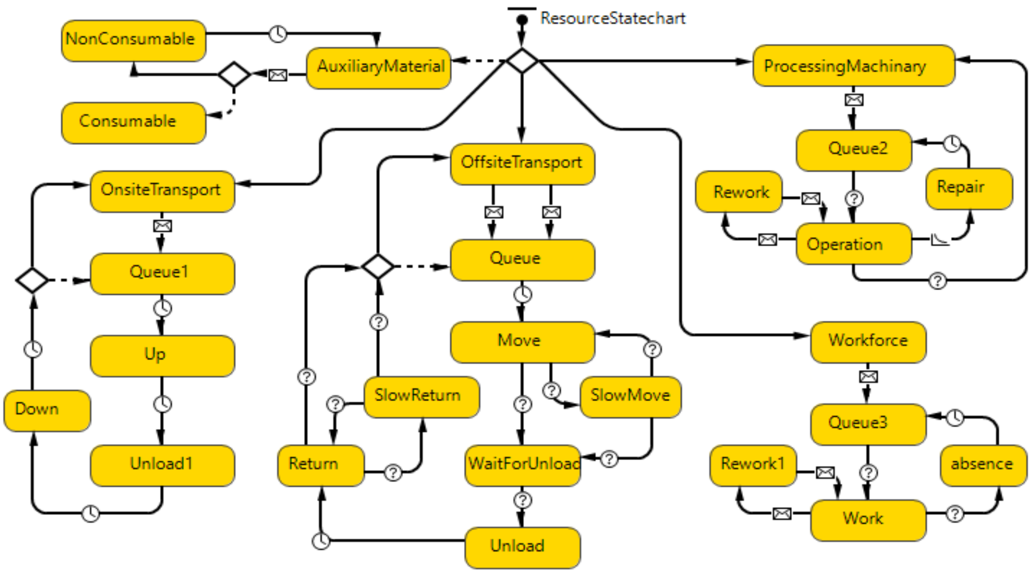

Figure 4: Statechart of construction resources

Agent interaction protocol

In the Multi-Agent System, autonomously active agents interact directly with their predecessors and successors. First, following predefined operating mechanisms, operation agents register their required resource proposals on a central blackboard, a central control system for all agent negotiations. Then, depending on the specific expertise for the registered activity and the availability of resource agents, the control centre processes all the information in a particular protocol and acts respectively to allocate the resources.

INTEGRATION SYSTEM DYNAMICS INTO THE MULTI-AGENT SYSTEM

System dynamics simulation is a top-down approach based on the information feedback to analyse a complex system behaviour between project elements from a macro and holistic perspective within a predefined boundary (Ding et al., 2016). Typically, system dynamics models are structured by stocks-flows diagrams that describe the movement of entities from start to end in a model and causal loop diagrams that capture the chain influences of a cause are traced through a set of related variables back to the original cause. In the literature, many SD models have been developed to analyse the behaviour in the construction field, such as the quality assurance cycle, rework cycle, and errors management cycle (Alzraiee, 2013). In this paper, the feedback processes, including the schedule pressure loop and rework loop, are embedded in the MAS (within the AnyLogic simulation environment) to capture the system behaviour.

Schedule pressure loop

The schedule pressure factor of a construction operation, which represents the discrepancy between the planned schedule and actual progress, is calculated by dividing the required time to complete this operation by the actual remaining time to finish it. If schedule pressure is too low, the productivity will be reduced because performers likely think they have more time to complete their tasks than planned (Alzraiee, 2013). However, excessive schedule pressure can deteriorate productivity considerably. Conventionally, adopting work overtime can decrease the schedule pressure, although it might cause fatigue, lower quality, and generate more errors ().

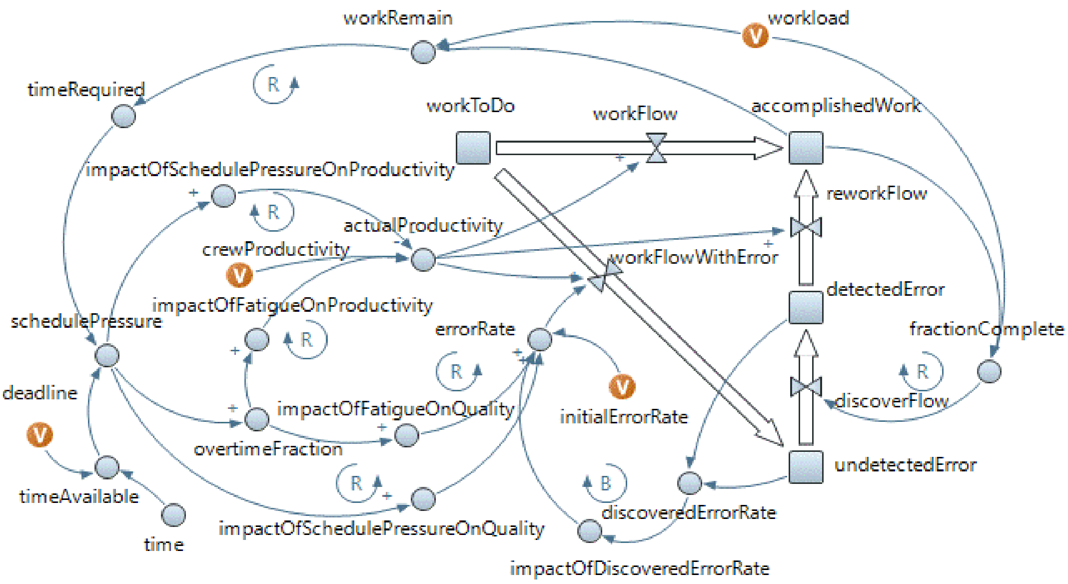

Figure 5: Causal-Effect loops in operation agents

Rework feedback loop

Errors in construction tasks are often inevitable because of the unreliable workflow in an uncertain environment. Errors lead to rework that consumes more resources than expected, so the impact on the environment also increases significantly. In addition, rework can itself be flawed, requiring additional rework in a recursive cycle that can extend project duration and work scope. Several factors that can affect the rework loop, such as labour experience, schedule pressure, and error detection time, usually are omitted by previous environmental impact assessments. The errors can be detected during the working process or by inspection. The crews are usually aware of their mistakes when the work comes nearly to the end, so the error discovery rate depends on the fraction completion of work. When an error is detected, the team can fix it immediately or wait until the ending stage, depending on management policy. By being aware of mistakes, the error rate can be decreased. This relationship is modelled as a cause-effect loop through the impact of the error discovery rate on the error rate in Figure 5.

EFFECT OF LEAN METHODS ON ENVIRONMENTAL PERFORMANCE

The MAS is operated through predefined rules, describing different process management mechanisms. Although many lean methods can be embedded into the developed simulation model by setting up the agent interaction protocol or adding causal loops, this section only mentions some potential lean methods that positively affect the environmental performance of the construction phase.

Last planer system

The LPS can create a stable, highly productive construction environment through reliable planning and efficient control (Ballard & Tommelein, 2021). The LPS tends to plan in greater detail as planned tasks get closer to performing and involves people who are going to carry out the work based on their active coordination and negotiation. In the LPS, activities' duration and due date are set to be consistent with the performer's capacity. Therefore, the schedule pressure of tasks is maintained at an appropriate level to ensure productivity and avoid overtime. Thus, LPS can reduce errors caused by working under high pressure and fatigue due to overtime and indirectly reduce environmental impacts. In the developed simulation model, by setting up pull-driven process management, tasks' deadlines can be adjusted depending on actual demand after each weekly work plan cycle. This effect on construction operations is captured by the schedule pressure loop mentioned in the previous section.

Mistake-proofing (Poka-Yoke)

Researchers suggest that the rework cost in construction projects can range from 10% to 22% of the contract cost (Forcada et al., 2017; Trach et al., 2021). Lean construction tries to prevent errors through simple ways of mistake-proofing. First, tasks in the construction operations prone to errors should be identified. These mistakes could be a quality problem, delays in needed elements supplying, etc. Second, after the problem is recognised, suitable solutions should be researched and implemented to prevent the recurrence of problems in the future. In the proposed simulation model, the effect of different quality inspection strategies is captured by the discovered error loop, which can consider the relationship between the time to detect error and the error rate variation.

Daily huddle meetings

Some construction disruptions are related to the project team's inadequate perception of the project status as a whole, including their work and others' (Ma & Sacks, 2016). This disruption resulted in missing milestones and derailed projects. By contrast, Daily Huddle can connect project teams to synchronise information flow and verify that work is progressing as promised; if not, identify resources for immediate help or adjust schedules. In the MAS, daily huddles were simulated by setting agent meeting events. After the meeting, agents are actively updated with new information from their predecessors and successors. If there is some negative impact on them, these agents can propose solutions to ensure they can operate in the right environment, such as adjusting the due date or requiring more resources to reach the predefined deadline.

SIMULATION EXAMPLE CASE

This section presents a simulation example to test the applicability of the proposed methodology in applying lean methods to improve the environmental performance (this example considers only GHG) of the construction phase. A virtual building of four floors with a total floor area of approximately 8130 m2 in Hanoi, Vietnam, was selected to apply the proposed methodology. The building is a reinforced concrete frame structure built by the cast-in-place concrete method, widely applied in the Vietnamese construction industry. Three primary operations of the cast-in-place concrete method, including reinforcement, formwork, and concrete work, were analysed according to the VSM approach (Figure 1). All necessary data regarding material and resource consumption rates were queried according to Vietnam's construction norms (BXD-VN, 2007). The GHG emissions rates of impact sources were obtained from Vietnam's Ministry of Natural Resources and Environment data or previous international studies (Nguyen & Sharmak, 2020a). The scope of impact sources is within the contractors' area of decision-making, such as vehicles for material transport (construction material and building material), equipment, machinery, and construction material in the construction phase, while the upstream design stage determines other primary building materials.

Four scenarios are analysed using the proposed simulation model to quantify the effect of lean methods on the environmental performance of the construction phase.

Scenario 1: The typical stories of the building are divided into two zones. Construction processes are operated by push-driven process management (so-called conventional process), in which a construction schedule is developed by calculating early, and late activity starts and finishes by applying the critical path method (CPM). Each operation agent always tries to hold needed resource agents to start at their earliest possible time so as not to delay their successors. Process control adheres to the predefined schedule. If an activity is estimated not to meet the deadline, working overtime in night shifts solution is used instead of adjusting the due date. Project member meetings take place twice a week. Quality inspection only focuses on onsite activities such as installing reinforcement and formwork. Other activities in the processing yards, such as cutting and bending rebars, are not regularly checked. (This situation is quite common in most construction sites in Vietnam).

Scenario 2: The typical stories of the building are divided into two zones. The LPS approach is adopted (so-called lean process). In which pull-driven process management distributes resources selectively so that the operation's output is a product needed further downstream in the process. Also, operation agents only start when they are required for downstream operation agents instead of starting as soon as possible. In contrast to scenario 1, the deadline of the activities can be flexibly adjusted to accommodate the available resources updated from daily huddle meetings. In addition, onsite activities and all activities in processing yards are inspected to detect errors as early as possible to prevent a recurrence.

Scenario 3: The operation mechanism of construction processes is the same as in scenario 1, but the typical stories of the building are divided into three zones (the number of zones can be two, three, or four, but this paper only considers the first two cases).

Scenario 4: The operation mechanism of construction processes is the same as in scenario 2, but the typical stories of the building are divided into three zones.

RESULT AND DISCUSSION

The GHG emissions (expressed as carbon dioxide equivalents CO_2eq) and the duration of the four scenarios' performance are shown in Table 1. By applying lean methods, scenarios number two and four can significantly reduce emissions and time compared to scenarios number one and three (conventional processes). For example, with the same number of zones per story, applying lean methods eliminates the GHG emission by 10.7% (34809-31055=3754 kg, compare scenario 1 with scenario 2) and 12.1% (33633-29589=4044 kg, compare scenario 3 with scenario 4). The reason for this reduction is that the application of LPS maintains appropriate schedule pressure, thus indirectly reducing the error rate due to working overtime and fatigue while ensuring labour productivity of crews. In addition, strengthening the quality control of all tasks in process yards can detect errors early, thus avoiding the accumulation of errors for downstream tasks.

Table 1: Simulation results (for one typical story)

Scenarios	Note	CO_2-eq (kg)	Duration (hr)
1	2 zones per story, conventional process	34809	173
2	2 zones per story, lean process	31055	146
3	3 zones per story, conventional process	33633	161
4	3 zones per story, lean process	29589	132

Some previous studies have suggested that reducing batch size in production processes leads to a reduction in project time but does not affect the environmental performance (Golzarpoor et al., 2017). However, this study indicates that increasing the number of construction zones per floor (which means decreasing batch size) can also reduce GHG emissions by 3.3% (34809-33633=1175 kg, compare scenario 1 with scenario 3) and 4.7% (31055-29589=1466 kg, compare scenario 2 with scenario 4). Reducing batch size leads to shorter cycle times for each zone and avoids waiting time for downstream tasks. Therefore, the energy consumption of machinery and equipment in standby mode is eliminated. Besides, reducing batch size also results in minimal inventory levels, thereby reducing defects or deterioration during storage. However, this aspect has not yet been simulated in this example, so the effect of batch size reduction on emissions is relatively low, just under 5%.

CONCLUSIONS

The main contribution of this research is the development of a hybrid simulation method that can enhance the VSM method in estimating environmental impacts and quantifying the effect of lean methods on the environmental performance of the construction phase. By applying process patterns, the hybrid simulation-based VSM can be conducted in the execution planning stage to assist builders in selecting environmentally friendly processes. The simulation example shows that the systematic implementation of lean methods, including LPS, mistake proofing, and daily huddles, can indirectly reduce the GHGs emission by around 12%. Furthermore, it is worth mentioning that reducing the batch size also leads to a decrease in emissions by nearly 5%. In the future, this hybrid simulation model will be further developed to quantify the effect of other lean methods on environmental performance. Moreover, combining this model with the building information model will facilitate adopting lean methods in the construction phase.

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METHOD OF INDUSTRIALIZATION POTENTIAL ANALYSIS OF CONSTRUCTION SYSTEMS

Alejandro Vásquez-Hernández[1], Jesús Ortega[2], Zulay Giménez[3], and Luis Fernando Alarcón[4]

ABSTRACT

Construction is a production system characterized by inefficiencies associated with its processes. Industrialized construction (IC) is a promising approach as an optimization mechanism based on decreased variability. In this regard, it stimulates the standardization of work, which is an essential lean management principle to improve the production system. However, IC presents an incipient level of adoption and implementation. This paper describes a method for the industrialization potential analysis of construction systems (IPA), allowing design teams to identify construction systems whose standardization, modular coordination, and preassembly have more potential to improve project performance. It was developed through an action-oriented framework based on the action research methodology. Researchers, construction companies, and the cohesive entity of the construction sector (Industrialized Construction Council, ICC) participated.

KEYWORDS

Industrialized construction, standardization, modular coordination, preassembly.

INTRODUCTION

The construction industry has low productivity rates, with 40% less real gross value added per hour worked than the manufacturing industry (McKinsey & Company, 2017). This low performance has been associated with craft production logic, low specialization, precarious working conditions, and high impact of labor (Escrig Pérez, 2010).

Industrialized construction (IC) is a production process characterized as systematic, controlled, and standardized, oriented to constructing well-defined systems (Lessing, 2015). IC has been associated with greater efficiency, related variability reduction (Wangwe et al., 2014), continuity of material and information flows (Vrijhoef, 2016), constructability, and control over work environments (Jaillon & Poon, 2009). However, IC presents an incipient level of adoption and implementation (Lundberg et al., 2019).

A paucity of studies specifically address methodologies oriented to the systemic application of industrialization strategies from the early stages (Mohamad et al., 2014). Because of the above, the decision to use these is often not made early enough in the

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construction design process, and conventional designs have to be adapted later (Aldridge et al., 2001). Furthermore, these decisions are not based on rigorous data but on anecdotal evidence (Pasquire & Gibb, 2002).

The paper presents a theoretical model developed to allow design teams to identify construction systems whose standardization, modular coordination, and preassembly have more potential to improve project performance as support for decision-making associated with industrialization efforts.

CONCEPTUAL APPROACH

STANDARDIZATION

Standardization (ST) has been a concept used in the construction industry at different scales: standards of materials and processes, particular specifications of a client related to standard items or processes, standard products or produced with standard components and processes, and use of standard components or procedures in a particular project (Gibb, 1999). For the purposes of this research, it was taken to be the extensive use of components, methods, or processes in which there are regularity, repetition, and background of successful practice and predictability (Gibb, 2001).

MODULAR COORDINATION

Modular Coordination (MC) is a measurement standard for elements of construction systems (Yunus et al., 2016) to coordinate the dimensions and spaces of the building and its components as multiples of a basic unit or basic module. The implementation of the MC concept in component design can improve the total constructability of the construction project (Zainol et al., 2013). Likewise, MC contributes to optimizing materials and elements by eliminating waste in terms of variability options and margins of error of the products and enabling them to be assembled without cuts or with the least of them (Banihashemi et al., 2018).

PREASSEMBLY

Preassembly (PA) has been related to changing the industry's mentality (Aapaoja & Haapasalo, 2014). It refers to how different materials and components are joined in another place from the subsequent install following (Qi et al., 2021). So a substantial part of the work part of the final assembly work is completed before installation in its final position (Pasquire & Gibb, 2002). It transforms the fragmented linear construction of buildings based on the installation site into integrated manufacturing and assembly of value-added factory-made building components (Wuni et al., 2020). It is related to benefits in time, cost, and quality, associated with economies of scale, increased productivity (Xue et al., 2018), greater workflow continuity, reduced number of contractors on site, and shorter construction time (Hwang et al., 2018).

RESEARCH METHOD

The proposed model was developed through an action-oriented framework based on the action research methodology. This actively drives change in real contexts through action (Davison et al., 2004). The framework consists of cycles of action and reflection, carried out in a collaborative workgroup comprised of representatives from the Research Group, the cohesive entity of the construction sector (Industrialized Construction Council), and representatives of construction companies. The framework has four phases: Pre-Action phase, Action planning phase, Action implementation phase, and Learning phase. These and their associated activities are presented in Figure 1.

The Pre-Action phase seeks to build a knowledge base and identify the challenges and the specific need. In the diagnosis is desired to identify the problem that the action will address and understand the current context (Staron, 2020). The referencing consists of a literature review in scientific databases and a review of the state of practice in the local context, oriented to decision support methods associated with selecting processes to industrialize. In the Action planning phase, the collaborative working group established the objectives of the action, its scope, terms of the industrialization concepts to be integrated, and the way to evaluate the goals. In the Action implementing phase, the specific action is carried out: developing a theoretical model to allow design teams to identify construction systems whose standardization, modular coordination, and preassembly have more potential to improve project performance. The learning phase is a moment of reflection on the previous action research cycle. Following the cyclical process model, a decision is made on whether additional cycles are needed (Davison et al., 2004), and future implementation actions are defined.

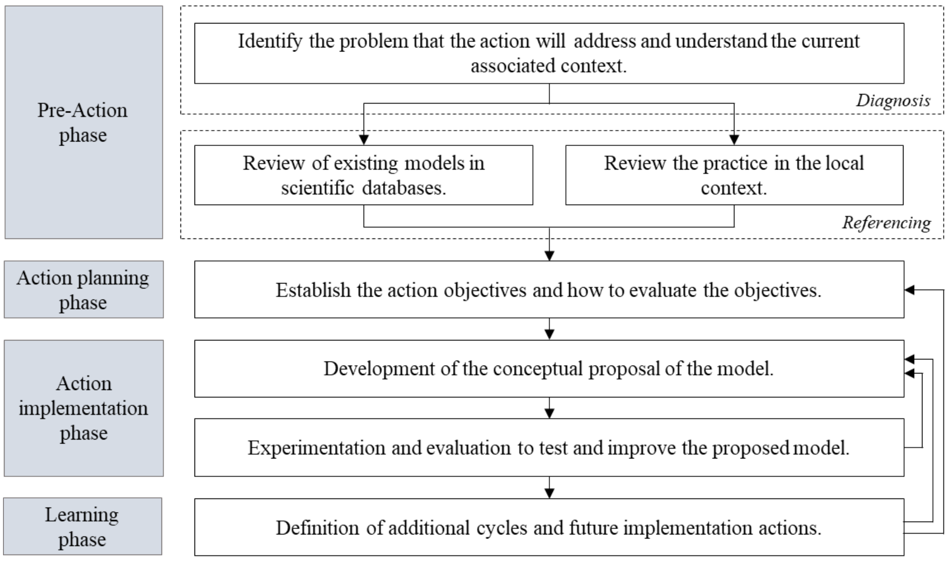

Figure 1. Action-oriented framework

INDUSTRIALIZATION POTENTIAL ANALYSIS METHOD (IPA)

INTEGRATED INDUSTRIALIZATION STRATEGIES

The theoretical model developed integrated the following industrialization strategies:

- *Standardization (ST):* Project standardization was integrated into the developed model from the scope of standardization of components typologies.
- *Modular coordination (MC):* It was integrated based on the basic module, known as M, which is equal to 100 mm (Noor et al., 2018) and can be defined in n*M, resulting in several modules.
- *Preassembly (PA):* Preassembly was integrated based on the degree of integration proposed by (Gibb, 1999): *(i)* component manufacturing and sub-assembly, where components that integrate various materials are manufactured and assembled in one place, *(ii)* Nonvolumetric preassembly, where the preassembled units do not create a usable space, *(iii)* Volumetric preassembly, where the assembled elements

enclose usable space, and *(iv)* Modular Building, where the volumetric units, in addition to enclosing the useful space, themselves form the building.

POTENTIAL ANALYSIS PROPOSED

IPA is based on two temporary approaches: past experiences and present conditions, and six lines of approach: previous implementations, project performance, relevance characteristics, implementation feasibility, factors, and contribution measures. These and their associated analysis elements are presented in Figure 2.

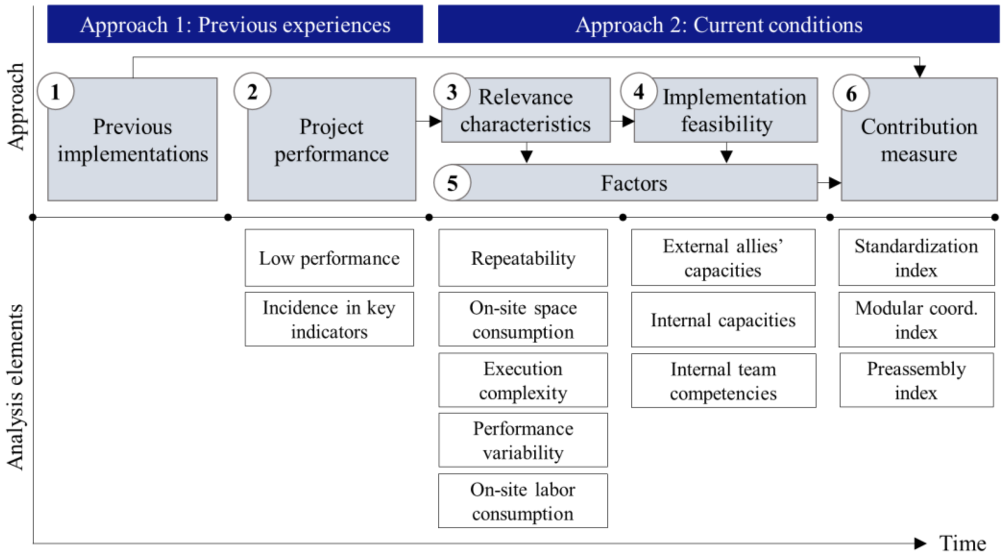

Figure 2. Potential analysis proposed

PREVIOUS EXPERIENCES

Step 1: Previous implementations

Construction systems are selected based on reviewing previous implementations, both successful and those with identified elements to improve. These systems are related to specific industrialization strategies implementations, are pre-selected, and directly go to step 6: contribution measure.

Step 2: Projects performance

Construction systems are selected based on performance analyses of previous similar projects. The analysis must be oriented toward the identification of *(i)* construction systems with the most significant incidence in indicators of interest specific to the current project; and *(ii)* low-performance construction systems in previous projects. Since these systems are selected for their weaknesses but are not linked to implementing a specific industrialization strategy, they must go to steps 3 and 4 to analyze those in the function of the type of intervention.

CURRENT CONDITIONS

Step 3: Relevance characteristics

Pre-selected systems from step 2 are analyzed based on the potential associated with the following characteristics:

- **Repeatability (R)**: Number of times a specific process must be carried out.

- **On-site space consumption (SC):** Total on-site space required for execution or installation, storage, and transportation of elements/materials related to the system.
- **Execution complexity (EC):** It is defined in two terms: Variety, which is related to the diversity of components or variants of the system (Tommelein, 2006), and Connectivity, which corresponds to interdependence with other project systems (Weber, 2005)
- **Performance variability (PV)**: Disparity of results associated with key performance indicators of the different executions of the system.
- **On-site labor consumption (LC):** It is defined in two terms: labor intensity, which refers to the total person-hours associated with carrying out the execution, and density in front of work, which refers to the number of workers concentrated simultaneously in front of work (person/m^2).

The project team must evaluate each of the relevance characteristics. According to the evaluation scale, the score is the value between 0 and 1, assigned to Affectation Elements. The Relevance Characteristic Factor is the average of scores from respective Affectation Elements (Figure 3).

	Affectation elements	Score: 0	0.25	0.50	0.75	1	Relevance Characteristics Factors
R	Repetitions (R_1)	$R<5$	$5\leq R<10$	$10\leq R<20$	$20\leq R<30$	$R\geq 30$	$\mathbf{R}f = \text{Score}(R_1)$
SC	Space consumption (SC_1)	Very low	Low	Average	High	Very high	$\mathbf{SC}f = \text{Score}(SC_1)$
EC	Variety (EC_1)	Very low	Low	Average	High	Very high	$\mathbf{EC}f = \frac{1}{2} * \sum_{i=1}^{2} Score\ (EC_i)$
	Connectivity (EC_2)	Very low	Low	Average	High	Very high	
PV	Cost variability (PV_1)	Very low	Low	Average	High	Very high	$\mathbf{PV}f = \frac{1}{3} * \sum_{i=1}^{3} Score\ (PV_i)$
	Time variability (PV_2)	Very low	Low	Average	High	Very high	
	Quality variability (PV_3)	Very low	Low	Average	High	Very high	
LC	Intensity (LC_1)	Very low	Low	Average	High	Very high	$\mathbf{LC}f = \frac{1}{2} * \sum_{i=1}^{2} Score\ (LC_i)$
	Density (LC_2)	Very low	Low	Average	High	Very high	

Evaluation scale

Figure 3. Relevance characteristics factors

Step 4: Implementation feasibility

Pre-selected systems from step 2 are analyzed based on the feasibility of implementing industrialization strategies, integrating the analysis of:

- **External allies' capacities (EA):** External support, in the local context, is necessary for the implementation in terms of the offer of existing solutions, supplier production capacity, and availability of transportation methods.
- **Internal capacities (IC):** Internal support needed for implementation in terms of production capacity, financing capacity, and on-site space availability for execution or installation, storage, internal transportation, and lifting.
- **Internal team competencies (TC):** Internal support for implementation in terms of project team competencies and a skilled workforce.

The project team must evaluate each of the feasibility elements. According to the evaluation scale, the score is the value between 0 and 1, assigned to Affectation Elements.

The Feasibility Elements Factor is the average of scores from respective Affectation Elements (Figure 4).

	Affectation elements	Score 0	0.25	0.50	0.75	1	Feasibility Elements Factors
EA	Existing solutions (EA_1)	Very low	Low	Average	High	Very high	$EAf = \frac{1}{3} * \sum_{i=1}^{3} Score\ (EA_i)$
	Supplier capacity (EA_2)	Very low	Low	Average	High	Very high	
	Transp. availability (EA_3)	Very low	Low	Average	High	Very high	
IC	Production capacity (IC_2)	Very low	Low	Average	High	Very high	$ICf = \frac{1}{3} * \sum_{i=1}^{3} Score\ (IC_i)$
	Financing capacity (IC_2)	Very low	Low	Average	High	Very high	
	Space availability (IC_3)	Very low	Low	Average	High	Very high	
TC	Team competences (TC_1)	Very low	Low	Average	High	Very high	$TCf = \frac{1}{2} * \sum_{i=1}^{2} Score\ (TC_i)$
	Skilled workforce (TC_2)	Very low	Low	Average	High	Very high	

Evaluation scale

Figure 4. Feasibility elements factors

Step 5: Factors of Standardization, Modular coordination, and Preassembly

The potential associated with the relevance characteristics and implementation feasibility emerge based on their relationship with integrated industrialization strategies; that is, the type of implementation in which each characteristic acquires more significant importance.

The collaborative workgroup established the relationship between relevance characteristics and the analysis elements linked to the implementation feasibility. According to this relationship, the factors of each industrialization strategy, that is, the Standardization factor (*STf*), Modular coordination factors (*MDf*), and Preassembly factor (*PAf*), are calculated as the media of the factors of the characteristics/elements with which is related, as presented in Table 1.

Table 1. Factors of Standardization, Modular coordination, and Preassembly

Characteristics/ Elements	Standardization	Modular Coord.	Preassembly
Repeatability	$ST_1=Rf$	$MD_1=Rf$	$PA_1=Rf$
On-site space consumption			$PA_2=SCf$
Execution complexity	$ST_2=ECf$	$MD_2=ECf$	$PA_3=ECf$
Performance variability	$ST_3=PVf$		$PA_4=PVf$
On-site labor consumption			$PA_5=LCf$
External allies' capacities			$PA_6=EAf$
Internal capacities	$ST_4=ICf$	$MD_3=ICf$	$PA_7=ICf$
Internal team competencies	$ST_5=TCf$	$MD_4=TCf$	$PA_8=TCf$
	$STf = \frac{\sum_1^5 (ST_i)}{5}$	$MDf = \frac{\sum_1^4 (MD_i)}{4}$	$PAf = \frac{\sum_1^8 (PA_i)}{8}$

Step 6: Contribution Measure

The measure of the contribution to implementing the industrialization strategies on each pre-selected construction system is related to *System Weighting* (Sw), the specific weight of the evaluated system in the project. For the present research, Sw is calculated based on the cost because construction companies use it in their usual practices to measure systems incidence. According to the above, Sw is defined by the equation (1).

$$\text{Sw} = \frac{System\ cost}{Project\ \text{direct}\ cost} \tag{1}$$

The contribution of each pre-selected system is given in terms of the type of intervention (step 5). For construction systems related to standardization, the contribution measure is labeled as *System Standardization Index* (*SSTi*) and it is defined by the typological variability in the system.

$$SSTi = \text{TV}f * \text{Sw} \tag{2}$$

where:
TVf = Typological variability factor

If the Number of types = 1, then, TVf= 1; else, if, Number of types > 1, then,

$$\text{TV}f = \left(\frac{1}{\text{Number of types}}\right) * (1 + Rf) \tag{3}$$

For construction systems related to modular coordination, the contribution measure is labeled as *System Modular Coordination Index* (*SMCi*) and it is defined by the concentration of modular dimensions in the system.

$$\text{SMC}i = \text{MD}f * \text{Sw} \tag{4}$$

where:
MDf = Modular dimensions factor

$$\text{MD}f = \frac{\text{MD}}{\text{TD}} \tag{5}$$

where:
MD = Number of dimensions that adjust to the basic module or multiples.
TD = Total number of dimensions in the evaluated system.

For construction systems related to Preassembly, the contribution measure is labeled as *System Preassembly Index* (*SPAi*) and it is defined by the preassembly intensity of the system.

$$\text{SPA}i = \text{PA}f * \text{Sw} \tag{6}$$

where:
PAf = Preassembly factor: Intensity of the preassembly type of the evaluated system, according to Table 2.

Table 2. Preassembly factor according to the preassembly type

Level	Type	PA*f*
Level 1	Preassembled components and subassemblies	0.2
Level 2	Nonvolumetric preassembly	0.6
Level 3	Volumetric preassembly	0.8
Level 4	Modular Building	1

THE FRAMEWORK OF THE PROPOSED METHOD

The presented model is not oriented to the measurement of the general industrialization of a project but rather to the analysis of the potential of a construction system, in terms of the impact of its industrialization, on the general performance of the project. According to above, this is a method of comparative analysis in which the values resulting from the measurement of an individual system must be interpreted in reference to the values resulting from the evaluation of other systems.

The framework of the proposed method is presented in Figure 5.

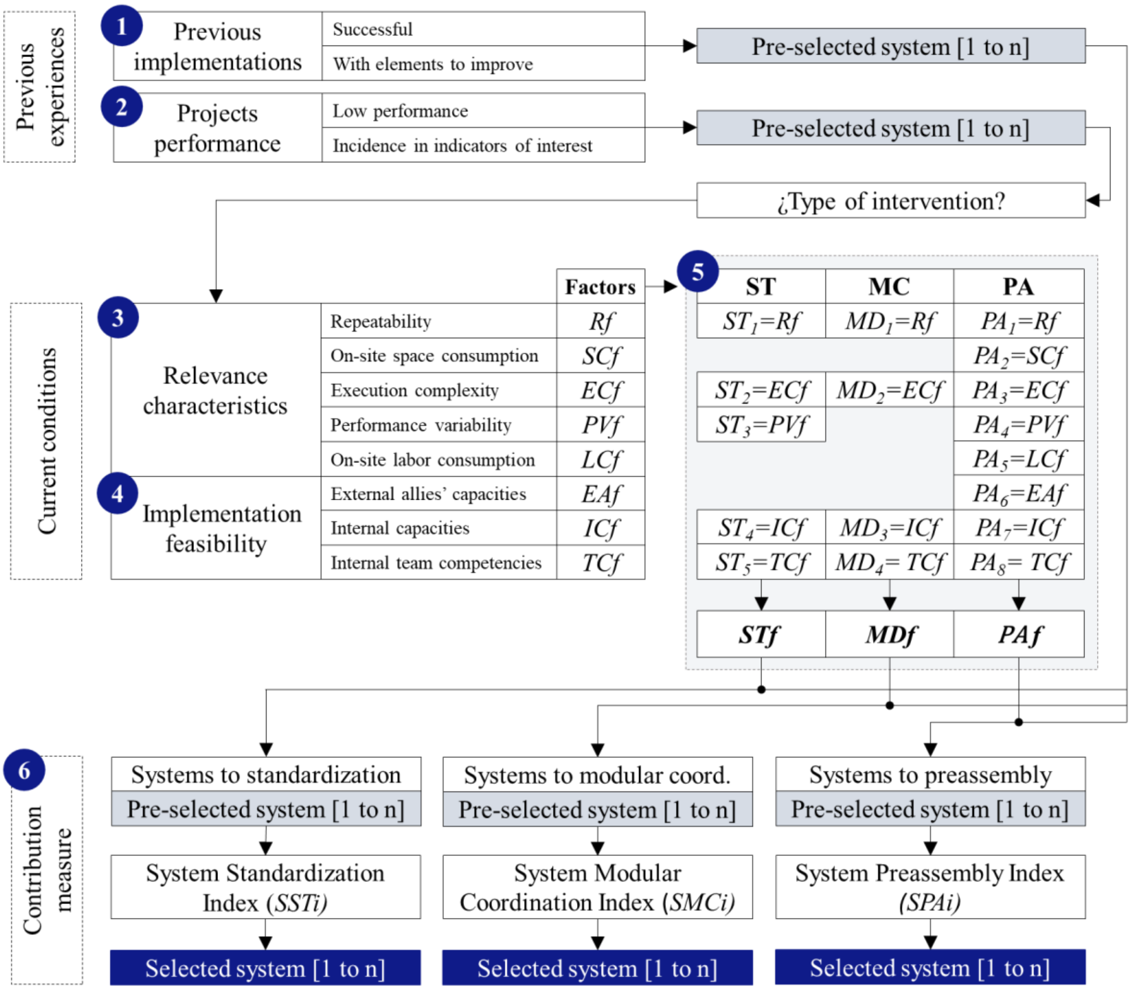

Figure 5. The framework of the proposed method

APPLICATION EXAMPLE

To illustrate how the model is implemented, its application in evaluating the window system of a specific project is presented below. Regarding said illustration, it is opportune to give the following clarifications: *(i)* Its scope is limited to illustrating the evaluation process of a system. It does not integrate the comparative analysis associated with the referencing among systems oriented to selecting the specific systems to intervene, based on their potential impact on project performance. *(ii)* Steps 1 and 2 of the method associated with Approach 1: Previous Experiences were not included in the illustration. Only Approach 2: Current Conditions is included, which is directly related to the proposed metrics, whose application is intended to provide clarity. (iii) Contribution measures are presented in two scenarios: actual and hypothetical—the hypothetical scenario results from the inclusion of changes in the evaluated system related to the industrialization strategies.

Window system information is presented in Table 3:

Table 3. Windows system information

Type	Quantity (un)	Dimension (m) X	Dimension (m) Y	Location	Specification
W1	103	0.8	1.5	Bedroom 1,2,3a	Fixed/sliding panel; clear
W1A	10	0.8	1.5	Bedroom 3b	Fixed panel; opaque
W2	28	0.8	1.5	Kitchen	Aluminium shutter + fixed/sliding panel; clear
W2A	9	0.8	1.5	Kitchen	Projecting panel in aluminum shutter; clear
W3	37	0.55	0.6	Bathroom	Aluminum shutter + fixed/sliding panel; opaque
W4	1	0.8	0.6	Garbage room	Fixed panel in aluminum shutter
W5	3	2.8	1.5	Living room	Two fixed and one sliding panel; clear
W6	1	0.8	0.3	Technical room	Fixed panel in aluminum shutter
W7	8	0.15	0.6	Electric shaft	Fixed panel in aluminum shutter
GD1	35	2.8	2.4	Living room	Two fixed and one sliding panel; clear

According to the above information and specific conditions of the project, the collaborative workgroup evaluated the Relevance characteristics and the Implementation feasibility factors (steps 3 and 4). Based on this, Standardization, Modular coordination, and Preassembly factors were calculated (step 5) (Figure 6).

		Affectation elements	Score	Factors	ST	MD	PA
Relevance Characteristics	R	Repetitions (R_1)	1	$Rf = 1$	1	1	1
	SC	Space consumption (SC_1)	0.75	$SCf = 0.75$			0.75
	EC	Variety (EC_1)	0.75	$ECf = 0.50$	0.50	0.50	0.50
		Connectivity (EC_2)	0.25				
	PV	Cost variability (PV_1)	0.75	$PVf = 0.58$	0.58		0.58
		Time variability (PV_2)	0.50				
		Quality variability (PV_3)	0.50				
	LC	Intensity (LC_1)	0.75	$LCf = 0.75$			0.75
		Density (LC_2)	0.75				
Feasibility Elements	EA	Existing solutions (EA_1)	0.75	$EAf = 0.92$			0.92
		Supplier capacity (EA_2)	1				
		Transp. availability (EA_3)	1				
	IC	Production capacity (IC_2)	0.75	$ICf = 0.92$	0.92	0.92	0.92
		Financing capacity (IC_2)	1				
		Space availability (IC_3)	1				
	TC	Team competencies (TC_1)	1	$TCf = 0.87$	0.87	0.87	0.87
		Skilled workforce (TC_2)	0.75				
					$STf = 0.77$	$MDf = 0.82$	$PAf = 0.79$

Figure 6. Relevance characteristics and implementation feasibility evaluation

Contribution Measure (step 6)

Contribution measures are presented in two scenarios: real and hypothetical. The hypothetical scenario is the result of the inclusion of three changes: *(i)* reducing the number of window types from 10 to 4, *(ii)* passing the means on the X-axis of W3 and W7 to the upper multiple of the closest module, and *(iii)* moving from level 1 to level 2 of the preassembly, starting from proposing nonvolumetric preassembly, with the previous assembly of the wall-window interaction.

The results of the calculations associated with the indexes of system standardization, modular coordination, and preassembly are presented in figure 7. The project's direct cost is USD 275,445.79, and the windows system's cost is USD 19,446.73. Based on these values, the System Weighting (Sw) was calculated.

		Scenario	
	Affectation elements	**Actual**	**Hypothetical**
SW	Window System Weighting (*Sw*)	0.071	0.071
ST	Number of types	10	4
	Repeatability factor (*Rf*)	1	1
	Typological variability factor (*TVf*)	0.2	0.5
	System Standardization Index (*SSTi*)	0.014	0.036
MD	Total dimensions (*TD*)	470	470
	Modular dimensions (*MD*)	425	470
	Modular dimensions factor (*MDf*)	0.904	1
	System Modular Coordination Index (*SMCi*)	0.0642	0.071
PA	Preassembly factor (*PAf*)	0.2	0.6
	System Preassembly Index (*SPAi*)	0.014	0.043

Figure 7. Contribution measure

CONCLUSIONS

IPA provides concise data regarding two scales. *(i)* The state of the construction system, that is, the level of standardization, modular coordination, and preassembly of the system: Typological variability factor (*TVf*), Modular dimensions factor (*MDf*), and Preassembly factor (*PAf*). *(ii)* The system's capacity to contribute to the project based on standardization, modular coordination, and preassembly of the System: System Standardization Index (*SSTi*), System Modular Coordination Index (*SMCi*), and System Preassembly Index (*SPAi*).

IPA constitutes a comparative analysis tool. It provides an analysis of a line of different construction systems, from formal measurements and oriented to comparable results. To provide the construction industry with a systemic process that supports decision-making related to industrialization efforts, applicable in the early stages.

Systems weighting (Sw) is calculated based on the cost because construction companies use it in their usual practices to measure systems incidence. However, since a decrease in system cost decreases the system's weight in project direct costs, a desirable reduction (the system cost) would negatively affect the resulting index of *SSTi*, *SMCi*, and *SPAi*. Therefore, Sw must be calculated with the initial system cost, and its calculation must not be updated in improvement iterations. As a future line of work, it is recommended to calculate Sw related to a different variable.

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TOWARDS A CITIZEN CENTERED SMART CITY: INTEGRATING LEAN THINKING AND SOCIAL WELLBEING

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ABSTRACT

Smart Cities have long been viewed from the triple bottom line of the environmental, social, and economic sustainability dimensions paired with an overemphasis on technology adoption. Recently, researchers started to unveil the importance of the social aspect as a core "smartness" indicator on the one hand, and the synergy between "smartness" and lean thinking on the other hand. While lean philosophy aligns well with the sustainability context, it (more importantly) places people at the root of its practices. This paper argues for a Lean Smart City model that elevates the citizens' social wellbeing and places their values at the core of decision-making to establish for a Citizen-Centered Smart City (CCSC). This is achieved through: (1) investigating the Smart City concepts through a thorough literature review, (2) synthesizing a comprehensive list of social wellbeing indices and mapping them with the underlying lean management principle(s) and (3) developing a framework for a CCSC implementation plan. The framework considers citizens' social wellbeing indices as key values in implementing smart city principles.

KEYWORDS

Lean thinking, smart city, collaboration, integration, social sustainability.

INTRODUCTION

The earliest form of human civilization started off thousands of years ago at our ancestors' discovery of agriculture. The new ability to cultivate crops allowed them to give up on hunting and form settlements. The location of these settlements relied on the availability of natural resources such as fertile land and water and the decisions and lifestyles of people were centered around securing basic needs for survival. Later on, people started seeking trade to widen the variety of available resources. As trade, economic activity, and opportunities for education and cultural exchange became more attractive, people started to migrate from traditional rural areas to relocate in busy hubs and urban areas (Sandvick et al., 2021). However, since cities have always been prone to threats by invaders who aimed to take control of their available resources or strategic geographic locations, they have become conventionally designed to protect the economic activities (particularly trading) of their citizens. This would be primarily achieved through securing safe and continuous development and growth for their citizens through pre-emptive architecture designed in ways that would guarantee the systematic flow of both the economic and social activities within their boundaries.

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Post the French revolution in 1789, different cities started to be integrated into one single entity and nation states started to emerge and grow roots. This new system provided an edge for the central states, but cities maintained a degree of autonomy and certain unique privileges (Torpey, 2015). Development, growth, and planning existed significantly not only on the national level, but also on the level of cities. This has been fostered through tailoring national policies to be aligned with the historical ongoing role of different cities, achieved through the adoption of certain administrative systems that provide a margin of freedom for cities (could vary from one country to another) known as decentralization (Shao et al., 2020).

Despite the great evolution that cities witnessed over the course of multiple centuries, the fundamental human needs of safety and security to conduct daily activities remain unchanged (Collins et al., 2021). However, key historic events such as the industrial revolution in the late 18th century, followed by great technological advancements, exacerbated urbanization and cultural shifts, elevating people's expectations in what cities should offer. Upon having their basic needs secured, people started evolving in pursuit of higher standards of living and an elevated set of psychological needs relating to forming and expanding social interactions, experiencing social integration, cooperating towards securing survival and sustenance, achieving a sense of belonging, and contributing back to society.

The concept of Smart Cities started gaining massive popularity in the past decade with the anticipation of an even greater population shift to cities by the year 2050 (Lara et al., 2016). This popularity came along an ever-increasing concern for the environment, whereby Smart Cities are expected to be a solution to sustainability problems in a technologically advanced way (Toli & Murtagh, 2020). Namely, as the world's resources are scarce and limited, cities need to adopt sustainable policies and strategies to be able to cater for the basic demands of the occupants and maintain a solid ground for future growth and development (Collins et al., 2021). Therefore, we find governments either investing or planning to invest in today's cities to transform them into sustainable and technologically oriented spaces.

In order to successfully build, operate, govern, and optimize such arising smart entities, applying lean practices becomes a very appealing proposition. Lean thinking was found to be highly compatible with Smart City principles from economic, social, environmental, and democratic viewpoints, and as such, can serve as guidelines towards achieving and evaluating "*smartness*" (Herscovici, 2018). Lean focuses on creating value systems through *holistic* approaches, while the concept of a smart city could evidently facilitate for such approaches since it hosts networks of interconnected systems operating in real-time through the integration of Information and Communication Technology (ICT). Additionally, Lean aims to abolish traditional organizational hierarchies and "open up the work process" (Hanna, 2007), while Smart Cities require exactly that, wherein systems are ideally decentralized and set to be bottom-up to better engage citizens and consider their needs. Furthermore, a smart city community is potentially most harmonic when its residents share a unified set of values and principles, and lean management proves most effective when it is promoting a "culture" rather than a mere set of tools and techniques. This evident compatibility between the general smart city model and the core of lean thinking shows that pre-established lean principles and practices have promising potentials in delivering Smart City objectives of optimizing processes and elevating the social wellbeing of citizens. Namely, a smart city model, being an aggregation of different public and private institutions operating in different sectors of industry, could benefit from lean thinking as a standardized process applicable across many industries and aiming for excellence and perfection when it comes to delivering value to customers based on their exact definition of it. To this end, this paper promotes lean thinking as one of Smart Cities' fundamental pillars and, as such, presents a framework for an implementation plan to create a lean culture centered around citizens to help elevate their social wellbeing as part of establishing for a Citizen-Centered Smart City (CCSC).

LITERATURE REVIEW

Different studies tackled the concept of smart cities from different angles, however, one prominent and recurring theme among references is related to the vagueness that revolved around defining a smart city (Lara et al., 2016 & Özdemir et al., 2019), and the lack of a commonly agreed upon definition (Bouzguenda et al., 2019). While most of the definitions found in the literature revolve around the intensive use of ICT, a more comprehensive human-centered characterization of smart cities emphasizing on the importance of the social dimension and placing people at the heart of smart cities (Lara et al. 2016) emerged. For instance, Toli & Murtagh (2020) reveal that the most prevalent sustainability definition of smart cities includes the focus on the social dimension as opposed to the economic or environmental dimensions. An environmentally Smart City is viewed as a city that implements systems to optimize processes (by levelling resources, recycling, creating waste plans, and utilizing renewable energy) and reduces carbon footprint (by decreasing emissions through the infrastructure and buildings constructed); which in turn enhances the quality of life (QoL) of its residents (Collins et al., 2021). A socially Smart City has "a high level of citizen engagement and participation aimed at improving the well-being quality of life of its citizens" (Collins et al., 2021).

All these definitions share the common objective of placing people at the heart of Smart Cities by (1) enabling them to participate and take empowering actions and (2) focusing on elevating their social wellbeing and QoL. Leveraging the role of citizens in the Smart City (primarily by creating interlinks between all citizens and other private and public institutions) becomes essential not only for the sake of achieving social wellbeing but also to create a sustainable Smart City which self-generates solutions (Trencher, 2019). It is critical to understand that focusing on the social dimension in smart cities is not intended to undermine the economic, environmental, or technological dimensions. Rather, by doing so, cities will directly and indirectly contribute positively to developments in all other sustainability dimensions. Moreover, people often mistake social smartness with citizen-centered smart cities; the two do not map each other. Social smartness reflects the concept of having individuals that are technologically educated and aware yet does not necessarily imply high levels of community engagement in significant processes (Bouzguenda et al., 2019).

Quality of life, wellbeing, satisfaction, and happiness in urban contexts are interchangeably used terms that refer to the common and consistent objectives that people seek across cultures with some subjective discrepancies attributed to a specific culture or circumstance. The foundation of this paper is based on that the core of Smart Cities should no longer be about the integration of disruptive technology without the proper evaluation and consideration of whether people derive a sort of value from the use of the technology. What's almost certain is that the universal goal that humans seek in urban and social contexts is happiness and the elevation of their social wellbeing and quality of life. The first underlying assumption is that almost all people have similar preferences when it comes to defining a good QoL. Even though there are no clear and common key performance indicators (KPI)s identified in relation to QoL and social wellbeing in smart cities, there is a good record of indices which identify some key factors related to objective and subjective social wellbeing. Daniel Kahneman, economics Nobel prize winner, argues that subjective factors are more predictive of happiness and social wellbeing (Lara et al., 2016), as such, it is essential that both objective and subjective indices are equally considered by smart city initiatives.

On the one hand, despite that Smart City definitions and proposed frameworks reveal a good awareness about the importance of social sustainability and wellbeing, Smart City initiatives seem to lag behind on implementing social agendas related to improving citizen livelihood as they are faced with immense difficulty predicting and deciding what promotes and elevates people's objective as well as subjective social wellbeing. This is due to current literature lacking in the proposing of a unified framework that outlines what a quality life encompasses to citizens, and how it can be achieved in an urban context (Toli & Murtagh, 2020). On the other hand, the literature review reveals that lean thinking can be used to assess the performance of smart cities and outlines key principles that can be used in developing practical management strategies for accomplishing smart city objectives. Lean management contributes positively to all three triple bottom line sustainability; however, results indicate that the wider body of knowledge is focused on the economic dimensions of lean and calls researchers to investigate further into the social and environmental dimensions, emphasizing that the social dimension is the most difficult to quantify (Solaimani & Sedighi, 2020).

When it comes to defining specific services expected to be delivered by Smart Cities and indicators to achieving elevated QoL, followed by measuring and assessing the "smartness" of a smart city, experts may find themselves facing a "wicked problem". Whelton & Ballard (2002) define a wicked problem as one that poses itself as ill-structured or ill-defined, has multiple objectives, and is viewed differently from the perspective of different stakeholders due to the complexities and uncertainties present in it. In reference to this, it is safe to consider many aspects of a smart city as wicked problems due to (1) the limited and fragmented implementation of smart city services, (2) their innate socio-economic and socio-technical complexities, and (3) the stakeholders' and policy (and decision) makers' uncertainty towards smart city objectives and initiatives. However, based on the propositions made by Whelton & Ballard (2002), acknowledging the nature of problems, identifying decision agents, involving key stakeholders, understanding diverse interests, empowering users to make decisions, adopting an interconnected process view, and seeking critical and reflective feedback may help planners and decision makers pave their way towards more defined solutions.

In the case of Smart Cities, constant criticisms have been directed towards initiatives which intend to install technology based on top-down approaches, making governments and corporations the primary beneficiaries. Alternatively, administrators could better devise technology and the power of Big Data to collect information about residents for the purpose of better understanding their needs and delivering services accordingly. Such approaches could address aspects of smart cities (i.e., social sustainability) from a wicked problem perspective by identifying key users (citizens) and key agents (government authorities and private institutions), attempting to understand and fulfil citizens' interests (i.e., needs and objectives), and empowering citizens to participate in the decision-making process. That said, and as part of resolving the Smart City "problem", this study aims to establish for a Citizen-Centered Smart City (CCSC) that elevates the citizens' social wellbeing and places their values at the core of decision-making with the help of lean thinking and management.

METHODOLOGY

The methodology of work includes three main stages. First, a thorough literature review is performed to extract the various social wellbeing indicators on the one hand, and the various lean principles and practices that addressed social wellbeing on the other hand. Then, the extracted indicators were synthesized and categorized into "objective" and "subjective" indices according to their social wellbeing category. The former includes the indices that are generally applicable to a good portion of the population and in different cultures, whereas the latter includes the indices that require deeper understanding and analysis in relation to each individual and every culture. The result of this stage is a comprehensive list of social wellbeing indices, each brought in parallel with the underlying lean management principle(s) and defined (as such) from a lean thinking perspective. Finally, a framework for a CCSC implementation plan is presented. The suggested framework (1) considers devising questionnaires to address both subjective and objective categories of the indices based on the presented definitions and (2) calls key agents or decision makers to answer to these indices through suitable policies and services. The following sections elaborate on each of those stages.

SOCIAL WELLBEING INDICES

A synthesis of the social wellbeing indices related to social sustainability in cities retrieved from the reviewed literature is displayed in Table 1. The indices are categorized into Objective and subjective indices according to their social wellbeing category. Namely, the "Material", "Physiological", "Human Capital", "Environment", and "Governance" wellbeing categories are regarded as objective since they are generally applicable to a good portion of the population and in different cultures. "Psychological", "Work", and "Community" wellbeing categories are regarded as subjective since they require deeper understanding and analysis in relation to each individual and every culture. The categories, their corresponding indices, and the underlying lean principle(s) are explained in the following subsections.

OBJECTIVE WELLBEING

Material

Income and financial security are indices relating to material wellbeing and have been continuously proven to have a positive relationship with social wellbeing even though the exact value of these varies based on citizens' subjective needs and standards of living (work "compensation" implies the same and is listed under subjective indices). Lean practitioners are aware of this as they pay their employees relatively high wages while remaining efficient, reliable, and competitive. Pay scales are thoroughly studied and workers are paid well and offered job security. Furthermore, in reference to Toyota's practices (as a Lean founder), workers are rewarded through semi-annual bonuses based on the performance of the entire company which is also ensured through unmatched optimization practices (Liker, 2005).

Physiological

Physiological wellbeing is related to maintaining physical health as well as basic underlying psychological health. It includes relief from mental and physical stress, freedom, mobility, a sense of safety and security, and the fulfilment of basic needs and wants. Taiichi Ohno, founder of Lean, emphasizes that safety is at the core of any lean activity. These are ensured through training and improved work conditions paired with methodologies that protect workers' health and reduce accidents. Visualization (includes visual management and control) is a practice that ensures safety as it reveals hidden problems in a clear and concise manner. *Jidoka* (equipment autonomation) and *andon systems* (manually operated cords or buttons that halt entire production line) are also key to ensuring safety and are paired with workers' empowerment to monitor and use these anytime an abnormality is detected. Stress is relieved through fair practices, fatigue policies, and balance of workload as the elimination of *Muri* (overburdening of people) suggests. When it comes to the fulfilment of needs and wants, both internal and external customers are considered in Lean and are focused on to be offered exactly what they want, when they want it, with the desired quality and price.

Human Capital

Lean management is keen about encouraging, challenging, and investing in its people to unleash their creativity; allowing them to take initiatives, learn, and experiment continuously. This is emphasized through the *5S* (sort, stabilize, shine, standardize, sustain) waste elimination methodology, in which the *S* in *sustain* is core and is achieved through educating, training, and rewarding employees. When it comes to empowering people, *standardization* in Lean allows work standards to be specific enough to guide employees, yet flexible enough to allow for improvement, innovation, and growth. In addition, lean philosophy, based on Toyota practices, seeks to hire internal and external mentors (*sensei*), to educate and transform by doing, and promote an intrinsic lean culture willing to self-sustain and grow.

Governance

Participatory governance is a democratic system frequently highlighted as key to establishing for a citizen-centered city whereby citizens are engaged in the decision-making process as part of increasing their political and social participation. Participatory governance requires that authorities are honest, competent, transparent, trustworthy, and open to different views. Lean management seems to understand this as it reflects commitment to *consensus decision making* (*nemawashi*), engaging all stakeholders, considering their different views, and weighing all pros and cons before taking any decision as part of avoiding *backtracking*. Lean promotes *nemawashi* to be part of the organizational culture across all managerial levels and project life cycles. On a community level, Toyota documents one of its successes in extending its consensus decision making process and reaching a *win-win* agreement for all parties in an external development project that was taking place near its Arizona base, threatening the long-term water supply for the surrounding community (Liker, 2005). Cross-sectorial partnerships is mirrored in Lean practices through *cross-functional teams* who solve problems collaboratively through a unified vision that prioritizes the company's best interest.

SUBJECTIVE WELLBEING

Psychological

Psychological health has been argued by many physicians to be as important as physical health. It is related to a person's sense of pleasure, achievement or accomplishment, and purpose. Often times it is achieved through work-life balances and can be better understood by considering a person's emotional intelligence (emotional regulation and problem-solving abilities), motivation, and self-efficacy. In Lean, practitioners realize the importance of securing their employees' psychological wellbeing and 'work by the book' by referring to Abraham Maslow's hierarchy of needs, Frederick Herzberg's theories of motivation, and Taylor's scientific management, behavior modification, and goal setting; all these achieve intrinsic motivation by improving work conditions and fostering for continuous personal growth and improvement. Additionally, a core pillar that lean principles abide with, is the respect for people through valuing their mental and physical capabilities and entrenches mutual respect and trust among internal and external stakeholders.

Work

Productivity, autonomy, and fair compensations are important indicators of social wellbeing experienced at work. The Toyota Production System (TPS) on which Lean thinking is based, is considered a master at achieving the highest levels of productivity and getting the best out of their employees. This is done by constantly redesigning and enriching jobs through job rotation and feedback loops, challenging employees granting them a degree of autonomy, and helping them become proactive problem solvers. Accordingly, employees are rewarded both financially and non-financially and placed in a safe and healthy working environment.

Community

A community which contributes for an elevated social wellbeing is one that nurtures for the prosperity of different people through incorporating similar values. According to Maslow's hierarchy on needs, social belonging is essential, so, in reference to this, Lean strives to build a culture of consistent principles and approaches to be firmly adopted by all teams. Achieving this is possible by fostering for diversity through fair and equal social opportunities, training and building people towards becoming exceptional leaders and team players who dedicate their energy into bettering the organization as a whole. Mutual trust and respect are further emphasized as the backbones of collaboration and teambuilding.

Table 1: Synthesis of Social Wellbeing Indices and Lean Management Principles and Practices

Description	Social Wellbeing Category	Social Wellbeing Indices*	Lean Management Principles/Practices**
Objective Wellbeing	Material	Income [1]	Equal Renumeration [6]
		Financial Security [2]	
	Physiological	Health [1,2]	Occupational Health & Safety [6]
		Mobility [1,2]	Ergonomic Workstations Design Standards [6]
		Freedom [1,4]	Autonomation [8]
		Safety & Security [2]	Decrease working accidents [7]
		Fulfilment of Needs & Wants [1,5]	Fostering Customers' Macro Necessities [8]
			Visualization & Self-Management [8]
			Balance Between Workload & Labor [8]
	Human Capital	Education [1,2]	Education [6]
		Qualification [3]	Coaching [6,8]
		Empowerment [3,5]	Empowerment [7,8]
		Digital Engagement [4]	
	Environment	Access to Nature [2]	
		Reduced Pollution [2]	
	Governance	Participatory [3]	Employees Participation in Decision-Making [7]
		Competent [2]	Quality Management [8]
		Trustworthy [2]	Fair Labor Practices [8]
		Cross-Sectorial Partnerships [5]	Cross-Functional Teams [8]
			Customer/Client Centricity [8]
Subjective Wellbeing	Psychological	Sense of Purpose [2]	Employees Value & Respect [8]
		Accomplishment [2]	Continuous Improvement Opportunity [8]
		Sense of Leisure [2]	Optimal Working Hours [8]
			Intrinsic Motivation [8]
	Work	Compensation [2]	Improved Working Conditions [7,8]
		Autonomy [2]	Responsible Autonomy [6,8]
		Productivity [2]	Productivity [7,8]
	Community	Civic Participation [4]	Collaborative Learning & Experimentation [8]

	Social Interaction [1,3]	Collaborative Problem Solving [7]
	Sense of Belonging [1,2]	Equal Opportunity [6,8]
	Mutual Trusting [2,5]	Diversity [6]

*[1] Lara et al., (2016), [2] Musikanski et al., (2017), [3] Özdemir et al., (2019), [4] Collins et al., (2021), [5] Kim et al., (2021)

**[6] Resta et al., (2016), [7] Varela et al., (2019), [8] Solaimani & Sedighi, (2020)

SUGGESTED FRAMEWORK

The suggested framework places citizens at the center of processes by creating interlinks between them and the other decision agents as part of ensuring their engagement, as shown in Figure 1. Citizen engagement, established to be core to achieving a CCSC, aligns with the identified social indices namely “digital engagement”, “participatory governance”, and “civic engagement”. According to Herscovici (2018), citizen engagement can be achieved through “Physical Infrastructure” and “Applications Infrastructure”, both focused on the integration of ICT. Application Infrastructure is a software platform used to address “specific needs” through designed apps, whereas the Physical Infrastructure connects people to the internet providing a public virtual space for citizen participation and data exchange (Herscovici, 2018). Of course, as highlighted in the literature review, smart citizens who are technologically educated and aware are required, however, this alone is not sufficient to achieve citizen engagement. Similarly, citizen participation and empowerment cannot be achieved without the facilitating infrastructures. On the other hand, since *specific needs* must be identified in order to feed into the physical and applications infrastructures proposed by Herscovici (2018), the suggested framework in Figure 1 benefits from the previously defined objective and subjective social wellbeing indices to better identify citizens’ preferences. Objective social wellbeing categories (material, physiological, human capital, environment, and governance) and their corresponding social wellbeing indices are demanded by all citizens irrespective of their subjective preferences. Consequently, these are meant to be considered by government authorities and other acting agencies to design and issue questionnaires that would ultimately guide social policies and public initiatives. These might include (1) generating funds to support individual and social initiatives, (2) providing key public facilities such as education and healthcare and other supporting infrastructure, (3) accommodating for work and growth opportunities, (4) providing training to engage and empower citizens, and (5) ensuring public safety and security among other policies which can contribute to reducing social inequality and elevating social wellbeing. The management systems of these public initiatives shall be designed by lean practitioners before they are executed upon as means to ensure their optimization and their success in fulfilling the citizens’ exact perception of value.

Subjective social wellbeing categories (psychological, work, and community) are concerned with citizens’ emotions, personal experiences, and preferences. Identifying these is essential for private institutions to better evaluate and fulfil the citizens’ needs. The same procedure would apply to private institutions wherein they would issue questionnaires and answer to citizens’ subjective social indices and needs by proposing initiatives as well as innovative products and services to further elevate social wellbeing. Prior to executing upon their initiatives, optimized management systems shall be proposed by lean experts.

Besides planning and designing optimized management systems, lean experts and practitioners shall offer government and public institutions, as well as private institutions, adequate training to ensure all processes abide by lean standards. They shall also raise awareness about lean thinking to be integrated daily by providing citizens with well-designed and engaging training programs, such as workshops, competitions, games, and activities.

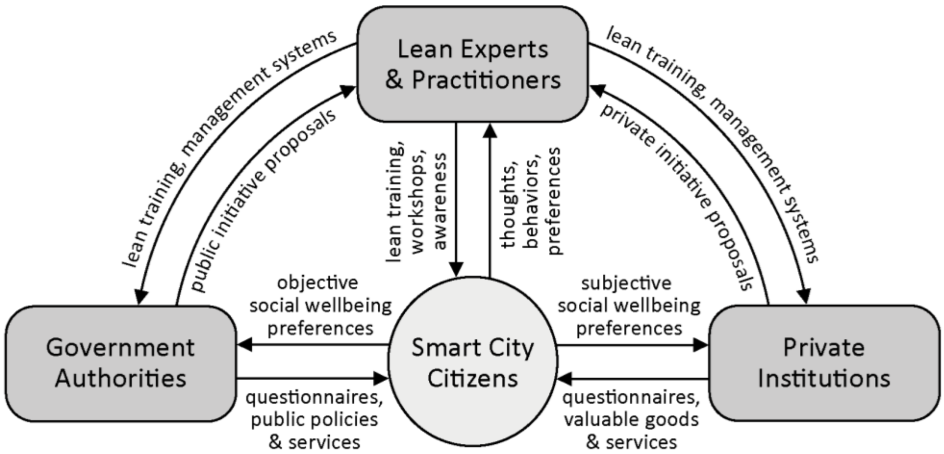

Figure 1: Framework for Citizen Centered Smart Cities (CCSC) implementation plan

Questionnaires are effective research tools which help measure and understand respondents' values, thoughts, behaviors, attitudes, and preferences particularly if properly designed and worded. For this reason, they are fit for understanding citizens' preferences in relation to their social wellbeing and the proposed smart city initiatives. For instance, government authorities who wish to tackle citizens' objective "physiological" need of "mobility", and plan on building a new transportation system for the citizens, could start by collecting data about the method of transportation used by these citizens (e.g., to go to work), the time, cost, and effort required to reach their destinations, their rating of the journey, and the alternative transportation methods of preference. Post collecting all relevant data, government authorities would consult lean experts to develop an optimized user experience through proposed value management systems. Ideally, follow-up questionnaires are continuously issued to citizens to guide relevant decisions and reaffirm the "righteousness" of decisions taken towards the betterment of citizen's day-to-day standards of living. A company concerned for the social wellbeing of its employees and dedicated to ensuring that they are working and living up to their full capabilities (harnessing maximum energy and creativity) may address subjective "psychological", "work", and "community" needs by conducting surveys which help better understand employees interests inside and outside work. Lean experts would come to play in creating systems that would situate people in optimal environments, while better assisting them to fulfil their "sense of purpose" and "accomplishment" and accordingly create customized plans for a better work-life balance.

Value stream mapping (VSM), a key lean methodology used here, is meant to track, and document every activity in the process of delivering value to customers (i.e., citizens) from start to end, eliminating any type of waste they are not willing to pay for. Such methodology makes every activity well studied and deliberate, encouraging planners to innovate and think deeply. From a lean perspective, waste includes any activity which incurs extra cost, time, and effort. Such activities include overproduction, waiting, unnecessary transportation, over processing or incorrect processing, excess inventory, unnecessary movement, and defects (Liker, 2005). If the concept of eliminating waste is extended onto the citizens of the Smart City through the integration of lean thinking and the developing of a lean culture, then waste will be eliminated in all institutions and among all individuals, elevating the city culture, leaving citizens with more time, energy, money, and resources to perform activities that they view core to their satisfaction and wellbeing.

CONCLUSION

This study aims at establishing for a citizen centered smart city (CCSC) through integrating lean thinking and social wellbeing. The literature review stresses on the significance of the social sustainability dimension, but reveals a lack of clear, concise, and universally adopted social indices that could help in evaluating the social smartness of Smart Cities. On the other hand, given the complexity of smart city systems and its proved compatibility with lean thinking, it is only fair to integrate a pre-established mechanism (i.e., lean management principles, tools, and practices) that would help guide and govern its initiatives. Similar to smart cities, lean management has been explored against the triple bottom line of sustainability, however the social facet of lean remained relatively obscure. As a result, this paper focuses on the social dimension of Smart Cities and Lean thinking as part of establishing for a Citizen-Centered Smart City (CCSC). Based on a thorough literature review, a synthesis of social wellbeing indices was generated and mapped along with the underlying lean management principle(s). Such an alignment helps in defining the social wellbeing indices and, more importantly, offers pre-established guidelines to deliver Smart City objectives of optimizing processes and elevating the social wellbeing of its citizens. To this end, this paper suggests lean thinking as a core mechanism for Smart City initiatives and proceeds to present a framework for an implementation plan that would help in creating a lean culture centered around citizens' needs, and as a result, establishing for a Citizen-Centered Smart City (CCSC).

According to lean practitioners, lean practices, tools, and techniques are rendered ineffective if integrated in isolation or randomly. Instead, it is mandatory that lean promoters view the "big picture" and plan thoroughly to integrate all lean practices in 'tightly knit' systems. This concept is key because it emphasizes the importance of promoting and facilitating for the creation of a Lean culture when promoting Lean thinking in Smart Cities. From a proposed smart city perspective, authorities and institutions have a mutual responsibility in becoming Lean promoters and playing the role of human resource managers in creating a city scale lean culture. Lean promoters should 1) respect people and be consistent in placing them at the center of all initiatives, 2) tailor the lean culture around citizens' thoughts and behaviors, 3) build close relationships with citizens and reflect full transparency in policies and practices, 4) leverage on people's trust place and help them realize the mutual communal benefits from adopting lean, 5) set up systems that allow for clear and concise two-way communication, 6) empower citizens to become effective members in the decision making process, 7) train citizens to become continuous lean learners and problem solvers, and 8) recognize efforts and achievements of successful lean adopters.

Unfortunately, it is difficult to achieve a total lean buy-in from all stakeholders particularly on a city scale, because despite lean management proving to be revolutionary across many industries, it entails a radical behavioral change which requires extensive training and experience. Constant efforts are usually placed in communicating both the "why" and the "how" of lean to motivate buy-ins in organizations; however, this is certainly not sufficient on a city scale. Exhaustive studies on behaviorism and different perceptions towards lean must be conducted in order to devise hard core strategies to compel people to shift to lean thinking. Moreover, creative, and interactive training methods must be developed to make the process of learning about lean and adopting it seamless and exciting.

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IDEATION FRAMEWORK IN INDUSTRIALIZED CONSTRUCTION

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ABSTRACT

Currently, industrialized construction (IC) is no longer an option, as it has become a necessity for companies that wish to maintain competitiveness and mitigate the pressures in terms of quality, cost, time, and sustainable performance in the construction sector. However, the way to industrialize effectively is still full of uncertainty; companies do not conceive of the incorporation of IC from the early stages, but they start late in the advanced design or even close to the execution phase, which results in the failure of the adoption of these industrialized systems, because such systems require, as a basic condition, thinking early about its incorporation and developing new design integrated and collaborative practices/knowledge. This paper proposes an Ideation Framework in Industrialized Construction (IFIC) that mainly improves the ideation process of ideas/actions within the IC design phase. The IFIC was developed under the design science research methodology. For the evaluation of this framework, the research was based on four case studies. The main contribution is the creation of two fundamental axes for ideation processes: *(i)* Ideation by self-assessment and *(ii)* Referral Ideation, which allows devising and incorporating industrialized solutions in a reliable way in IC projects.

KEYWORDS

Industrialized construction, DFMA, design science, integration, collaboration.

INTRODUCTION

Industrialization of construction has been seen as a solution to mitigate the low performance in terms of time, cost, and product quality of the architecture, engineering, and construction (AEC) industry (Durdyev & Ismail, 2019; Pikas et al., 2021). In this context, this research has been developed at the request of the Industrialized Construction Council of Chile (CCI) and its member companies. The term industrialized construction (IC) is defined as a system in which components are manufactured in mass production under a controlled environment (on or off-site), transported, positioned, and assembled into a structure with minimal additional site works (Osman et al., 2015), under the logic

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of three key concepts: standardization, modularity, and pre-assembly (CIRIA, 2001). The IC benefits include enhanced productivity and building quality, reduced project execution plan, simplified construction process, mitigation of the lack of skilled labor, less environmental impact by reduction and better control of off-site activities, reduced waste, increased occupational safety and health, and reduced overall cost of construction (Durdyev & Ismail, 2019). However, the evidence in the literature shows that there are still impediments at the level of design which prevent its effective adoption (Jaillon & Poon, 2010; Wuni et al., 2021)

IC design process is a strategic phase for improving performance and achieving all the benefits promised by IC because it is where the project objectives are idealized and constitutes the earliest stage where performance requirements can be controlled in the project life cycle (Bogue, 2012; Boothroyd, 2005). It is widely recognized that the design stage determines around 70% of a product's manufacturing costs (Bogue, 2012) and up to 80% of building operational costs (Bogenstätter, 2000). As a result, early-stage decision-making has an important impact on the design phase of IC projects.

IC design implies developing an interactive process that requires adequate integration and early collaboration between architects, contractors, and manufacturers (Jaillon & Poon, 2010; Pikas et al., 2021). Nevertheless, the fragmented nature of the construction industry and the lack of experience and knowledge regarding its use hinder the effective adoption of IC, resulting in errors in IC design owing to conflicts and omissions of considerations that should have been taken at the beginning of the project (Hyun et al., 2022; Zhai et al., 2014). Furthermore, the current state of industrialized design methods is generally based on the traditional design system, which does not consider practices and processes that meet the requirements of the manufacturing and assembly on-site; and organizations operate separately at different stages of the project, not meeting the integration requirements of IC (Andersson & Lessing, 2017; Yuan et al., 2018). For the mitigation of these challenges, Integrated Project Delivery and Design-Build are delivery methods recommended to be implemented in the context of IC projects (Osman et al., 2015; Wu et al., 2019) due to they promote more collaboration and early involvement of the stakeholders. However, they do not provide an explicit framework to support stakeholders in guiding the design process in IC design.

The design for Manufacturing and Assembly (DfMA) principle is widely considered to support the design process in IC by providing considerations to simplify design, production, and assembly. (Yuan et al., 2018). Despite this, the fragmented results of the previous studies difficult built a comprehensive design process that addresses the challenges of IC (Hyun et al., 2022). Another approach is Design for Excellence (DfX); it constitutes an emerging design concept which is based mainly on the principles of DfMA and is considered an integrated design methodology that provides a broader perspective to IC project design (Wuni et al., 2021). However, the same author points out several limitations to apply DfX, from which it is interpreted that being DfX a holistic approach requires a high degree of knowledge of those who implement it, generating difficulties in identifying the appropriate tools to be used; and an important economic investment for the organization.

In summary, to achieve project requirements in IC, collaboration must be intensified from the early stages (design stage) among the stakeholders (Zhai et al., 2014), the project design must be co-created (Wuni et al., 2021), and the interested parties must be organized through necessary administrative and economic instruments (Wang & Li, 2013).

Most of the research recommends more collaboration, early stakeholder integration, and general consideration to guide the design process in IC projects. Nevertheless, there is a lack of research that has developed and tested approaches that show how to organize stakeholders during the process of ideas generation in IC design, which includes activities/tools tailored to address the core elements of IC and structure them step-by-step. In this way, this paper addresses the research gap by proposing an ideation framework in industrialized construction (IFIC) that works within the design phase as a drive and accelerator in the creation of industrialized solutions, based on early integration and intense collaborative work among architects, contractors, and manufacturers as a prerequisite for the success of its application.

LITERATURE REVIEW

The design process must ultimately pass through three spaces: *(i)* inspiration, *(ii)* ideation, and *(iii)* implementation (Brown, 2008). In this research, the focus is the ideation space which is defined as a process of generating knowledge and ideas to support the development of new solutions applicable to the project (Brown, 2008; Peffers et al., 2007). To understand the start-point and define the scope of the IFIC, a variety of ideation methodologies were explored and analyzed. The following methodologies only are used as a reference to guide the structuration process of the IFIC.

IDEATION METHODOLOGIES

Design thinking (DT). Leads the designer to new ways of thinking and ideas so that they can find optimal designs through breakthroughs in design conceptions, based on understanding the real needs of people and by promoting a collaborative work environment among stakeholders to drive continuous improvement (Lo et al., 2019). In DT, the ideation process must respond to human demands and deliver technically and commercially viable solutions (Brown, 2008).

Deep Dive (DD). Deep dive is a technique that allows to quickly getting into the ecosystem of the problem to be solved, with the intention of having a broad understanding of all the variables involved in it and capturing valuable information that serves to generate solutions focused on the improvement of the service or product under study, considering the real limitations of the environment (Horton-Jones et al., 2019).

Open Innovation (OI). The traditional closed innovation paradigm can-not maintain the companies' competitive advantage in the current conditions of markets, in which technological progress is accelerating, and the conditions of satisfaction are changing rapidly. (Xin & Qian, 2011). The same author states that this condition has led to the creation of a new innovation paradigm called open-innovation, in which the premise is that the company must have the ability to leave its comfort zone to explore and acquire new knowledge and originalities offered by new markets; and combine them with internal assets in terms of capabilities and knowledge to develop new solutions that allow delivery an offer that satisfies the market needs and keeps the company competitive.

Agile Design Management (ADM). It is an adaptation of the scrum approach into the design phase of construction projects with the objective of increasing coordination, interface management, collaboration, integration, and transparency throughout all design phases between multidisciplinary teams (Demir & Theis, 2016). In such manner, from Demir & Theis (2016) study, it can be interpreted that as an agile approach, ADM involves many rapid iterative planning and development cycles, allowing constant evaluation focused on continuous product improvement and embracing changes to meet customers' requirements.

Around the generation of ideas and acceleration of the ideation process, other approaches/tools that fall under the umbrella of the Lean Construction were also studied:

Target value design (TVD). It is a management practice that seeks to make customer constraints drivers of design through intimate collaboration between members of the project team (designers, suppliers, builders), focusing on exploring problems and developing solutions for the sake of continuous improvement, waste reduction, and assurance that customers get what they need (Ballard, 2011). In addition, Ballard (2011) states that implementation of TVD has also consistently resulted in the faster and under budget delivery of projects over market expectations.

A3 report. The A3 report has been widely used in the implementation of lean production to serve as a tool to support the improvement processes, which is based on the PDCA system management method, promoting the interaction and integration of all people and areas involved in the problem or situation to be enhanced (Bordin et al., 2018). Furthermore, the author points out that the A3 report implies a significant questioning of the importance of addressing the problem for the organization and clearly establishing the current context as a basis for defining objectives, conducting a root cause analysis, generating countermeasures, developing an action plan and monitoring and controlling the results.

Figure 1. shows the points of overlap of the methodologies presented above, allowing to understand the fundamental phases prior to the ideation process and the different ways of approaching the process itself.

References Methodology	Identify and formulate the problem		Producing solutions
	Phase 1 Understanding the needs	**Phase 2** Problem definition	**Phase 3** Generation of actions/solutions
	Understand	**Define**	**Ideation**
Design Thinking	Empathize with the user needs to define the problem.		Focus on human demand and Market/Technical feasibility
Deep Dive	Identification of direct and indirect causes through quick immersion in the ecosystem where the undesired situation is generated.		Generate a reliable solution covering the risks and current constraints.
Open Innovation	Adopting "open originality" which means getting out of your comfort zone and accepting different perspectives external or internal		Based on internal and external knowledge to meet market demands and company requirements
ADM	Through user stories		Aimed at satisfying customers by adding value
TVD	Understand and define customer value		
A3 report	Understand the context of the problem by going to the site and establishing a shared vision among all stakeholders.		Actions and Shared solutions based on a deep root cause analysis of the problem

Figure 1: Common ground between ideation methodologies

In general, all these approaches are designed to generate a collaborative environment and accelerated ideation process of solutions linked to a need or problem of people/organizations, considering keep or adding value of the service/product. Consequently, the IFIC as a starting point must be made up of strategies/activities that allow a deep understanding and definition of the problem or current situation in a shared manner among those involved to avoid individual biases and to ensure an effective ideation process that navigates within the real context. In addition, the value proposition is a constant that should be the compass that guides the ideation process.

INDUSTRIALIZATION VARIABLES

The findings from a literature review revealed that prefabrication, combined with modular design conception and standardized design, are the core of industrialization in construction, and they help to save time and construction/design costs as building systems are used across projects (Jaillon & Poon, 2010). In this way, it must be the main variables to keep in mind when a design phase starts out in the IC design.

Prefabrication. The main characteristic of the prefabrication construction method is that this method can achieve the integration of the whole process of design, production, transportation, and assembly stages (Zhou et al., 2019), which is a high demand in IC. Therefore, it is a key element to include in the IC design process.

Modular design. In the context of IC, modular design means designing to generate standard volumes to make more efficient production and optimize on-site work, reducing constraints and providing repeatability (Jaillon and Poon, 2010). This process promotes standardization, mechanization, and computerization of construction, improves quality and consequently helps to reduce time and costs due to the simplification of design and assembly (Pons & Wadel, 2011; Yuan et al., 2018). Consequently, thinking about developing a modular design force to consider the implications of the ideas and design solutions downstream (e.g., production and assembly).

Standardized design. This means that IC buildings with different functions and shapes are designed according to a uniform architectural design criterion seeking a symmetrical and repetitive arrangement of the elements that compose the building. (Jaillon & Poon, 2010; Yuan et al., 2018). In other words, standardized design in its simplest form involves establishing the use of standardized components and procedures at the project level (Gibb, 1999).

RESEARCH METHODOLOGY

Design science research (DSR), or constructive research, is an approach commonly used for performing studies in the field of Lean Construction and, in general, in construction management (Da Rocha et al., 2012). The same author argues that several studies in the field of Lean Construction have used this methodology because it serves the dual purpose of solving practical problems and contributing to the body of knowledge at the same time. Some examples of research conducted under DSR and aimed at improving the design process in the AEC industry include the development of a value analysis model to support the building design process carried out by (Giménez et al., 2020) and the work done to improve the process of learning of design management operations by (Lehtovaara et al., 2019).

The artifact developed and evaluated for its intended benefits is an Ideation Framework in Industrialized Construction (IFIC), which is to serve as a framework for the generation of ideas/actions in a faster and more effective way within the design phase in IC projects. The IFIC was tailored under the DSR proposed by Peffers et al. (2007), which includes five iterative steps (See Figure 2): *(1)* problem identification and motivation; *(2)* definition of the objectives; *(3)* design and development; *(4)* demonstration; and *(5)* evaluation. The development and refinement of the artifact was done through four "case studies" (which might rather be understood as means for testing and refining prototypes of the IFIC process) and involved three stages comprising the five steps mentioned.

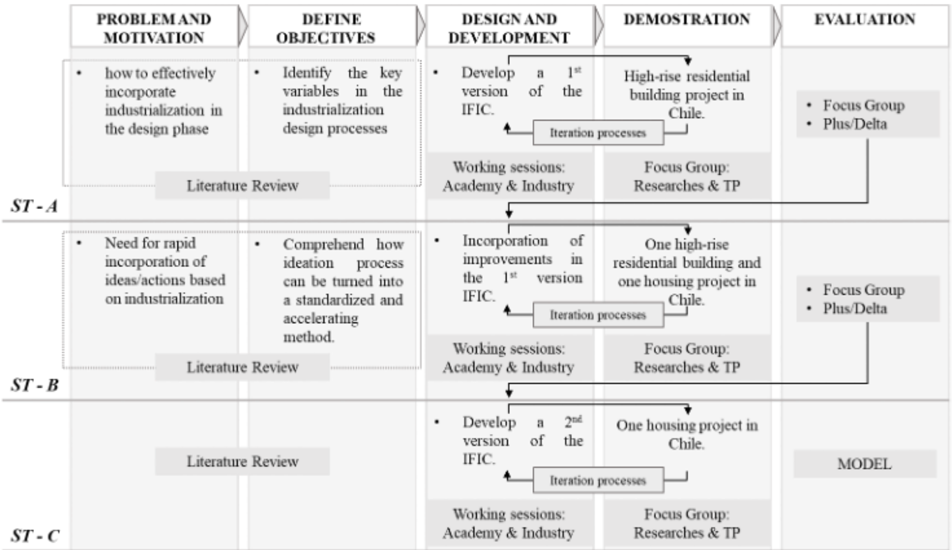

Figure 2: Research processes based on DSR

STEP 1 AND STEP 2: LITERATURE REVIEW AND OBJECTIVES DEFINITION

The systematic literature review (SLR) was performed through specialized journals on engineering and construction project management, conference papers, dissertations, and relevant reports in the construction industry. The search topics were industrialized construction, industrialized design process, barriers in IC, ideation processes, and collaborative methodologies. Based on SLR a clear understanding of the ideation process was achieved, its location within the design phase, and to identify and classify the different methodologies available to carry out the ideation process effectively, into those methodologies that cut across different fields of science and those that have greater proximity to the field of construction. Likewise, it's helped to comprehend the way that these methods promote collaborative work and adequate early integration of actors and identify the relevant variables that conform to the core of industrialization. In addition, the literature review also made it possible to visualize the study gap and to guide the development and approach of the objectives. In this way, two specific objectives associated with stages A and B were proposed: *(i)* identify the basis for incorporating industrialization at the design stage and *(ii)* comprehend how the ideation process can be turned into a standardized and accelerating method.

STEP 3: DESIGN AND DEVELOPMENT

The first version of the IFIC was developed in collaboration with academics and professionals with at least 10 years of experience in management and in the AEC industry and who are part of the CCI and Chilean construction companies. Based on the SLR and the proposed objectives, it was possible to frame the boundaries within which the IFIC would operate. Three fundamental spaces were identified: understanding, definition, and ideation. The spaces of understanding and definition were established because of the coincidences raised in the literature on ideation models, which indicate that they are essential to establish a clear shared understanding of the situation within the project team (TP) and lead the ideation process directly to the solution of the problem. The activities that would comprise the IFIC framework were selected and prepared based on three key aspects *(i)* to enable a clear understanding and definition of the problem, *(ii)* to be adaptable to address the core elements of the IC, and *(iii)* to establish a chronological sequence of implementation among them. After all, version 2 of IFIC was a product of the improvements included in the previous instantiations in stages A and B.

STEP 4 AND STEP 5: DEMONSTRATION AND EVALUATION

Design science research is conducted under many scenarios: experimentation, simulation, case study, proof, or other appropriate activity (Peffers et al., 2007). In the context of this research, multiple cases of study will be applied. This method was selected because of the richness, depth, and quality of the information it allows to collect. In total were four case studies of Chilean projects, two of which are high-rise buildings, and the rest are housing. The selection criteria for the case studies obeyed practical interests such as their similar characteristics of scope, user profiles, and level of design progress, in addition to the researcher's access to the stakeholders involved. All case studies were in their design phase and involved 3 different companies. The demonstration process was divided into three stages: *stage A* was applied to one case study (high-rise buildings), *stage B* to two case studies (high-rise buildings and housing) simultaneously, and *stage C* to one case of study (housing). The application of the IFIC was carried out progressively and sequentially between each stage, generating instances of partial application that served to obtain feedback and to incorporate and test improvements that were then transferred to subsequent stages, allowing for small adjustments to be made. Therefore, several subcycles of instantiations, testing, and refining of the solution were carried out between stages until a proper version of the IFIC was created and then reviewed with the TP and directors.

The evaluation step consists of monitoring and measuring the solution's effectiveness in addressing the needs or problems detected. It implies comparing the objectives of a solution to actual observed results from the use of the artifact in the demonstration and can be done in various ways depending on the nature of the problem and the artifact; such ways include quantitative performance measures, satisfaction surveys, or activities that collect feedback from project stakeholders (Peffers et al., 2007). The usefulness of the IFIC was evaluated in each case study through a focus group meeting comprised of directors and TP of each project, which includes architects, civil engineers, electrical engineers, mechanical engineers, and industrial engineers. Additionally, to measure the results achieved through the implementation of the model, a plus/delta analysis was carried out.

RESULTS · GENERAL OVERVIEW

The main outcome of this research is the framework to support the ideation process in IC design. The IFIC was developed within the umbrella of the research project "Methodology for early incorporation of industrialization in construction projects in Chile". Therefore, some activities must be done before and after the ideation process. Prior, it is recommended to apply methods that allow identify the items/processes/activities (IPAs) with the greatest potential for industrialization and have a relevant impact at the project level. This issue is being addressed within the aforementioned project with studies that are currently in progress; however, in the meantime, available tools and methods must be used. Likewise, after the ideation process, it is recommended to carry out a deep technical and economic evaluation of the ideas/actions generated.

To implement the IFIC, the organization must comply with the following guidelines: *(i)* to have a conceptual or reference project on which to start the ideation process and incorporation of the ideas, *(ii)* to be clear about the incentives that drive the ideation process, *(iii)* to understand the innovation capabilities of the organization, and *(iv)* forming the integrated project team (IPT), which consists of incorporating suppliers and builders in the early stages of the design to know their solutions, production capacity, manufacturing processes, logistics, and production requirements. The ideation process is oriented to create a set of ideas/actions based on core elements of industrialization that allow the IPT to effectively co-create the industrialized system through two fundamental axes: *(i)* ideation by self-assessment and *(ii)* referral ideation.

The IFIC ideation process is approached as an iterative process. The ideation by self-evaluation is the first axis of action within the IFIC, which focuses on clarifying the current state of the design to the IPT. In addition, at this point, the industrialization criteria are established on which the IPAs with the greatest potential to be industrialized will be evaluated. From the self-evaluation, the problems or aspects of the different IPAs that could be improved will emerge, as well as the initial proposals or ideas for improvement. Referral ideation is presented as the second axis of action, given that, at this point, it is assumed that the problems are defined from the previous stage, allowing a precise and rapid ideation process. However, this does not mean that new problems or situations that can be improved may arise. The problems identified during the process will be evaluated based on two criteria: *(i)* impact on the project; and *(ii)* the effort involved in addressing them. Likewise, ideas/actions will be evaluated by measuring their *(i)* impact on solving the problem(s); and *(ii)* the effort involved in carrying them out. Figure 3 shows how the IFIC is structured.

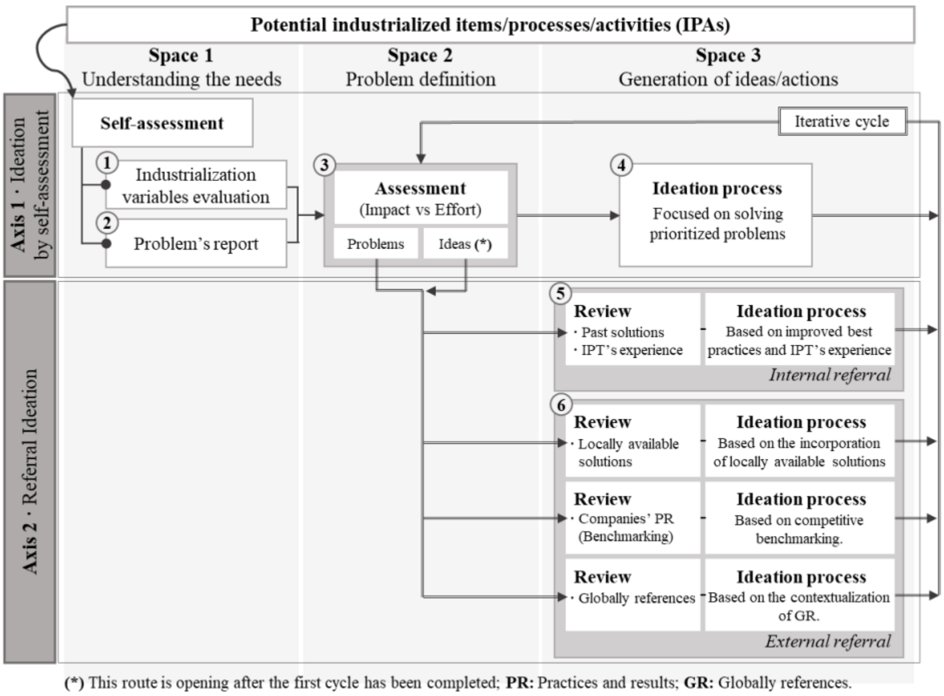

Figure 3. Proposed Ideation Framework in Industrialized Construction (IFIC).

IDEATION BY SELF-ASSESSMENT (ISA)

The focus of ISA is to generate a set of ideas/actions based on the review of the organization's internal capabilities and affectations. The ISA is composed of 2 activities:

Industrialization variables evaluation. This activity is the baseline for the subsequent steps that make up the IFIC. At this point, based on the core elements of industrialization (prefabrication, standardization, modularization), the IPT defines the criteria to be considered in the design, ensuring a framework in accordance with the requirements of the IC. Then, the prioritized IPAs are evaluated by the IPT to verify which criteria have been considered and which have not, to determine if there is room for improvement in the criteria incorporated, and define the problem in those that were not included. An immediate solution/action is proposed for problems that are easy to address. Nevertheless, subsequent activities are designed to deepen the understanding of the problems detected and to continue in the ideation process of ideas/actions.

Problem's report. The objective is to review with the IPT formal organization's problem reports of similar projects to the current one (e.g., post-sales reports), then prioritize these problems based on the incidents that *(i)* have the highest recurrence with end-users and *(ii)* have the greatest direct or indirect impact on the construction phase due to failures in the process or product developed in the design phase. Then, based on the industrialized criteria evaluation, solutions to the problems detected should be devised. Value stream mapping (VSM) is the suggested tool to assist the activity, as it allows to clearly identify the current status, identify the problem(s) and propose opportunities for improvement.

REFERRAL IDEATION (RI)

It consists of the development of ideas/actions based on what has already been devised and implemented in the IC field globally (external referral - ER) and locally (internal referral - IR). This is based on 4 key activities:

(IR)·Past Solutions and IPT's Experiences. In collaborative workspaces, the IPT highlights its capabilities and shares best practices that currently exist or that can be reused from other industrialized projects in which they participated in the past and that are relevant to solve the problems detected or improve the ideas generated.

(ER)·Available solutions. Refers to the periodic search and updating that the IPT must make of those constructive systems, materiality, and industrialized processes that are relevant at the local level and have been successfully put into practice. It also includes an exhaustive review of experiences with suppliers that work directly with the company and have a successful performance in the market. The above is intended to generate a technical sheet that facilitates the use of the opportunity detected.

(ER)·Benchmarking. It consists of comparing the company's practices/methods and results with other companies that apply industrialized principles and systems in their projects to identify differences in performance and detect successful initiatives.

(ER)·Global references. It is associated with conducting periodic technology watches at the product level and industrialized processes in the AEC industry that have been successfully implemented globally. Depending on the size of the IPA, the organization must decide whether to do it for the current project or as a cross-cutting activity at the project program level.

DISCUSSION

Due to the COVID-19 pandemic, all work sessions had to be conducted online, conducted in an interactive way through platforms such as Miro, Mentimeter, Zoom, etc. This made it difficult to fully execute the activities since many members did not feel familiar with the use of the platforms, sometimes generating frustration and demotivation. Moreover, additional work had to be done for the facilitators in terms of training before the start of certain work sessions. In addition, not having mid-level personnel within the IPT, who are the ones who generally materialize the ideas and guidelines that are established, resulted in many ideas with clear viability being left on standby. Among the important contributions, it is the ease and speed with which precise ideas and actions were generated, since within the logic of the application of the activities, once the problem was identified and defined, it was requested to co-create a solution to avoid latencies between both spaces. The virtuous circle that is generated is enriching and possibly more productive than the traditional way, where the changes between the spaces of "understanding and defining the problem" and "generating solutions" is slower.

CONCLUSIONS

The IFIC provides a framework for the generation of ideas/actions at the early stages of IC design and constitutes a multiple analysis tool since it considers temporal aspects (past, present, and future experiences) and three dimensions: people, processes, and technologies (experiences of the IPT and suppliers, problem reports, world references). This framework calls for early integration and intensifies the collaborative work among different disciplines of the project. Moreover, IFIC places the core elements of industrialization as the baseline of the design process and collects successful Lean tools/activities (e.g., A3 Report, VSM, etc.) to be tailored to the IC context and be implemented in chronological way. The context of the development of the IFIC was in projects of early incorporation into the implementation of Lean tools and methodologies. The ideas developed were very diverse in the topics related to IC: from the point of view of *(i)* management: planning, analysis, control, and improvement of processes, and *(ii)* technologies: prefabrication, robotization, automation, standardization, modularization, pre-assemblies, mechanization, and skilled labor. These management and technology approaches were implemented considering aspects to make the process systematic, repetitive, rhythmic, simpler, and more precise within a controlled environment. Nevertheless, most of the ideas generated were related to prefabrication, the area of execution, and the standardization of repetitive elements such as windows, doors, and general furniture.

A limitation of the study is the evaluation of the framework, which was done through activities (e.g., plus/delta analysis) that gather the opinions of the stakeholders and which is planned to be reinforced by measuring it quantitatively in future studies. Furthermore, the focus of the research is not on presenting the results of the practical implementation but rather on showing how the framework was structured. Therefore, future research should focus on showing practical results of IFIC implementation.

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Soliman-Junior, J., Awwal, S., Tzortzopoulos, P., Ayo-Adejuyigbe, M., & Kagioglou, M. (2022). Eliciting Requirements in Social Housing Retrofit Projects: Tools and Processes Within a Living Lab Setting. *Proceedings of the 30th Annual Conference of the International Group for Lean Construction (IGLC30)*, 468–479. doi.org/10.24928/2022/0152

ELICITING REQUIREMENTS IN SOCIAL HOUSING RETROFIT PROJECTS: TOOLS AND PROCESSES WITHIN A LIVING LAB SETTING

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ABSTRACT

Requirements' elicitation is a critical step in construction projects as it affects design development, construction, and ultimately, impacts on value generation. In social housing retrofit projects it becomes especially relevant due to the improvement character underlying such initiatives, which offers an opportunity to better address residents' needs, but also to consider the effects of disruption and cost implications. Despite different tools and processes being widely acknowledged by existing literature, their practical application in this type of project is often shallow and do not effectively support the definition of requirements that meet users' and other stakeholders' needs. This paper reports on preliminary findings from an ongoing research project focused on the use of living labs during the retrofit of 8 social housing dwellings in West Yorkshire, UK. It aims to better understand how different tools (i.e., Virtual Reality immersive cave, virtual walkthroughs, and value cards) are useful in the context of generating value within living labs. Key findings relate to the description of how tools were used in this context, as well as the participants' assessment of their benefits and limitations.

KEYWORDS

Requirements, Value, Social Housing, Retrofit, Living Labs, Tools, Virtual Reality.

INTRODUCTION

Social housing construction projects generally consist of top-down approaches (Karvonen, 2013) in which essential project drivers and requirements may not be clearly specified in accordance with the end-users needs. This process can result in a disconnection between

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housing provision and users' requirements, impacting their life quality and wellbeing (Chaves et al., 2017; Crawford et al., 2014), and ultimately affecting the success of initiatives by undermining value generation (Kowaltowski & Granja, 2011).

Different participatory approaches have been explored by existing research and in practice to shift from traditional top-down initiatives to bottom-up approaches (Karvonen, 2013). In this context, the use of living labs highlights end-users' (i.e., residents) inputs and needs (Oliveira et al., 2013). Living labs can be generally defined as user-centred initiatives that focus on the collaborative development of innovative solutions in real-world environments (Leminen & Westerlund, 2017). In living labs, different stakeholders actively collaborate and co-create solutions (Eriksson & Kulkki, 2005). Existing research acknowledges their application in different contexts and initiatives (Soliman-Junior et al., 2021; Bridi et al., 2022). Their use in the construction and housing domains becomes promising especially when focused on retrofit projects (Bridi et al., 2022), as motivations of these initiatives are often diverse, resulting from cultural and societal evolutions, changing comfort needs and standards, and the advent of new housing systems and technologies (Karvonen, 2013).

In the UK, social housing retrofit projects are usually associated with energy and thermal performance upgrading (Swan et al., 2017). In this context, a considerable part of the retrofit works relates to replacing or adding wall insulation by modifying the external building envelope and replacing energy systems and equipment, mainly by switching gas systems to fully electrical. Retrofit projects are especially challenging and of high complexity as end-users often remain in their houses during construction, leading to a very disruptive situation in which construction works happen simultaneously with residents' daily lives (Chaves et al., 2017).

Considering both design and construction stages in this type of project, understanding users' needs and requirements is fundamental to improve value generation (Koskela, 2000). However, there is a lack of systematic approaches to ensure that end-users and other stakeholders are effectively understanding the information they receive, as well as adequately communicating their needs and requirements. This issue can be a source of disruption, mostly affecting end-users and therefore, potentially increasing dissatisfaction and impacting value generation. Such uncertainty is also understood as a major challenge in retrofit projects, alongside the lack of approaches to assess different design alternatives during the project development (Gholami et al., 2013).

This paper aims to better understand how different tools (i.e., Virtual Reality immersive cave, virtual walkthroughs, and value cards) are useful in the context of generating value within living labs. These tools have been used during living lab workshop sessions to support better understanding and requirements' elicitation towards improved value generation in social housing retrofit projects. The paper reports preliminary findings of an ongoing research project focused on the use of living labs during the retrofit of 8 social housing dwellings in West Yorkshire, UK. This work is part of a larger research project named User-Valued Innovations for Social Housing Upgrades via Trans-Atlantic Living Labs (uVITAL). This initiative involves institutions from Brazil, England, Germany, and the Netherlands collaborating on user-valued solutions for social housing upgrades by using living labs.

It is structured as follows: after the introduction, the theoretical background associated with the paper is presented, followed by the research method. Key findings are described and discussed according to the different tools that were used in the workshops, leading to a closing section of discussion and final remarks.

THEORETICAL BACKGROUND

VALUE GENERATION IN SOCIAL HOUSING PROJECTS

In this research, the understanding of value generation aligns with Koskela's view of a process in which value is created from the fulfilment of customers' requirements (Koskela, 2000). In this paper, customers should be understood as all stakeholders which are part of the living lab, including end-users, designers, local government etc. From a design perspective, De Los Rios & Charnley (2017) discussed design's value role as a social construct, whereas Koskela (2000) highlights that the focus of value generation should be on the best possible and achievable value. Nevertheless, there is often a mismatch between users' expectations and designers' predictions of product usage (Hasdogan, 1996). This issue highlights the need for robust methods to capture needs and requirements, ensuring they are adequately managed and fulfilled during construction projects (Koskela, 2000).

In this context, surveys and post-occupancy evaluations are often used to capture and elicit users' requirements (as reported by Miron & Formoso, 2003). The same authors indicate a strong relationship between clients' values and requirements, supporting Koskela's view (2000), which demands a better identification and understanding of requirements. Therefore, managing requirements is a vital aspect that focuses on improving value generation of construction projects by capturing stakeholders' needs through a systematic approach of processing information, specifying requirements, and controlling their implementation throughout the design and construction stages (Baldauf et al., 2013).

LIVING LABS

Living labs are described by existing research as an umbrella concept-methodology which includes a diverse range of research methods, tools and approaches (Leminen, 2015; Tang & Hämäläinen, 2014). Across the different methodological understandings associated with living labs, there is generally a focus on user-centred and collaborative approaches used to create and evaluate an innovation (Bridi et al., 2022; Eriksson & Kulkki, 2005).

In terms of process, existing living labs developed within the housing context typically consist of four generic and iterative phases: definition, ideation, co-creation and evaluation (Bridi et al., 2022). They usually involve different actors, such as end-users, private and public organisations, as well as knowledge institutions (Steen & van Bueren, 2017) who collaborate directly together within the living lab.

Existing literature highlights that there are multiple definitions for living labs, leading to multiple applications in practice (Bridi et al., 2022). Despite the lack of conceptual clarity, which might suggest the existence of different ontological assumptions on the terminology (Soliman-Junior et al., 2021), different authors and researchers often highlight similar characteristics (Bridi et al., 2022), such as their focus on end-users and the use of collaborative processes to identify, co-create and implement innovations in real contexts (Leminen & Westerlund, 2017).

Early living lab applications understood the 'lab' setting as a real-life environment in which behaviour, performance or perceptions were analysed (Eriksson et al., 2005). Different understandings over time have led to a multitude of applications and, recent living labs have been proposed more dynamically. Some studies (e.g., Liedtke et al., 2015; Sharp & Salter, 2017; Lockton et al., 2017) use a series of workshop sessions that allow the development of required interactions and relationships between participants to support the development of a living lab environment. The research reported in this paper adopts a similar understanding, by conducting user-centred workshops sessions focussing on co-creation and development of shared understanding in a living lab setting.

VIRTUAL REALITY

Virtual Reality (VR) supports visual management in the design and construction of building projects (Orihuela et al., 2019); it entails visualising environments through immersion for effective interaction with end-users (Sherman & Craig, 2018). VR is identified as a tool that can be used together with other technologies to enhance decision making, improve communication, coordinate clients' requirements in the design process and promote collaboration among stakeholders (Orihuela et al., 2019; Woksepp et al., 2005). Another efficient output of VR includes error forecast, reduction of negative iterations, and avoiding delays resulting from inadequate project understanding (Orihuela et al., 2019). These VR attributes are associated with the various interventions of lean tools and lean principles to achieve integrated and collaborative design, early engagement of stakeholders, budgeting, information and communication using visual management and BIM (Ladhad & Parrish, 2013; Vrijhoef & Dijkhuizen, 2020).

Previous studies identified the importance of using tools and techniques to improve efficiency in managing social housing retrofitting projects (Kemmer et al., 2013; Woksepp et al., 2005). The exploration of VR spans through architectural modelling for proposal and generation of the virtual environment, engineering, and construction to reduce project cost, solve quality problems, and ensure adequate delivery time (Orihuela et al., 2019).

VALUE CARDS

Value cards were originally proposed by Kowaltowski & Granja (2011) aiming to better understand how social housing residents expressed and prioritised their needs. In this context, the cards can be understood as a tool for recognising values through users' perceptions and improving project decision-making (Carvalho et al., 2020). They are an example of a game that can be used to improve communication and understanding among stakeholders in different projects.

Kowaltowski & Granja (2011) show that using value cards provided a shift from satisfaction levels to the introduction of the concept of desired values, which can be seen as an important tool to assess building performance and improve the design and construction process in social housing retrofit (Kowaltowski & Granja, 2011). The use of this tool can also be linked to lean research, as it is easy to use and there is an opportunity to capture requirements and values (Soliman-Junior et al., 2021).

RESEARCH METHOD

This paper is motivated by the following research question: how different tools (i.e., Virtual Reality immersive cave, virtual walkthroughs, and value cards) can be useful in the context of generating value within living labs? It is part of an ongoing research project focused on the use of living labs during the retrofit of 8 social housing dwellings in West Yorkshire, UK. This project aims to improve value generation in social housing retrofit projects by advancing on social innovations. A series of workshop sessions are part of the research design, and, so far, two events were carried out and led to the preliminary findings presented in this paper. They included representatives from a Local Authority (public stakeholders), which is responsible for the dwellings being retrofitted and for the construction project, as well as social housing tenants (end-users), who are the current occupiers of the houses and remained living in them during all stages of the project.

These two sessions have been organised as workshops, in which participants were introduced to living labs, describing the characteristics of such initiatives and how they were expected to engage with them. In each of the sessions, different tools were used with different participants aiming to improve their understanding of the ongoing retrofit project and to support requirements' elicitation. They include the use of: (1a) a Virtual Reality (VR) immersive cave, in which participants explored Building Information Models of both existing and retrofitted dwellings, simulating both current and designed scenarios; (1b) a real-time rendering software (Enscape) linked to BIM models, which allowed enhanced visualisation and quick design optioneering; and (2) value cards, which consist of a methodology developed by (Kowaltowski & Granja, 2011) to prioritise different needs according to individual preferences and perceptions.

It is important to highlight that such tools were chosen at this stage because they provide different approaches to support requirements' and values' elicitation, either due to their visual and immersive features (1), which have been key drivers from the major project; as well as because they provide a structured approach to prioritise requirements that has not been explored in this context yet (2). Conversely, the above does not mean that other tools could not be used or adopted in this stage. In fact, there is a variety of tools used in different living labs reported by existing research, such as visual boards to support a better understanding of the proposed renovation (Boess et al., 2018), as well as the use of traditional prototypes (Lockton et al., 2019) for example. Because of the nature of the project, we decided to use the tools discussed above. Furthermore, it should be noted that the cost element has not been directly explored in the workshops, although cost implications and inferences emerged during the proposed activities.

In both sessions, after the exploration of the tools, a 'discussion and evaluation' exercise was undertaken in which participants were asked to describe how tools were useful in better understanding design and construction information and how they helped to express their needs, as well as what could have been different in the retrofit project if such tools and processes were used at earlier stages. It is important to highlight that these sessions could not be synced with the main project programme because of Covid-19 restrictions which delayed face to face interactions, and this consists of a limitation of this study from a methodological perspective. Hence, this research has been developed retrospectively in contrast to the retrofit project.

RESEARCH FINDINGS

This section includes key findings emerging after the development of two workshop sessions within the social housing retrofit living lab. It is structured according to the key tools that have been explored during the sessions, discussing how they have been used from a process perspective, highlighting how they supported requirements' elicitation, as well as the participants' perceptions on their use and effectiveness to improve understanding, elicitation, and communication of needs and values.

VIRTUAL REALITY (VR)

Virtual reality has been used in different ways during the workshop sessions. As discussed in the previous section, the VR immersive cave and the real-time rendering software were used to provide different types of immersive visualisations of BIM models. The BIM models, in that context, were used as a source of information to the VR tools in place and consisted of the alternatives that were explored by participants, representing both the existing and designed scenarios (figure 1).

Figure 1: BIM models of existing (left) and designed (right) scenarios

From a living lab process perspective, the use of VR tools can be introduced at different stages. In the reported process, they supported the 'definition' and 'ideation' phases, in which the existing model of dwellings was used to aid requirements' elicitation; as well as to assist design optioneering and evaluation in 'co-creation' and 'evaluation' phases, through rapid design modifications and what-if explorations.

In the first case described above, examples of emerging requirements relate to the overall aesthetics of the houses, and how some specific elements (e.g., fences, external wall render, and roof chimneys) are not pleasant from that perspective. The existing timber fence in front of the houses was particularly a topic of discussion, which impacts the perception of the garden area, and does not allow the beauty of the garden to show through. One of the participants highlighted that it also affects their mental health because they are very proud of their garden and wish others could see it in that way.

Conversely, when virtually immersed in the proposed designed model (figure 2), participants revealed requirements mostly related to privacy and aesthetics. Examples of participants' elicitation of requirements and values from the workshops are presented below:

- *"What is this here in the front, is it just a normal fence? And what is the fence here in the back garden? Are we getting this tall fence in the back garden? I just had new panels for the fence in my back garden before the retrofit. It costed me a lot of money, and I would appreciate having something as nice there now.* (Inference from researchers: but why do you want tall fences there?) *I've placed these panels there because I've got a hot tub and I need privacy."*
- *"Oh, it looks so good!* (Right after stepping into the cave). *I am going to look at my house only, so that is mine* (pointing at the house with the controller). *I have chosen teal for the colour on the window frame, and I do not like the yellow you have here at the moment, as it comes out like a mustard colour."*
- *"I want a back door with a glass panel and mailbox on it, similar to a front door as I had before. I do not like how this door is at the moment."* (Referring to the solid panel door).

The use of Enscape, which is a real-time rendering tool linked to the BIM model on Revit supported the exploration and testing of different design options, enabling rapid design modifications and what-if explorations (e.g., changing colours of façade elements, adding and removing canopies, changing door types). This tool allows participants to walk through the BIM model by using VR equipment or simply running as a desktop add-in to modelling tools.

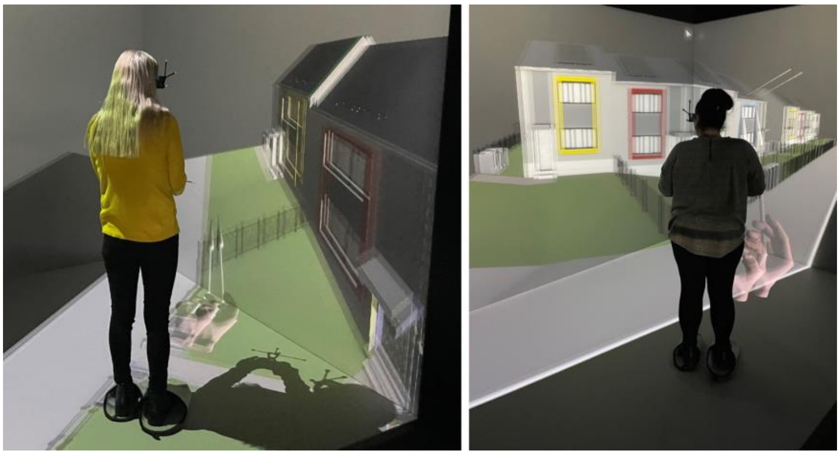

Figure 2: Participants using the VR cave to explore BIM models

One of the benefits of Enscape reported by participants is that it provides a much more realistic perception in comparison to the models explored in the VR cave, as materials, textures and effects are visually enhanced and more accurately represented (as seen in figure 1). It also supports testing different weather and climate settings and e.g., how the model is impacted by shading and sunlight at different times of the day. In the workshop sessions, participants suggested one example of application would be to aid the definition of the position of solar panels to be installed as part of the retrofit works, concerning tree shading and maximising sunlight, as seen in figure 3.

Figure 3: Different times of the day simulated on BIM models through Enscape

VALUE CARDS

Value cards have been used in the workshop sessions as a tool to capture participants' preferences of attributes and values related to different categories of social housing retrofit. These categories consist of: layout and remodelling, thermal comfort, accessibility, maintenance, security, privacy, sustainability, and environmental quality (examples included in figure 4). The cards have been developed based on information emerging from the other sources of evidence that are part of the project and are not included in this paper (e.g., participation in retrofit project meetings, development of interviews with project stakeholders and social housing residents).

A set of 45 cards was developed in the UK, illustrating design requirements and values. In the first round, participants were asked to order cards from the same category, according to their priority. In the second round, participants were asked to prioritise based on the first chosen cards from each category, ranking the most important cards overall. The value cards were used in the living lab process as part of the 'definition' phase, which is predominantly focused on understanding participants' needs, requirements, opinions, and constraints. This tool enabled participants to inform about their preferences and priorities considering the categories described above in a straightforward exercise.

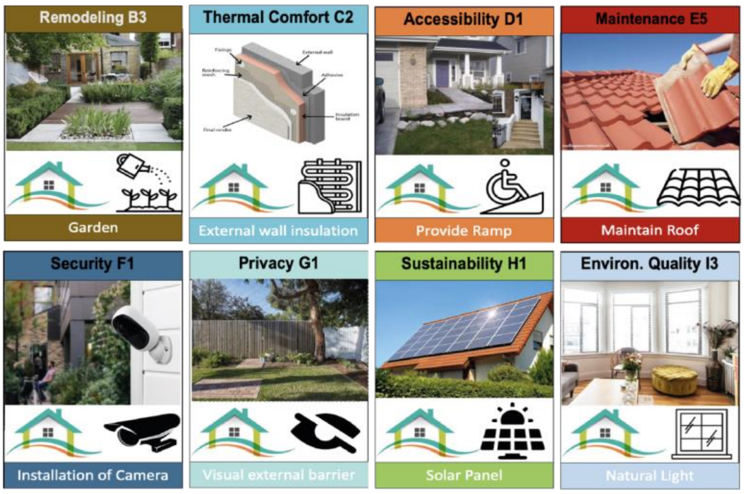

Figure 4: Examples of Value Cards as a tool to infer desired user value

During the use of this tool in the workshop sessions (figure 5), different needs, requirements, and values emerged, and they relate to various categories, such as security, privacy and thermal comfort:

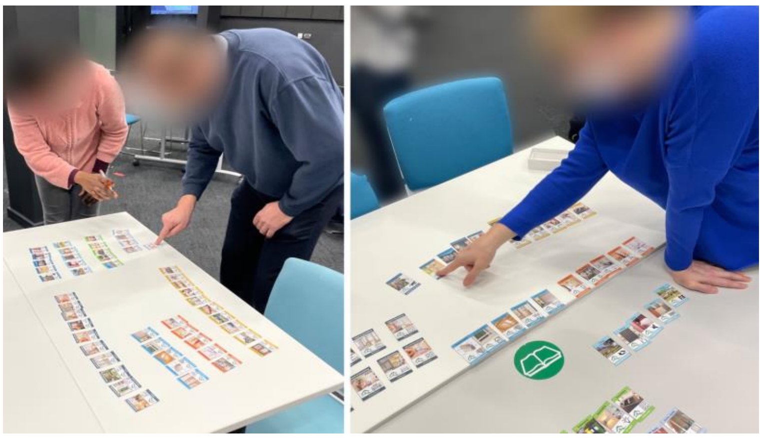

Figure 5: Application of the Value Cards with living lab participants

Examples of these requirements are described below, based on comments made by the participants while using the tool.

- Security: participants highlighted that the installation of an external motion-enabled light system was needed, as some areas around the houses and in the back garden become very dark relatively early in winter. They also prioritised the installation of cameras (CCTV system) because of local burglary in the area, as well as door security, through the installation of new doors and locks which are easier to use.
- Thermal Comfort: workshop participants prioritised the installation of external insulation systems as well as replacing doors and windows. One of

the participants later associated such changes with reducing the household running costs, when prioritising the cards in the second round. Their reasoning was to first replace doors and windows, because '*there is where we lose most of the heating'*, and then install solar panels to *'save even more money on energy bills'*.

DISCUSSION AND CLOSING REMARKS

During the 'discussion and evaluation' exercise, participants assessed the tools that were explored during the workshops according to a set of questions. These questions were later used to foster a discussion on how tools supported better requirements' and values' elicitation, their benefits and limitations. A summary of this assessment is presented in figure 6, followed by a description of key points highlighted by participants in that regard. It is important to highlight that this paper reports preliminary findings from the living lab process and, therefore, a more comprehensive living lab evaluation has not yet been developed and is planned for a future workshop. Nevertheless, participants provided a positive feedback based on the activities and tools reported in this paper, which is described below.

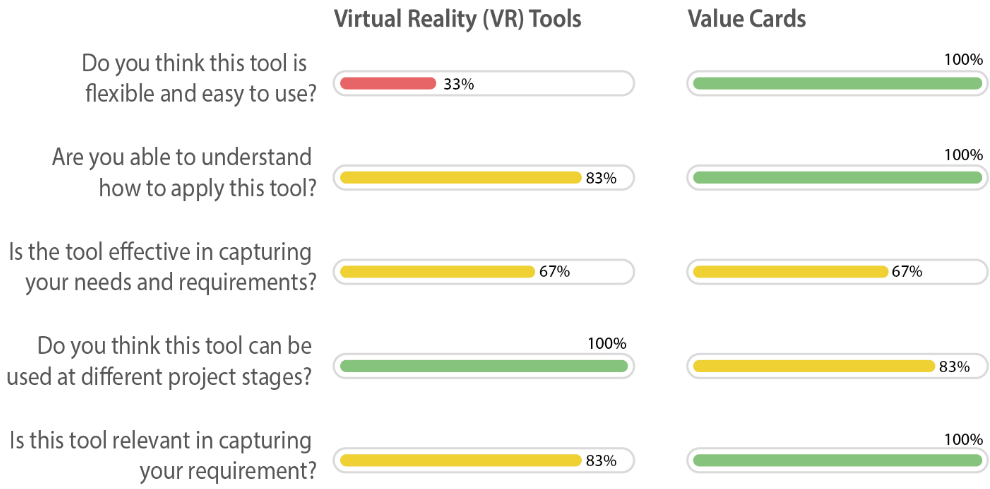

Figure 6: Participants' assessment of tools used during living lab workshops

The workshop participants highlighted that using VR and especially the immersive cave is not very simple nor flexible and that some further training might be required to successfully explore this tool. It is important to highlight that at times when the workshop sessions were undertaken, there were some limitations associated with the software that supports the VR cave. This temporary issue compromised the visualisation of materials and textures, resulting in some of the BIM model elements appearing 'flat'. Considering the living lab context, and especially the requirements elicitation intent, this becomes a potential challenge, as it can decrease the participants' perception of the virtual environment, not allowing needs and opinions to emerge.

Whereas some participants had difficulties in using the VR cave, others were more familiar with this type of system, mostly due to its similarities with video game consoles. In this context, workshop participants highlighted they could relate the virtual experience with the real environment and felt immersed in that context. They suggested that this tool could be used as part of different living lab phases aiming to improve stakeholders' understanding of the project and of its next stages, fostering communication, and enabling emerging needs to be discussed and addressed more appropriately and transparently. During the exploration in the cave, VR helped elicit both technical and clients' requirements, and the different BIM-related tools helped analyse how the proposed design was responding to them, as well as how participants perceive such requirements.

When comparing the two different VR tools that were used in the workshops (i.e., VR cave and real-time rendering software linked to BIM models), participants generally preferred the latter. This is because it was perceived as more efficient and easier to use, allowing a richer visualisation of materials and textures in the BIM models. It was also suggested that because it better supports design optioneering, it can potentially be used with larger audiences to address their emerging opinions more efficiently.

While assessing the use of value cards, participants mentioned they are very simple and easy to use, and they have a familiar format that can be transported to different places and replicated within different contexts and projects. They highlighted that this tool prompts discussion and reasoning on upgrading priorities and that even outside the living lab setting, it should be used during initial project stages as part of a 'consultation pack' with end-users. Conversely, they agreed that the cards are not suitable for late living lab stages, when the design is more developed and evolving requirements emerging from the use of the cards could be difficult to be incorporated, leading to a potential dissatisfaction and ultimately, affecting value generation.

Participants also suggested that both VR tools and the value cards support eliciting requirements and values to some extent, and they complement each other in that process. They suggested that whereas VR tools help participants to get immersed in the virtual environment, being mostly related with the visual sense, the prioritisation exercise which is part of the value cards deals with different types of reasoning and, therefore, allows other perceptions and needs to emerge. In that sense, the different categories that are included in the value cards support participants to expand their reasoning to a broader set of requirements in contrast to the VR tools, which rely on their individual perceptions only.

While the value cards have been more widely accepted and the benefits arising from their use were more directly identified, participants also appreciated the VR tools and suggested they have a great potential in the context explored by the research. It was also acknowledged that both tools within a living lab setting prompted discussion and fostered collaborative decision-making. They improved participants' understanding of each other's needs in the project, ultimately helping to reduce conflicts and misinterpretations of requirements, hence collaborating towards improved value generation in social housing retrofit projects.

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SOCIAL INTERACTIONS AND TEAM DYNAMICS IN A LAST PLANNER MEETING: AN OBSERVATIONAL METHOD

Elnaz Asadian[1] and Robert M. Leicht[2]

ABSTRACT

The Last Planner System ™ (LPS) is one of the most widely recognized lean techniques in construction to improve production planning reliability. Previous studies have suggested there is still room to maximize the benefits of LPS by identifying the missing parts in the implementation process or identifying the barriers to the effective adoption of this strategy. As one of these shortcomings, LPS has had limited study concerning its human aspect and participants' social interactions to inform the technique's effectiveness.

This study seeks to understand the relationships among the LPS technical procedure, social interactions and team dynamics, and the actual planning outcomes in construction projects. An observational methodology is proposed to investigate the hypothesis that if construction teams more closely adhere to LPS procedures, the technical processes would be aligned with positive social interactions among team members leading to improved team dynamics. To support this hypothesis, the procedures and norms from literature were extracted to define the observable characteristics for capturing and comparing the implementation. This methodology can be used as a resource for construction companies to investigate the quality of the current operating procedures of LPS and develop corresponding implementation and improvement standards to secure the full benefits of LPS.

KEYWORDS

Last Planner System, process, observable traits, team, collaboration.

INTRODUCTION

Production control has always been considered a challenging area under traditional construction practices, where the ad-hoc control methods foster uncertainty and variability, limiting smooth production flow (Dave et al., 2015). In Ballard’s (2000) view, the root cause is that traditional production management practices are dominated by the conversion model, which conceptualizes production as a process of converting inputs into outputs, ignoring the value generation model and flow management techniques. To tackle this issue, the Last Planner System ™ (LPS) has been introduced as a production planning and control tool, contributing to increased planning reliability and improved workflow through the collaboration of the entire project team and greater involvement of the *“last*

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planners" (Ballard, 2000; Hamzeh & Bergstrom, 2010). In this environment, by promoting effective communication among the project team at appropriate levels of detail and before issues become critical, LPS significantly improves program predictability, reliability, and feelings of well-being among project staff (Mossman, 2012).

Previous studies recognized that the LPS effectiveness in projects is not achieved due to partial, short-term implementations and without continuous feedback. The variation in LPS execution suggested developing a tool to measure the level of LPS implementation to help organizations achieve improvement actions (Perez-Apaza et al., 2021). From one perspective, LPS can be viewed as a social system comprised of project participants who come together to collaboratively plan and control project production. Therefore, social interactions among the project participants play a critical role in improving the project coordination and, thus, the workflow (Ghosh et al., 2019). Hence, studying and analyzing the participants' social interactions and their impact on creating positive team dynamics, along with how those behaviors match the technical processes of LPS, can bring insight into realizing the full benefits of LPS. In this context, research studies have investigated social aspects of LPS implementation, such as applying the Linguistic Action Perspective (LAP) to understand the effectiveness of LPS by measuring and controlling the management of commitments (Retamal et al., 2021, Salazar et al., 2018, 2019), or using Social Network Analysis (SNA) to analyze information flow (Retamal et al., 2020). However, how the technical procedures occurring during Last Planner meetings can be interpreted into social interactions by using behavioral metrics is missing from the current literature. To fill this gap, the authors suggest that the key aspects of technical procedures of implementing LPS, such as making a release of work between specialists reliable, can be measured by observable traits between project team members.

Therefore, this paper presents an observational method to investigate social interactions and team dynamics within the LPS meetings as a means to examine their impacts on the successfulness and effectiveness of LPS. Studying how last planners interact can provide valuable insights into the way they collaborate and make decisions in creating/controlling production planning. By defining proper measurement metrics to track these interactions as observable traits, constructive trends may be identified to help in creating successful LPS. For this purpose, a literature review was undertaken, followed by developing an observational study's procedure, including a coding scheme for studying and evaluating the impact of social interactions on team dynamics and the LPS implementation. A key objective of this study is to present a methodology for measuring and analyzing the team's adherence to technical procedures through observational social interactions and behavioral metrics within LPS. This paper does not describe the outcomes of using this framework in a real case study, which will be the authors' future direction.

LITERATURE REVIEW

Construction is a project-based industry, which means for almost every new project, the construction team is organized and formed around specific trades and functions. For every project, different people are needed, many of whom must work with others from new and different companies (Levitt, 2011). In this context, understanding team member interactions and improving working relationships can influence project performance and success (Lin, 2015). Additionally, construction projects bring together multiple parties from various disciplines with diverse expertise and specialties. In organizational terms, each of these specialist firms has its own objective, resulting in a lack of shared goals and objectives. According to Ju et al. (2017), the lack of common objectives among team members usually limits understanding of how one team member's behavior affects the others. Koskela and Howell (2002) remarked that organizations could build on their capacity with other project members through collaboration, helping reduce fragmentation and mistrust among the team. This implies that collaborative planning keeps the project team focused on the project's goal and creates a sense of ownership (Daniel et al., 2014). Successful collaboration does not occur naturally; rather, it is fraught with challenges. Collaborative conversations in the LPS have been noted to bring the team together, resulting in learning, innovation and creativity as team members benefit from each other's know-how (Daniel et al., 2014; Mossman and Ramalingam, 2021). According to Perez and Ghosh (2018), many researchers affirmed that LPS encourages teamwork, enables proactive involvement, promotes participation, transparency and improves communication and coordination.

Previous studies have tried to shed light on the social aspect of LPS through understanding the effect of this technique on the participants' social interactions. Murguia (2019) emphasized the critical role of having a social approach to planning rather than a technical approach, resulting in collaboration among project stakeholders. Likewise, Daniel et al. (2014) demonstrated that integration and communication were important to successfully implement the LPS. In one of the recent studies on the LPS social aspects, Ghosh et al. (2019) adopted a critical case study method to analyze the interactions among the participants of two projects, one following LPS and another following traditional project planning. Observing weekly subcontractor coordination meetings revealed that LPS increased the participants' understanding and control of the work assignments, creating a social system with higher trust. More cooperation was also reported among participants using the LPS than traditional project planning (Ghosh et al., 2019).

Previous studies have also examined the behaviors that emerge from LPS implementation. For instance, Pavez and González (2012) highlighted the importance of studying the social dynamic of improvement driven by LPS. Their analysis showed how the LPS implementation could change team dynamics in the construction field, transforming the work environment by changing the perceived level of trust and trustworthiness, the team's attribution process, and the quality of goal setting. They have noted that during the LPS implementation, a tipping point occurs in the dynamic of the weekly plan meeting when the project manager starts to listen more, and the last planners are allowed to share their viewpoints. They witnessed that when this happens, the dynamic of the conversation starts to change, and the project manager's behavior during the meeting turns from advocacy to inquiry. In this environment, the project manager's comments start to be perceived as a way to understand others' perspectives to improve project productivity and performance rather than orders. Similarly, Fauchier and Alves (2013) stated that LPS teaches the participants foundational behaviors such as collaboration, transparency, making clear commitments and reliable promises, accountability, and metrics. They identified three main sets of behaviors related to or promoted by the LPS: building social networks, treating construction projects as production systems, and addressing multiple needs in a dynamic environment, which are closely related to the challenging attributes of construction teams previously noted.

All of these studies suggest that in a project using LPS, social interactions occurring during the LPS implementation are important aspects that need to be considered in the execution. In this respect, previous studies tried to investigate how these social indicators influence the effectiveness of LPS. For example, Retamal et al. (2020) explored the relationship between planning reliability by analyzing percentage plan completed (PPC) measures, Linguistic Action Perspective (LAP) indicators and Social Network Analysis (SNA) metrics in four construction projects using the LPS. This study revealed that better SNA metrics and better PPC are generally observed when better LAP indicators exist. Likewise, Castillo et al. (2016) conducted a study to analyze the relations between LPS implementation, social networks metrics and performance in construction projects. The correlation analysis demonstrated that the implementation level of LPS is related to social network average degree and density; however, it does not always mean better project performance. They claimed that further research is still required to identify social networks' optimum metrics related to project performance (Castillo et al., 2016). In other attempts by Salazar et al. (Salazar et al., 2018, 2019), researchers developed indicators of commitments based on the Linguistic Action Perspective (LAP) to measure, control and improve the management of commitments in planning meetings to enrich the implementation of the LPS. The authors proposed a series of Key Performance Indicators (KPIs) based on LAP to measure and control fundamental aspects of the commitments, requests, promises and foundations of trust.

Despite all these studies, detailed observational data points for the way the LPS procedures should be implemented have not been studied. As a contribution to this discussion, the present study investigates the human behaviors and social interactions in a LPS meeting and tries to link them to the LPS technical procedure, e.g., how the meeting is conducted and adherence to LPS best practices, and their impact on planning performance by defining observational traits between team members. The paper aims to be sufficiently descriptive of the observational processes so that team's behaviors can be understood and linked to the effectiveness of LPS implementation. This helps construction companies better take in strategies to realize the full benefits of LPS by considering human aspects of the method, in addition to the technical considerations.

PROPOSED METHODOLOGY

USE OF OBSERVATIONAL METHODS FOR LAST PLANNER MEETINGS

This section presents a method to employ direct observation using video recording of LPS meetings to analyze team members' interactions when planning and controlling a construction project. The goal is to assess the proposed correlation between LPS technical routines, social interactions that occur during a LPS meeting, and resulting team dynamics. We hypothesize (Figure 1) that if construction teams adhere more consistently to the LPS principles and procedures, those processes will reinforce the positive social interactions among team members. Subsequently, positive social interactions affect how people treat each other in the process. The resulting team dynamics promote open conversation among project teams that enhances the planning and scheduling performance, which cycles back to support the technical procedure of LPS. Figure 1 depicts a proposed framework to demonstrate the process between technical procedures, social interactions, and team dynamics.

As the first step, a review of the technical procedure of performing a LPS will be presented. This is an important step for the study's purpose since without understanding how the LPS should be implemented, the team interactions to bring effective outcomes cannot be studied. Moreover, as Perez & Ghosh (2018) discussed, without clear processes set out by management, personnel are unable to confidently take the steps necessary to implement the technique and see its benefits. Therefore, a review of technical procedures for implementing LPS serves as the starting point. A literature review on the previous studies on the LPS was conducted to extract the implementation procedures. Ballard's (2000) study was the primary reference for this step; however, other studies were also considered to depict an appropriate implementation process.

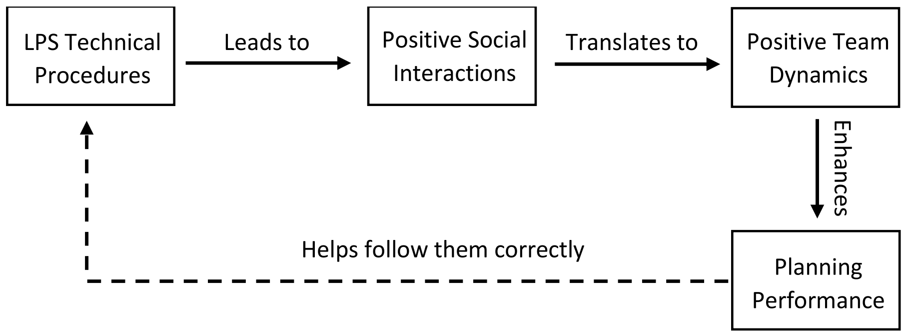

Figure 1: Hypothetical framework of the correlation between LPS technical routines, social interactions, and planning outcomes across the LPS teams.

LPS TECHNICAL PROCEDURE

A complete implementation of LPS consists of four scheduling and planning levels, including Master Schedule, Phase Schedule, Lookahead Schedule, and Weekly Work Plan (WWP) (Ballard, 2000). The first level, the Master Schedule, is the output of front-end planning describing work to be carried out over the entire project's duration, providing the basis for delivering the project and meeting milestones (Ballard & Tommelein, 2016). Phase scheduling aims at dividing the master plan into various phases to develop more detailed work plans and provide the project team with goals for each phase by using the *"pull planning"* technique and involving representatives of all organizations working on that phase (AlSehaimi et al., 2014). The third level, Lookahead Planning, contains major work items that must be completed to meet the milestone dates in the master pull schedule. To do so, a list of all activities planned to be carried out in the next 2-6 weeks needs to be prepared, and all the constraints preventing the execution of these activities need to be identified and removed (Ballard & Tommelein, 2016). At the last level, Weekly Work Plan (WWP) represents the most detailed plan in the system showing interdependence between the work of various specialist organizations containing the actual commitments to what is carried out on-site (Ballard, 2000).

Regardless of the planning level, an effective LPS meeting should include certain technical procedures to ensure the successful implementation of LPS. As explained before, the main objective of this study is to present a methodology for measuring the team's adherence to technical procedures through observational behavioral metrics. To propose these metrics, following the literature review, the authors observed six planning meetings in three different projects to understand behavioral traits within the implementation procedures. These projects were selected from construction organizations that actively used the LPS to schedule, plan, and coordinate their activities. Four observed meetings were Weekly Work Planning sessions, one was Phase Scheduling, and the last was Lookahead Scheduling. In addition to the direct observations, some data were obtained through unstructured interviews with team members, such as project managers or lean champions, about how they implement the Last Planner System and how they expect team members to interact with each other during these meetings.

Table 1: Procedures expected to occur during a successful LPS meeting

Expectations	Observable Activities	Data Points and Metrics
Attendance: All key players are invited in advance. **Preparation:** Participants come to the meeting prepared with their specific inputs. **Participation:** Everyone participates in the actual pull planning session.	• All trade partners and the owner are present in the meeting. • Attendees join the meeting ready, bringing notes for their activities and tasks. • Participants all actively provide inputs for the conversations. • Requests or questions are posed to the team (other trades) with direct responses.	• Duration of time each team member talks. • % of the time superintendent (or facilitator) talks. • % of trades participating (of those working on-site). • % of stickies created ahead of time vs. created "upon request." • % of trade responses provided directly to GC. • % of responses provided to other trade questions/requests.
Training: Effective coaching before and during planning sessions is provided for all participants.	• The facilitator provides the set-up (board, stickies) for trade partners, explaining how to fill in their activities. • The project master schedule has already been provided for the last planners.	• Duration/ frequency of time re-visiting steps or procedures (e.g., how to fill out a sticky correctly). • Who provides procedural information. • References to or questions about other 'levels' of LPS planning (6-weeks, major milestones)
Collaboration: The team collaboratively plans in alignment with the trades' production systems and the project milestones.	• Facilitator helps team members collaboratively build the plan by considering the trades' resources and capacities and pulling from milestones. • The facilitator does not force trade partners to commit to completing a task. Trades are asked their opinion on how they can better align their production performance with project milestones.	• Number of questions vs. statements by a facilitator/superintendent. • Number of instances where team members say 'no.' • % of 'no' instances where a team works out an agreeable solution to meet teams' needs. • Number of times where an issue is not resolved during the meeting. • Number of instances in which another team member volunteers a solution that involves them compromising their plan.
Being Committed: Last Planners make promises that they can reliably keep.	• Last Planners do not blindly agree to requests. • The inputs come from the Last Planners themselves, rather than forced by the facilitator. • Team members show agreement and commitment to reliably delivering assignments they are responsible for.	• % of commitments made based upon the request of others. • % of commitments where last planners identify constraints that need to be addressed first. • % of topics for which "What, where, when, and who" are discussed for activities. • % of stickies placed directly by trades.

Using Visual Management of the Project Information: BIM Model, design drawings and layout of work area(s) are made available for the team to reference during the session.	• Trade partners use drawings to communicate clearly about the sequence or locations of their construction activities. • The facilitator uses drawings or model images to raise questions or support discussions about segmentations of work to ensure all parties are on the same page.	• Number of times model is explicitly referenced. • Number of references (specific pointing) to design drawings or model images. • Number of drawings or model images to be brought up on a screen to support discussion.
Identify Constraints: Constraint analysis of all activities is applied as a proactive approach to problem-solving as a team.	• Constraint analysis of all activities in the Lookahead schedule (e.g., funding, design, materials, prerequisite work, direct and indirect labor resource availability, and all other potential constraints considered).	• Number of times team members volunteer information about their work disruptions (e.g., design, materials, prerequisite work). • Number of items added to constraint log during a meeting. • Number of times existing constraints are discussed.
Analyzing the trends: The team measures the extent to which the Last Planners and team leaders' commitments were realized.	• They perform the weekly analysis of PPC. • The team works together to identify reasons for disruption and failure to complete planned work. • The facilitator tries to investigate noncompliance reasons, providing solutions to prevent their recurrence. • The facilitator focuses on process improvement by asking for team members' suggestions and opinions. • Visual illustration of the PPC and trends are provided.	• Duration that team determines what assignments were completed or not based on the plan (PPC). • Duration that is devoted to reviewing the task reasons for non-completion (root cause) • Duration of time devoted to discussing (changes in root cause) across multiple weeks of data. • Number of references that the facilitator uses diagrams and illustrations to discuss their performance with the team. • Tracking / visual(s) of root cause reasons are created and shared.
Continuous Improvement: Systematic learning is shared at the point of work.	• Team members actively participate in the discussion session and propose suggestions for their encountered situations. • The GC record the lesson learned from their failures and how they handle those situations.	• Number of suggestions made by trade partners. • Number of suggestions made by GC. • % of suggestions or options suggested by (each) trade?

Although each of them had their organizational planning processes, their responses were beneficial to understanding how each pursues LPS in their projects. Using the triangular method, which means gathering the information in different ways (in this paper, literature review, observation, interview), helped consider different perspectives, providing insights into the technical routines of utilizing the LPS and suggesting data points and metrics for measuring them. A list of these technical procedures, along with observable activities, are outlined in Table 1 to help define what observable data points to look for during a LPS meeting. To capture and code those observable traits, a set of data points and metrics is also provided with each expectation.

OBSERVATIONAL METHOD STEPS

This section proposes observational activities with supporting data points to investigate how social interaction and team dynamics in construction teams impact the successful implementation of a lean method, the Last Planner System (LPS). To this end, the paper puts forward a process to study the relationship between team interaction and the LPS technical procedures by observing the attributes or traits of project participants during LPS meetings to identify what meaningful correlation between them may exist.

STEP ONE: DATA CAPTURE THROUGH DIRECT OBSERVATION OR VIDEO-RECORDING THE MEETING

We posit a possible correlation exists between social interactions and team dynamics with the successful implementation of LPS technical procedures. The observation method is proposed to investigate this hypothesis and collect data to indicate how construction teams interact during the LPS meeting. For this purpose, a list of technical procedures expected to occur during the successful LPS meeting was presented in Table 1. The data points and metrics provided in this table offer an initial set of data to investigate how closely the project team adheres to LPS best practices concerning the technical expectations of the method.

Knowing these technical procedures, a researcher takes the role of a third-party observer, attending a meeting and concentrating on team members' social interactions. The observation process should not be particularly disruptive for conducting the planning and coordination session. While observing, listening, and taking notes on teams' interactions seems to be a more natural procedure, video recording can add value to the observational study. Visual recording devices allow for capturing an activity under study, letting the observer return to the document for further analysis. Hence, the content analysis can achieve greater rigor or exactness (Leicht et al., 2010). Despite all these benefits, recording is not an absolute necessity; rather, it is highly desirable as a sort of *"insurance"* against accidental loss, and it is beneficial for examining the study's reliability (Bales, 1950). Yet, it is possible that the project team would feel uncomfortable being recorded. Moreover, the process of video-recording the team interactions carries the risk of unintentionally changing participants' behavior (Paoletti et al., 2021). Therefore, the benefits and potential impacts of video-recording need to be weighed carefully against the benefits in each project context.

STEP TWO: ANALYZE THE SOCIAL INTERACTIONS USING THE IPA METHOD

A common form of interaction analysis is Bales' (1950) *"Interaction Process Analysis"* (IPA). He proposed a method to observe social interactions in a small face-to-face group, including teams and workgroups. For this technique, he classified group ranges in the number of involved persons from 2 to 20 as *"small groups,"* which appears to be applicable for most construction project teams applying LPS. The heart of this method is a way of classifying direct, face-to-face interaction as it takes place, act by act, and a series of ways of summarizing and analyzing the resulting data to yield useful information. IPA is a 12-code taxonomy of team communication consisting of four groups and three codes under each category. These groups are (1) positive social-emotional reaction (e.g., shows solidarity/seems friendly), (2) negative social-emotional reaction (e.g., shows tension or anxiety), (3) task-related questions (e.g., asks for information), and (4) task-related attempted answers (e.g., gives suggestions) (Paoletti et al., 2021). By reviewing the meeting, the observer codes how often an action takes place and how much time is spent performing a given activity. As people in the meeting talk to each other, the observer breaks their behavior down into the smallest meaningful units that can be distinguished.

We posit that if team members properly follow the technical procedures of LPS (Table 1), we will witness higher positive social reactions, as well as task-related interactions. In contrast, the negative reactions would be decreased. This argument is based on the fact that the fundamental principles for implementing LPS, such as *"produce plans collaboratively with those who will do the work planned," "make and secure reliable promises,"* and *"reveal and remove the constraints on planned tasks as a team,"* (Ballard & Tommelein, 2016) are closely related to these social reactions, leading to positive interactions among team members. It should be kept in mind that LPS technical routines encourage effective and useful communication, transparency, and cooperation, bringing constructive social interactions, such as showing agreement and asking for suggestions.

Moreover, fewer negative reactions would occur if the project team adhered to the LPS procedures. For instance, the shared leadership style, a preferred type of leadership for collaborative planning, results in less antagonism or deflating of others' status. The autocratic control of traditional planning is no longer welcome under the lean mindset. Therefore, the observer probably sees fewer indicators of someone attempting to control or supervise in an autocratic manner, in which freedom of choice or consent for members is either greatly limited or non-existent. In contrast, in a true LPS, trade partners can freely talk about constraints they might encounter and request/suggest measures to solve them rather than follow the General Contractor (GC)'s directive immediately without argument.

STEP THREE: INVESTIGATE THE TEAM DYNAMICS THROUGH OBSERVATION AND INTERVIEWS

Having identified the technical procedures and social interaction among team members, the researcher seeks to answer the question of *"how these reactions can lead to positive team dynamics."* As Asadian & Leicht (2021) explained, team dynamics describe how unconscious psychological forces affect the behavior of groups of people working together. Understanding and identifying these dynamics within the project team helps align team outputs with project goals and ultimately increases the likelihood of project success. In this study, they used the A-B-C framework developed by Salas et al. (2008) to establish a meaningful correlation between team dynamics and lean principles. The proposed framework depicts three essential aspects of teamwork: Attitudes, shared Behaviors, and Cognition of the individuals that make up the team (Delice et al., 2019).

We believe there is a direct relationship between technical procedures of LPS, positive social interactions and team dynamics. Based on this assumption, if team members follow LPS procedures (Table 1) correctly, the emerging positive social interactions lead to constructive team dynamics. For example, Bales (1950) highlighted a permissive attitude, where the other is led to understand that a team member is accepted "as he/she is," as an indication of showing agreement, acceptance and understanding. When this positive social interaction occurs, team members believe that the incorrectness of their proposed solution to a problem does not adversely affect their status in a LPS meeting. They can *"make mistakes without blame,"* thus, they do not feel anxious when someone asks their opinion. These kinds of social reactions by their teammates encourage team dynamics, namely openness, trust and psychological safety, which are critical to the collaboration of multiple stakeholders and effective communication. This is the exact environment where the LPS processes can be implemented properly.

STEP FOUR: STUDY THE PLANNING PERFORMANCE USING PPC

One of the main processes of LPS is that the construction team learns together about the production procedures from their weekly performance. For this purpose, construction teams use metrics, such as Percent Plan Complete (PPC), Percent Constraints Removed (PCR), Tasks Anticipated (TA), and Tasks Made ready (TMR) (Perez-Apaza et al., 2021) to help update the next WWP accordingly by identifying and removing the reasons for the non-completion of tasks. As one of the most widely used metrics, Percent Plan Complete is calculated by the number of planned completions divided into the number of actual completions. This metric is used to track the performance of reliable promising at the weekly work plan level, helping initiate preparations to perform work as planned (Hamzeh & Bergstrom, 2010).

We postulate that since Last Planner System supports effective relationships by enabling open conversations and resulting commitments for action at the right level at the right time, leading to better planning. Therefore, we set forth that measuring the PPC of different LPS meetings, along with the data gathered by the observer on the team's adherence to the technical procedures and social interactions and team dynamics, will provide effective data to properly evaluate this hypothesis. In this regard, the observer needs to study the PPC as an indicator of how well the team conducted its planning production and compare this metric across different work teams. We predict that a higher percentage of tasks completed will be observed among the teams with a higher level of procedural adherence, corresponding with positive social interactions and team dynamics.

CONCLUSIONS

Most of the prior research studies in the lean construction domain have concentrated on lean instruments and applying new technologies. These studies have contributed to the development and advancement of lean adoption by pointing out principles, practices, methods, and techniques. However, understanding how project participants use the methods with a specific concentration on their social interactions and team dynamics can also bring valuable insight into how to enhance the effectiveness of these methods. Therefore, to achieve the best possible result from adopting a powerful planning production technique, namely the Last Planner System, in addition to focusing on the technical procedures of implementation, the question of *"how human dynamics influence the method's adoption"* is required to be answered.

In this article, we presented an observation-based mixed-method (including observation, interview, and analyze the data collected) that is advantageous and suited to study the relationship between social interactions and team dynamics and the technical procedure of LPS implementation. By explaining the four steps for this method, along with details of the needed LPS data collection, we demonstrate a potential method for systematically capturing ongoing processes of team dynamics for construction projects that use LPS. This study contributes to academic and practitioner knowledge by helping document what teams experience and hypothesizes how their experiences translate to performance. Our proposed method is not the only option. Still, it may illuminate a path forward for team-level research in the lean construction domain in hopes it will facilitate the investigation of human- and team-related aspects of lean techniques implementation.

The authors plan to test and validate the proposed methodology in case studies to improve data points and metrics for future research.

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IMPACT OF LEAN PRACTICES IN THE PLANNING OF DESIGN TASKS: EVIDENCE FROM TWO PROJECTS IN FRANCE

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ABSTRACT

Lean construction, through its different tools, has enriched the construction industry with several ways to present reliable planning for the construction process. Nevertheless, the focus on planning design tasks is still incomparable to that devoted to the construction tasks. Additionally, lean construction and its planning tools and principles are still not routinely practiced in many areas of the world. This article tries to contribute to the existing efforts and shows the integration of lean construction with digital tools to improve the reliability of planning activities for design tasks in two projects in France in time of the COVID-19 pandemic. The article results show that the use of lean practices helped avoid delays in design, better consider the client's expectations, and improve the collaboration between the participants in the design phase. The current study brings new insights into the applicability of lean practices in improving design management in the Architecture, Engineering, and Construction (AEC) industry.

KEYWORDS

Lean construction, Last Planner® System (LPS), lean design, planning, Key Performance Indicators (KPIs).

INTRODUCTION

One of the most essential keys to achieving success in construction projects is having reliable planning (Rizk et al., 2017). Reliable planning allocates the resources properly, defines the criteria and needs to achieve the objectives of the project, and helps to anticipate the risks early enough to be properly managed and mitigated (Aziz & Hafez, 2013). Thus, it is not surprising that some construction managers invest more than one-third of their time in planning activities (Daniel et al., 2020; Mustapha & Langford, 1990).

Design is the first process in construction projects when the objectives are defined and customer's requirements are translated into solutions (Koskela, 2000). Similar to construction, design is also a complex process as it requires a proper translation of the client's needs and requirements and includes decisions that affect all measures in the projects (Rosas, 2013). It is evident that although design includes the lowest expenditures, it has the greatest influence on the project cost among all the project phases due to the

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decisions made in this phase (Yang & Wei, 2010). Improper design is also considered one of the most popular reasons behind delays and poor quality in construction projects (Sweis et al., 2008; Zidane & Andersen, 2018). Nevertheless, design in construction still includes high levels of variability in workflow due to poor planning of design activities (Bolviken et al., 2010; Hamzeh et al., 2009; Khan & Tzortzopoulos, 2015).

The traditional planning for construction design is usually based between the upper management and the client who regularly meet to define the objectives and deliverables without matching what should and what can be done and without considering if the designers can achieve these deliverables. Usually, the planning is done based on a master schedule and due dates. Meeting these dates through the definition of activities' duration is left to each design department to decide, which confirms the levels of fragmentation and the lack of collaboration in design. Moreover, performance measurement, in most cases, is neglected (Khan & Tzortzopoulos, 2015; Koskela et al., 1997).

Reduction of variability in planning, improving workflow, waste reduction, and value creation have been always seen as the principles of lean construction (Ballard, 2000; Koskela, 2000). Therefore, massive efforts have been done to improve the reliability of the planning and workflow in several phases of the construction projects by lean researchers and practitioners; and the best example here is the Last Planner® System (LPS) that was presented by Glenn Ballard (Ballard, 2000) and was successfully implemented in the planning for construction processes (Hamzeh et al., 2009; Koskenvesa & Koskela, 2012). Nevertheless, despite the importance of the design, the efforts to integrate lean practices in the planning for design are incomparable to those made in the construction phase.

USE OF LEAN TOOLS IN PLANNING FOR DESIGN

The above-mentioned problems that face traditional planning for design are similar to those cited by Ballard (2000) when he introduced LPS to improve planning and control of construction processes (i.e. Planning is understood based on the skills and talents of planners rather than being understood as a system, neglection of crew level planning and focusing only on a schedule, lack of constraints removal and matching between "should" and "can", and lack of performance indicators and learning process). Therefore, following the success of LPS and due to having similar problems in planning for construction and planning for the design, it is worthy to shed the light on the possible ways to integrate lean tools and LPS to improve the planning for design.

Hamzeh et al (2009) investigated the applicability of LPS in the design phase and presented the adjustments that can be presented to LPS to better suit the design activities. Kerosuo et al (2012) presented a case study about the use of LPS in the design of renovation in a school. The study showed that the design was completed on time and the communications were improved between the team due to the implementation of LPS. Rosas (2013) investigated the impact of the integration between design structure matrix (DSM) and LPS in design management. The study showed that this integration can improve the reliability of the planning and the identification of corrective actions by the team. Fundli and Dervland (2014) introduced an LPS-based method that is usable during the planning for the design activities and is called Collaborative Design Management (CDM). The presented method was helpful to improve communication, collaboration, understanding, and commitment in the design phase. Khan and Tzortzopoulos (2015) showed how weekly work planning was effective to improve workflow, reliability of planning, and collaboration during the design of two building projects. Fosse and Ballard (2016) stated that LPS can help to improve quality and reduce design time and cost.

RESEARCH OBJECTIVES

The impact of lean tools on the planning of design activities is still overlooked in comparison to the efforts devoted to construction activities. Additionally, the last pandemic of COVID-19 affected the implementation of lean practices in general and planning activities and the last planner systems in particular. This is due to the measures that were taken to limit the spread of the virus, including social distancing, traveling reduction, and reducing the opportunities to organize meetings between the different projects' stakeholders. As a result, digital tools are more needed to connect different parties and stakeholders to achieve proper planning. The use of these tools while implementing lean construction can mitigate the impact of fragmentation, disseminate the lean culture, integrate different partners in the project, and decrease workload related to sticky notes management during the implementation of LPS (Hua & Schwartz, 2021; McHugh et al., 2021; Pedó et al., 2020; Salhab et al., 2021). Nevertheless, digitizing lean construction is still in its infancy and its acceptance of it still needs further investigation.

The current study, and through a presentation of two case studies that were conducted in France where lean construction is still not routinely practiced; especially in the design phase (Dakhli et al., 2017), aims to: Investigate the impact of lean tools adoption with support of digital tools to improve the planning for design activities.

RESEARCH METHODOLOGY

The study was based on three main phases: the first phase was conducting a preliminary survey that aimed to evaluate the current challenges and difficulties faced in the French construction sector based on the perspectives of different stakeholders in the sector. The second phase followed the analysis of the results of the preliminary survey and aimed to implement lean tools and practices in two projects in France, while the third phase aimed to investigate the perspectives of the participants in the two cases about the implemented tools and practices through a second survey. This section shows the development of the preliminary survey and its results as they were the guide for the discussions in the two cases, then it describes the two cases and the implementation of lean tools, and then it presents the second survey, whose results will be shown in the results section.

PRELIMINARY SURVEY

The first phase consists of the realization of a preliminary survey that was conducted as market research and developed to make a general understanding of the difficulties that face the different actors in the French construction industry. The development of the survey was using Google Forms and the survey was distributed by email to a list of 1,750 practitioners in the French construction industry representing different types of companies (contractors, owners, design and engineering offices, suppliers…etc.). The survey was developed to include six main parts with 23 questions. The questions covered the demographic profile of the participants, client's requirements and involvement, cost-related issues, time-related issues, methods of working, and current managerial practices.

The total number of participants in the survey was 260 participants; 29% of them were from general contracting companies, 25% were from project management offices, 13% were owner representatives, and 10% were from engineering studies offices. The participants were working on different types of projects including real estate, residential, hotels, industrial, and commercial projects.

The key findings of the preliminary survey are as follows:

1. More than half of the participants believe that the clients' requirements and inputs are incomplete and these requirements and inputs are not stable and keep changing.
2. 35% of the participants believe that the client is not sufficiently involved in the development of the project.
3. 88% of the participants believe that sharing knowledge between project partners would contribute to problem-solving and 39% believe that it can increase profitability.
4. Around two-thirds of the participants believe that sharing success and financial gains between the partners of the project is difficult.
5. To face the different challenges facing the management of construction projects starting from the design phase, participants believe that the most effective measures are the use of a shared software or a platform between the partners (reported by 82% of the participants) and establishing a collaborative and integrated unit between different companies (reported by 77% of the participants).

The results of the preliminary survey confirmed that although collaboration between project stakeholders and client involvement is considered very important, especially in the design phase, participants considered this collaboration not easy to do. Accordingly, lean tools and LPS were adopted as it is evident that these tools are very useful to focus on client's needs and satisfaction and improve collaboration in projects (Al balkhy et al., 2021; Albalkhy & Sweis, 2021, 2022; Fundli & Drevland, 2014; Hamzeh et al., 2009). Additionally, as the majority of the participants believe that a shared platform in a way of software is a possible solution to improve collaboration, the decision to use digital tools to improve lean adoption was taken.

CASE STUDIES

Following the analysis of the results from the preliminary survey, the work focused on presenting lean practices in two case studies. The two cases were selected based on having similarities in the design duration and teams. In both cases, the client, main contractor, specific sub-contractors, architect, and engineering consultants were involved during the design phase. Therefore, it was possible to implement the same tools in both cases.

Case study 1-

The first case was an aquatic complex project built as part of the Paris 2024 Olympic games. This aquatic center offers a total surface area of 1588m², including a sports pool 21m wide and 33m long, an activity pool of 150m² free forms, a 70 m² free-form awareness pool, and a wellness area. The project met solid environmental requirements to reduce water and electricity consumption and reduce the carbon footprint in the construction and maintenance phases. The construction contract was a Build-operate-transfer (BOT) contract. BOT is a contractual relationship between a public owner and a contracting company that is responsible for providing the design, constructing the facility, and then operating it for some time before transferring the operations to the owner. The intervention to introduce lean practices in the project was between February 2021 and October 2021. Lean practices were implemented to improve the design management starting from the beginning of the conceptual design phase, then the preliminary design phase, until the detailed design phase.

Case study 2-

The second case study was 40 000m² office and business campus on 11 levels. The project is schematically constituted by three parallel buildings in the direction of the slope, drawing sloping valleys, like "scarifications" on the hillside. The project includes the following activities: Labor code building for the office areas, business center, common areas, parking, technical premises, one arena located on the ground floor, four shops located on the ground floor, one fitness area, and one wellness area, and one crèche. The project had to meet ambitions in terms of sustainable development facing future users and local partners. The project would also respond to local efforts led by the public authorities, particularly the Greater Paris Climate Plan. The contract was a private contract of the Guaranteed Maximum Price type (GMP). This type of contract includes a maximum price that can be paid by the owner to the contractor (unless having a formal agreement on scope change). If the project costs less than the GMP, the owner retains the savings or may have an agreement to share them with the contractor. The intervention on the project was from January 2019 to August 2021, covering the preliminary and detailed design.

Implemented practices and tools in the case studies

Following analyzing the results of the first survey, a team seminar was presented for the design and construction stakeholders. This seminar aimed to raise awareness about lean management in the construction industry and covered the following topics: sharing the vision of the project by all the participants (clients, architects, design, studies, contractor), reviewing the conditions of satisfaction of the project by the client, risks and opportunities for each stakeholder, and initiate the collaborative planning using LPS.

LPS was implemented in the design phase by planning the whole deliverables and levels starting from the master schedule to the daily meetings. To do so, a series of meetings had to be done to reach all partners in the design phase as follows:

1. General study steering meeting: this is a remote meeting. It enables the progress of the design to be monitored (indicators, tasks to be carried out, blocking points, decisions, customer feedback).
2. Weekly organization meeting: 30-minute telephone meeting to confirm everyone's commitment to the tasks to be done, the agenda for the general meeting, and the topics to be covered during the week.
3. Owner's meeting: monthly meeting allowing to fix the reviews of the decisions to be taken by the owner, the thoughts on the evolutions and modifications of the project, and the reviews of the specific expectations of the owner.
4. Internal meeting between the project manager and the company: this meeting is used to deal with technical issues that do not require the presence of the whole team.

Measuring performance and progress between the planned and the actual work and identifying the root causes for the variance in the performance are among the essential differences between LPS and other traditional planning and control practices. Therefore, to support the implementation of LPS, Key Performance Indicators (KPIs), which are quantifiable measures that are used to assess the actual performance, were developed and used in the two cases. The list of KPIs included the following (as shown in Figure 1):

KPI 1: is a general key performance indicator for the whole project management in the design phase that shows the percent plan complete (PPC) for the project and was depicted as two curves; one is for the planned work and the other is for the actual finished work. **KPI 2**: was used to assess the involvement of partners in the meetings by presenting the present rates in each meeting. **KPI 3**: was to monitor the needed inputs from the client.

This KPI was digitally controlled by a vertical histogram bar showing the weekly number of client input data, and their status (to be received, late, received). **KPI 4**: was to track the completion of weekly tasks per stakeholders. It shows the status of the different number of tasks assigned for each stakeholder involved in this phase of the project (Architect, Company, Steering, Owner), the other status of each task shown in the bar of the histogram are: To do, in progress, late and done. **KPI 5**: was to show the overall number of tasks to be processed in the project design. **KPI 6**: This was used to show the consolidation number of changes and the sources of the changes. In addition, two other KPIs were used to show the progress in documentation production; one KPI was used to show PPC for the planned delivered documents by each employee involved in the studying phase in both projects. While the other shows the needed number of days required by each employee to deliver the remaining deliverables.

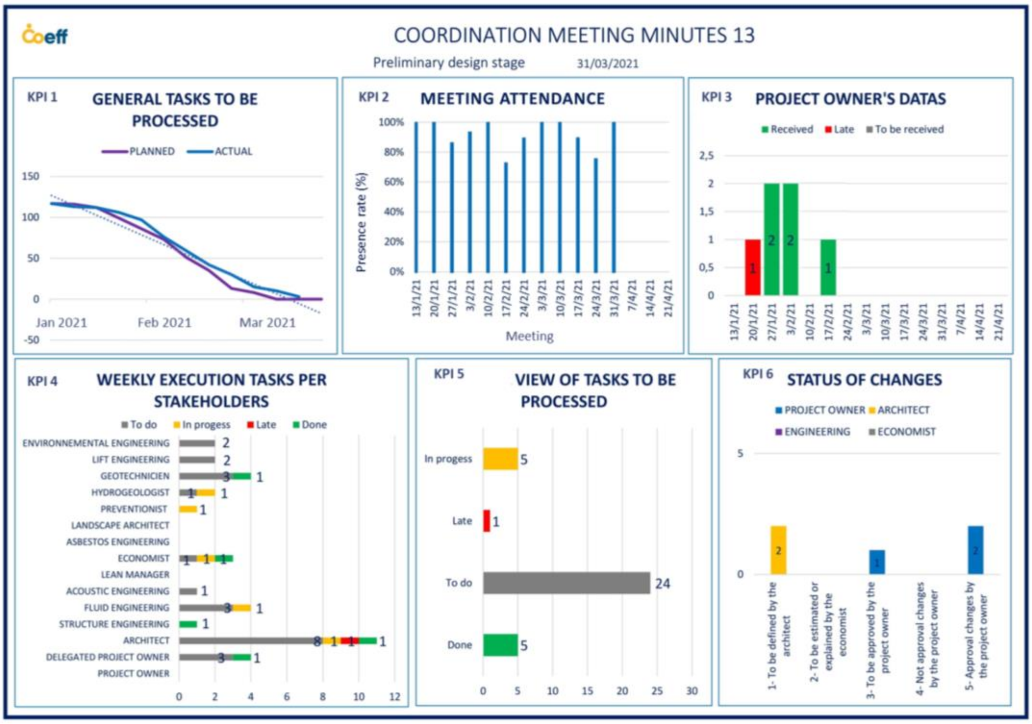

Figure 1. Key Performance Indicators (KPIs)

In addition to LPS, Visual Management (VM) and the KANBAN board were used in the two cases to manage and track the design of the two projects, visually present the progress of the work, and support the involvement of all employees in the work. VM is a lean tool that is based on the use of signs and posts, in a physical or virtual environment, to pass specific instructions to people in the project. In turn, KANBAN is one of the most important lean tools that is based on the use of inventory cards or signs to manage the flow of information (and materials on-site), monitor the progress, improve decision-making, and enhance communication and knowledge management and sharing in the project. Figure 2 shows the used digital KANBAN boards in the two cases. The Figure shows the classification of different tasks in the design phase to improve the monitoring of these tasks and the identification of actions to be taken.

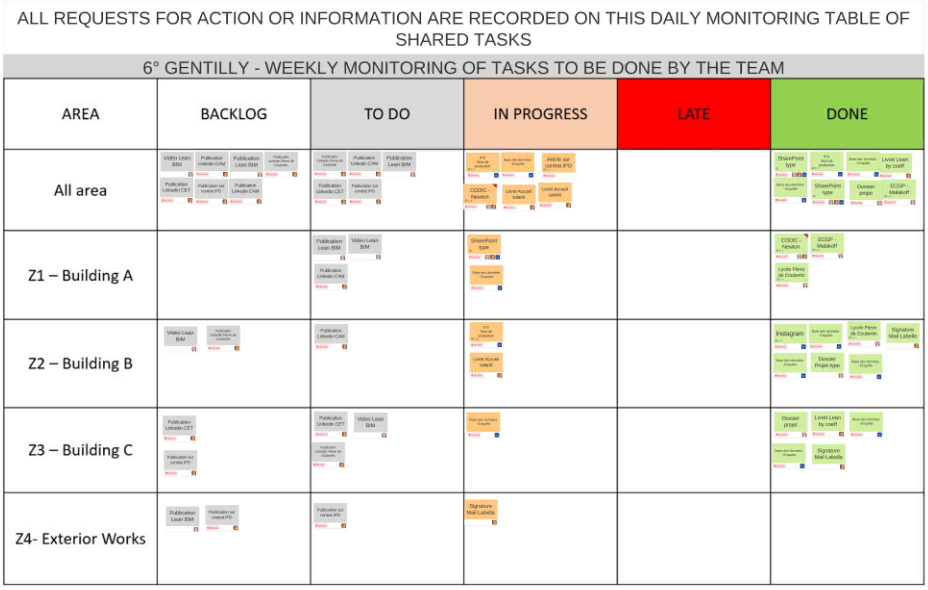

Figure 2. KANBAN Boards

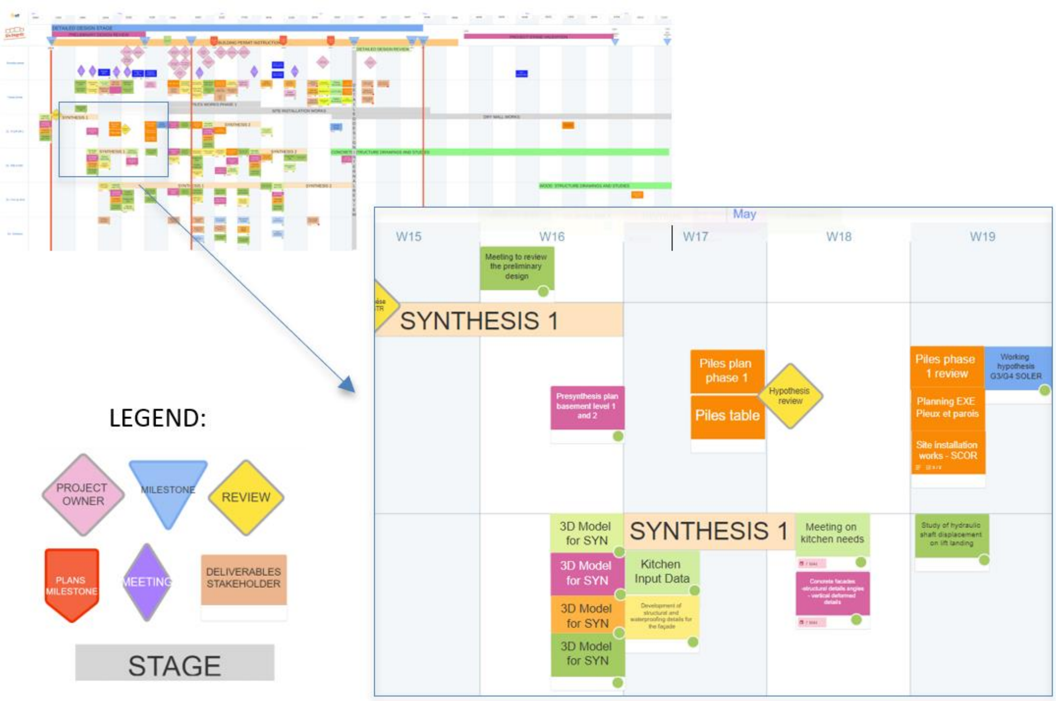

Figure 3. Use of digital tool “iObeya” to deliver the planning for design tasks

The integration of lean and digital tools was done through the whole design phase. In addition to the use of building information modeling (BIM) and digital meeting platforms to conduct online meetings between different partners, a digital space for sharing project information was established. This space served as a room for all managers, leaders, and employees to share their ideas, collaborate, and ask questions. This space was based on two main tools:

1. “iObeya”: a virtual collaboration platform that is based on the Obeya method, which is based on establishing a room for project partners designed to improve communication, collaboration, and decision-making. The use of the Obeya method

is helpful to track the progress, discuss the design, and engage different stakeholders in the discussions. For the two studied cases, "iObeya" included panels for LPS and KANBAN. Figure 2 shows an example of the use of "iObeya" in the planning for the design tasks. The figure depicts how partners were able to use notes and stickers during the implementation of LPS.

2. "SharePoint", which is a collaborative document-sharing platform. In this platform, partners were able to access all project information including project information and organization, details about meetings, weekly tasks, progress toward KPIs and milestones, requests for order and information, and reports and drawings, in addition to links to emails, shared calendar, and "iObeya" room.

THE SECOND SURVEY

To assess the impact of lean implementation and the effectiveness of the used tools in the two cases, a second survey was developed. The survey was developed using Microsoft forms and distributed to the emails of 37 stakeholders who participated in the design phase of the projects. The survey included five main sections, which are:

1. The role of participants
2. The created impact in the two projects due to the implementation of lean practices in planning for the design tasks (four point-Likert scale: 1) strongly disagree, 2) disagree, 3) agree, 4) strongly agree)
3. The contribution of the tools used to improve the planning for design activities (yes/no questions)
4. The benefits of lean implementation in the design phase (yes/no questions)
5. Readiness to implement lean management again (yes/no question)

RESULTS AND ANALYSIS

The second survey was filled by 25 participants, representing a response rate of 68%. The participants were from engineering studies and design office (9 participants), architectural office (5 participants), owner representatives (5 participants), general contractor (3 participants), in addition to three participants who were working as BIM manager, landscape manager, an employee in the control office.

Table 1. Created Impact in the two projects due to lean implementation

Lean Implementation Impact	**Overall**	**Case 1**	**Case 2**
Better consideration of customer expectations	3,30	3,28	3,31
Better responsiveness to integrate project changes	3,25	3,00	3,37
Compliance with work costs	2,64	2,67	2,64
Compliance with study deadlines	3,48	3,22	3,64
Improved working and collaboration conditions	3,36	3,00	3,47
Improved design brief quality and consistency	3,36	3,37	3,36
Better preparation for the works phase	2,89	2,80	2,91

The analysis of the results revealed that participants in the study believe that the use of lean tools in the planning for design tasks helped to present different outcomes (as shown in Table 1). The highest impact was found on the compliance with the study deadline (mean= 3.48 out of 4.00), which was the second most challenge found in the first survey. While the lowest impact was on compliance with cost, which was the most difficult challenge found in the first survey. Nevertheless, the rate is still acceptable as the mean equals 2.64 out of 4.00 (66%). Participants also give high and approximately similar rankings to improved design brief quality and consistency improved working and collaboration conditions (mean= 3.36), Improved design brief quality and consistency (mean= 3.33), better consideration of customer expectations (mean=3.30), and better responsiveness to integrate project changes (mean= 3.25). In comparison between the perspectives of the participants from the two projects regarding the impact of lean implementation, the analysis showed similar rankings for most statements with slightly higher ratings in the second case for the responsiveness to integrate project changes, compliance with the deadline, and improved working and collaboration conditions.

Regarding the benefits of lean implementation in the planning for the design phase. Figure 4 shows that most participants agreed that lean can help to organize the design smoothly, improve the efficiency of the planning, understand and share the objectives and expectations of the client, improve the collaborative environment between all stakeholders, and improve the decision-making process and validate the study effectively.

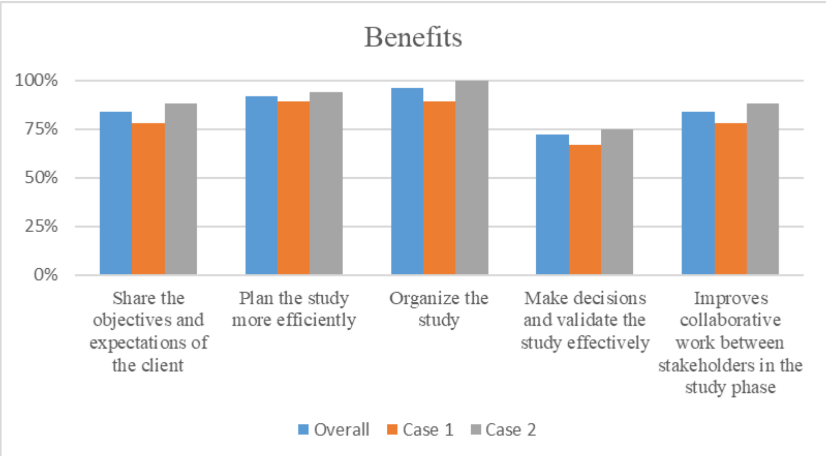

Figure 4. Perspectives about the benefits of lean implementation in the design phase

Regarding the contribution of the tools used to improve the efficiency of the planning for the design, the highest-ranking was for the meetings organized to conduct the planning; all the participants in the survey stated that these meetings were effective to improve the planning for the design. The meetings with the owner and phase planning that was done during the seminar received the second-highest rating (88% and 86% respectively). The implementation of digital tools (Sharepoint – iObeya) was considered effective to improve the planning efficiency by 16 participants (64%). While the lowest ranking was surprisingly for scheduling delivery of BIM models based on studies (48%) and establishment of production indicators (52%).

DISCUSSION

The purpose of this study is to investigate the impact of the use of lean tools during the planning of design activities. The main used tools in the cases are LPS, KANBAN boards, and visual management. The results showed that most participants in this study believed that the adoption of these tools is helpful to deliver the design on time, meet customers' expectations, improve the quality of the design, and achieving better collaboration between the team members. The results of this study are consistent with the studies about the applicability of lean tools in design management (Fosse & Ballard, 2016; Fundli & Drevland, 2014; Hamzeh et al., 2009; Kerosuo et al., 2012; Khan & Tzortzopoulos, 2015; Rosas, 2013). Additionally, it was noticed that the use of KANBAN boards improved the knowledge sharing, transparency, and decision-making during the design phase as it helps to improve information flow, focus on the priorities and pull the design to be consistent with the needs instead of pushing the design to finish based on predetermined deadlines. This result supports the finding of Modrich and Cousins (2017) who stated the combination of LPS and KANBAN is necessary to improve the design management. This combination was supported in the two cases by visual management, which helped to ensure better workflow and knowledge sharing among the partners.

Moreover, the results of the study showed that digitizing the used lean tools was effective in the design phase. The used digital tools helped to keep the partners connected with each other's and improved the collaboration environment, communication, and transparency between the partner. Additionally, these tools served as an easily-accessible reference that included information about the plans and progress in the projects. This was very helpful especially during the times of the lockdown due to the COVID-19 pandemic. The ranking for these tools was even higher than that given to BIM. This might be because the partners had already some knowledge about BIM, while lean and digital tools were newly presented to them.

Finally, during the analysis of the results, a slightly higher ranking for the impact and benefits of lean was given in the second case study. While this difference was not investigated during the conduction of the study, the authors believe that the duration of the intervention might be the reason for the difference. This is due to two reasons; firstly, the needed time to build a culture of lean and see the impact of lean adoption (Albalkhy and Sweis, 2021), and secondly, the impact of COVID-19 as in this project, participants were able to be exposed to the use of lean before and after the pandemic and noticed how lean can improve managing the design during uncertainty times.

CONCLUSION

Design is the first phase in construction projects. The deliverables of this phase should clearly and accurately reflect the client's needs and requirements to ensure that these needs are met along the whole project life cycle. Therefore, the planning for design to ensure the success of this phase is essential as it defines the objective, deliverables, and success criteria and the steps that are needed to achieve success. This study shows that lean implementation can be a key to the success of the design due to its role in improving the planning for the activities in this phase.

The current study was conducted during the time of the COVID-19 pandemic, which has affected all practices in all industries. Nevertheless, during the work in this study, all measures were followed and the levels of digitization increased to adapt to the new situation. Therefore, this study does not only serve as a good example of the applicability of lean tools in construction design management but also contributes to the provided solution about lean digitization and lean implementation during times of uncertainty. Moreover, this study used quantitative data collected from participants in two case studies to show the impact of lean and digital tools on the planning process; future studies can use other types of data collection methods such as interviews or focus groups. In addition, future studies can use thorough and detailed indices to assess some variables such as trust, communication, decision-making process, knowledge sharing, and other variables. Moreover, future studies can cover the integration of lean and other digital practices and tools in design management such as cloud computing, artificial intelligence, and big data analytics.

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DEVISING AND IMPLEMENTING PROCESS MODELS WITHIN INFRASTRUCTURE ENGINEERING DESIGN

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ABSTRACT

A plethora of process models have been developed over the years with the aim to improve the performance of design and construction processes. However, effective adoption of process models is still limited; lack of guidance on which model type would be applicable in the given contexts, and an excessive focus on the design of the process models themselves instead of their implementation may be some of the reasons for this. This research investigates how process models should be used within infrastructure engineering design, considering also how different methods suit different purposes. Findings from an ongoing research project in the UK are presented, following case study as its research strategy. This paper reviews the use of process models and clarifies their relationships by describing the adopted models and comparing them with the models explored in the literature, increasing the understanding of process models within infrastructure engineering design. Benefits, limitations and challenges are also discussed, supporting future applications.

KEYWORDS

Lean Design, Infrastructure, Process Models, Value Stream Mapping, Ji Koutei Kanketsu

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INTRODUCTION

Difficulties in managing the design in construction are a consequence of the complex nature of the process, as decisions need to be made in an uncertain environment (Ballard and Koskela 1998). Moreover, there are many factors that often push the design process away from the optimal design sequence, e.g. internal and external uncertainty, resulting in extended durations, low productivity and decreased quality of the design solution (Koskela et al, 1997). Thus, design processes are especially challenging to manage and navigate when compared with other processes, such as construction or manufacturing, as they tend to involve aspects of iteration, novelty and complexity to a great extent (Wynn and Clarkson 2018).

In this context, it has been recommended that development and improvement of process models can help to navigate and address those challenges in several ways (Cooper and Kagioglou 1998; Wynn and Clarkson 2018). Several methods for the analysis of business operations depend on representation known as business process models (Dumas et al. 2009), which are the combination of a set of tasks with a structure describing their logical sequence and dependence, aiming to produce a desired output (Aguilar-Savén 2004). However, no single model can address all the issues, as it involves taking into account the purpose of the analysis or uses of the models, and the knowledge of existing modelling techniques (Aguilar-Savén 2004; Wynn and Clarkson 2018). Further research is needed to investigate how models can be most effective. Thus, the aim of this paper is to increase the understanding of process models within infrastructure engineering design and clarifies their relationship by comparing them with the models explored in the literature. The contribution is related to the guidance on how process models should be used in civil engineering projects, considering different purposes.

DESIGN PROCESS MODELLING

INTRODUCTION

Even though the design process involves novelty, complexity and iterations, it also contains routine sequences and structures that can be modelled (Wynn and Clarkson 2018). Process models may be beneficial to reduce the possibility of missing an important step, allow design to be transferred and coordinated, enable planning, improve communication among disciplines, and generate or communicate conceptual insights (Gericke and Blessing 2011; Wynn and Clarkson 2018). It can also support standardisation, improvements, and optimisation of processes. Different definitions of processes can be found in the literature, and there has been an evolving debate about these definitions (Tzortzopoulos et al. 2005).

Two main process model types used for understanding, organising, and improving the work and information flows are described in the literature as 'as-is' and 'to-be'. The 'as-is' model, also described as true maps of what happens, can provide a clear understanding and description of the current state using a descriptive approach, whereas the 'to-be' model, also called as potential maps of what ought to happen, prescribes an action for improvement; and it is argued that both models are required (Tzortzopoulos et al. 2005). Models can also present different levels of process detail. They are described as: (i) generic or high-level maps, which can provide an overview of the entire process, including the key stages or sequences, the information flow between different actors, deliverables and stage reviews (Cooper and Kagioglou 1998; Tzortzopoulos et al. 2005); and (ii) detailed maps, which usually adopt structured modelling approaches (Sanvido

1990), focusing on information flows. Recent studies also refer to other key elements that can be measured to analyse the information flow in design, such as batch sizes, flow bottlenecks, and work in progress (WIP) inventories (Tribelsky and Sacks 2011). The process maturity is often recognised as: (i) initial processes; (ii) repeatable processes; (iii) standardised processes; (iv) measured and controlled processes; and (v) optimised process (Macintosh 1993). Levels one to three are associated with describing the process, whereas levels four and five are related to decision support to monitor the process (Aguilar-Savén 2004).

The sections below introduce commonly used design process modelling techniques, such as swim-lane, Value Stream Mapping (VSM), and Ji Koutei Kanketsu (JKK).

COMMONLY USED DESIGN PROCESS MODELLING TECHNIQUES

There are plenty of business process modelling techniques, and the most frequently used are identified as: flow chart, data flow diagrams, role activity or interaction diagrams, Gantt chart, business process modelling notation (BPMN), workflow technique and swim-lane, also called as cross-functional diagram (Aguilar-Savén 2004; Jeyaraj et al. 2014). Swim-lane diagrams are considered to be a primary modelling technique when assessing business procedures and rules as they convey information to stakeholders, especially when they include important visual signs, as well as collaborative and decision making activities (Jeyaraj et al. 2014). They help in visualising the flow of information, identifying how the information is exchanged among stakeholders, and highlighting the information deliverables (Al Hattab and Hamzeh 2013). Swim-lane differs from other diagrams in that it can consider user roles for the workflow, assigning activities or boxes to specific user groups, and it can include criteria to define which activity comes next if various activities are available, defining the sequence of activities (Jeyaraj et al. 2014). Design and construction efforts in lean projects start with collaborative process modelling, in order to create a common understanding of the process among all stakeholders and to enable the teams to identify and analyse waste (Chiu and Cousins 2020). Swim-lane is one of the techniques adopted in the collaborative process (Chiu and Cousins 2020), and usually each lane represents a function or discipline, and a timescale is considered as columns, in order to develop an achievable time-lined plan for the project.

VALUE STREAM MAPPING

Value stream mapping (VSM) is a technique that can help companies to identify long lead times, non-adding value activities, bottlenecks and other wastes, and then address the root causes (Rother and Shook 2003). VSM can provide a road map for process improvement, as it compares current (as-is) and potential future states (to-be) (Arbulu et al. 2003). This technique can help understand the flow of information and materials as a product progresses through the value stream (Rother and Shook 2003). A value stream map follows a product's production journey from the start to the end, i.e. customer to supplier, and visually represents every step in the information and material flow (Rother and Shook 2003). It can also look across individual functions, activities, departments and organizations and focus on overall system performance (Arbulu et al. 2003).Thus, VSM proposes a holistic perspective of how the work flows through the whole system. It can be carried out in three key steps, i.e. identifying and organising the process tasks and information flows, collecting performance data, and assessing how value is created (Mcmanus 2005). Martin and Osterling (2014) describe the key benefits of VSM, such as: (i) it provides means to establish a strategic approach for improvements through various degrees of granularity; (ii) it provides a highly visual perspective of the full cycle, its components and cross-functional work systems; (iii) it deepens the understanding of value adding activities and their delivery; and (iv) it provides data-driven decision making. This technique can be used to support important processes in product development (Wynn and Clarkson 2018). However, the VSM concepts need to be adapted from manufacturing to construction, e.g. defining the specific element to be investigated and the unit of analysis (Rosenbaum et al. 2014), and this can be considered a challenge. The time spent to collect the current state data can also create difficulties associated with the continuous use of VSM (Forno et al. 2014)

JI KOUTEI KANKETSU

Ji Koutei Kanketsu (JKK), which means 'complete your own process' in Japanese, is based on the fundamental concept of '*jidoka*' and tailored for non-production departments, which mostly deal with intangible products such as information (Manabe and Heller 2014). The JKK focus is the 'individual', which is frequently neglected in the whole management process. JKK is considered a process design method that designs and arranges activities in suitable order, simultaneously attaching the necessary conditions and judgement criteria to those activities (Manabe and Heller 2014). JKK's process model supports the individual to understand the whole process where their activities are embedded. The process model is normally presented in the Work Process Flow Chart, within which the process is described clearly and detailed from start to end (Manabe and Heller 2014). The implementation of JKK does not end at developing an overall process flow chart; in fact, its implementation comprises the adoption of all JKK's focal elements: (1) work purpose/target, (2) work processes, (3) necessary conditions, (4) judgement criteria, and the implementation of PDCA in daily work. After understanding the work purpose/target, and work processes, the individual continues to identify their own activities within the process and breaks them down into work units, down to the smallest element where one can make their own decision (Manabe and Heller 2014). Continuously, the two JKK's focal elements -necessary conditions and judgement criteria- should be attached to each work unit. The purpose of having these two elements for each work unit is to help the individual avoid producing defective outputs due to a lack of work required conditions, and to operate self-assessment of their own works.

RESEARCH METHOD

An empirical case study was carried out at an infrastructure design and consultancy company in the UK as part of a Knowledge Transfer Partnership (KTP) project. KTP is a partially government-funded programme, sponsored by InnovateUK, to encourage collaboration between academia and industry, and this project is exploring the integration of Lean and digital design. A case study explores a contemporary event in depth and within its environment, particularly when the boundaries between the event and context are not clearly defined (Yin 1994). The research consisted of the development and critical analysis of the process modelling methods adopted by the company. The investigation is limited to highways construction projects.

The study was conducted in four stages: (i) overall process modelling of all disciplines, carried out by the research team in collaboration with company staff; (ii) discipline specific, BIM and digital process modelling, developed by the research, design and BIM team members; (iii) VSM of selected disciplines and projects, carried out by the research team and an external consultant in collaboration with team members; (iv) JKK implementation on a design process developed by the research team in collaboration with company staff; and (v) analysis and reflection on the theorical and practical contributions. The processes were selected through a top-down approach, identifying relevant processes to the company, i.e. projects that characterise a significant portion of the business and interface with various disciplines, as well as processes that are carried out through informal and inconsistent approaches, with no clear definition of responsibilities and sequence of activities, such as the clash management BIM process. The main sources of evidence are: (i) open interviews with the design discipline leads to develop the overall process modelling; (ii) workshops with the design and BIM team members to develop the process models; (iii) workshops with key stakeholders to validate and present the process models developed; (iv) analysis of design documents and existing protocols; and (v) iterative cycles of reviews with the research team, external consultant and key stakeholders.

DESCRIPTION OF THE PROCESS MODELS ADOPTED IN THE COMPANY

The starting point of the process modelling activities was the overall process modelling of all disciplines (Figure 1), aiming to identify key interfaces and interdependencies among all disciplines involved in the design process. The company and the research team realised that a more detailed process map for each discipline (Figure 2) was required in order to identify the stakeholders involved, as well as the opportunities for improvement. The use of Lean techniques, such as detailed swim-lane, VSM and JKK, to map subprocess (Figure 3, Figure 4 and Figure 5) emerged as a necessity to better understand the necessary conditions and judgment criteria of each activity, as well as clarify the responsibilities, requirements and resources.

OVERALL PROCESS MODELLING

The focus of the process modelling exercise was to achieve a comprehensive understanding of the current BIM-based design processes, the interconnections between multiple disciplines and waste. This was the initial step in the company's effort in improving the design process performance. The BIM-based design process map was created through interviews with the design leads from various disciplines, which were a combination of face-to-face and online meetings. The company desired to examine all 17 disciplines involved in this practice; however, only 13 disciplines were assessed and mapped (Figure 1). The practice started by mapping activities for individual processes of the seventeen design disciplines, such as highways design, structures, and drainage. Then, individual processes were linked together to create a synthetic process diagram by connecting their shared activities. Beside the need to present a series of process steps, the design disciplines were also the central feature of the map, which led to the selection of a swim-lane diagram for this practice. The key benefit expected was associated with building an understanding between the cross functional discipline areas.

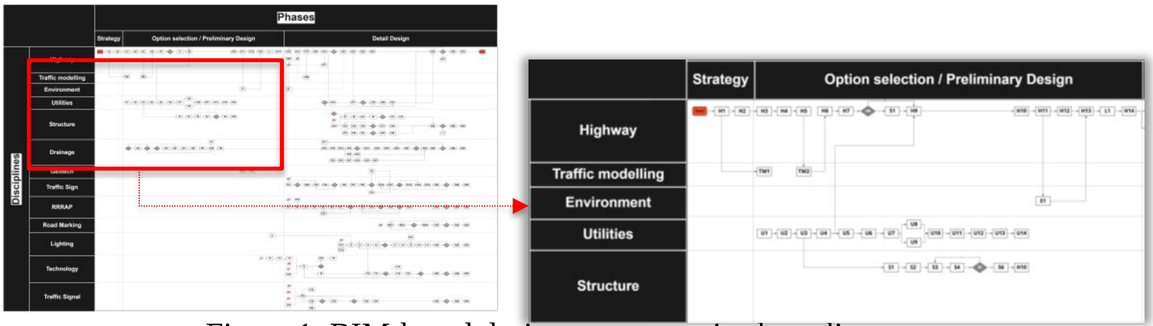

Figure 1. BIM-based design process swim-lane diagram.

Through the modelling practice, the company discovered several existing issues within the current design process including (i) rework, (ii) redundant activities and (iii) lack of input when starting of activities. Rework regularly happened due to the deployment of activities in various disciplines without having adequate input information and all the necessary conditions in place. Lack of awareness of which activities can be automatically carried out led to the occurrence of redundant activities. The involvement of multiple design disciplines caused numerous challenges for the process mapping, including (i) the difficulty in choosing appropriate design leads who have an in-depth comprehension of their own works, (ii) the time consumed while linking all individual processes into a synthetic process, (iii) laborious reviewing of the process maps, and (iv) the massive size of the diagram, creating barriers for its implementation and practical use.

DISCIPLINE SPECIFIC PROCESS MODELLING

The design discipline specific process models (Figure 2) were introduced as a countermeasure to the difficulties identified within the overall process modelling, identifying the key stakeholders, and opportunities for improvement within specific activities. The improvements were mostly related to early involvement of the internal and external stakeholders, checking and coordination activities, standardisation and automation of the design activities. It consisted in the following steps: (i) developing a process map based on previous experience and in collaboration with the key stakeholders, such as the discipline leads; (ii) validating with the team members through workshops; (iii) testing the process in a trial project with similar characteristics; (iv) identifying, analysing, planning and implementing the improvement opportunities, aiming to remove waste and generate value for the client; and finally (v) capturing, measuring and monitoring the benefits realised. It followed the same approach as the overall process modelling, i.e. swim-lane diagram, as the stakeholders and the key design phases had a central role in the model. The digital platform Miro (https://miro.com/) was adopted to support the initial and collaborative discussions regarding the identification and sequencing of activities. As soon as a process was agreed and validated with the team members, the information was transferred from to Microsoft Visio, aiming to connect it with the company intranet. The company mandated for all design discipline specific processes to be owned and developed by each community of practice and discipline leads, with the support of the Lean and digital team, in order to identify improvement opportunities and wastage.

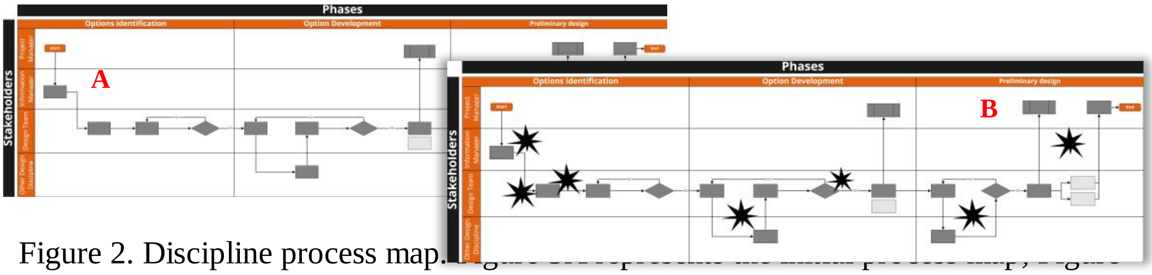

Figure 2. Discipline process map. Figure 3A represents the initial process map; Figure 3B, the improvement opportunities identified.

The key benefits realised from this modelling exercise were related to the visualisation of the process, creation of standard models with the potential to implement on similar projects, adoption of the model as a blue-print, training and educational tool for new staff. These can lead to the reduction of procedural errors, identification of missing activities in the current practices and understanding the complexity and interaction within the activities. The key challenges of this exercise were related to the lack of availability of the disciplines to engage in the mapping, reviewing and testing of the process map, as well as difficulties in implementing the process model itself.

BIM AND DIGITAL SUB-PROCESS MODELLING

BIM and digital sub-processes were the third level of the process analysis. The aim of this practice was to detail a key process, i.e. clash management (Figure 3), formalise the key steps and provide visual information of the process, as there is still a gap in its formalisation (Pedo et al. 2021). Most research considers only the software tools instead of the process elements (Pedo et al. 2021), leaving the resources, activity flows, and underlying purposes at a marginal level. The process modelling was also aligned with the overall BIM process maps developed by the company and with the ISO 19650 recommendations. The process modelling approach was very similar with the one adopted for the discipline-specific modelling, however, it was focused on the information flow. The activities were identified through workshops with the design and BIM leads and document analysis. The clash management process mapping exercise was restricted to highway design projects, however, the processes adopted in other projects within the company present a degree of similarity in key activities, which allows the standardisation of the model for other projects. The key challenges of this practice were related to the engagement of the BIM team to test and implement the process mapped within other projects, as well as to the capturing of efforts spent in the process.

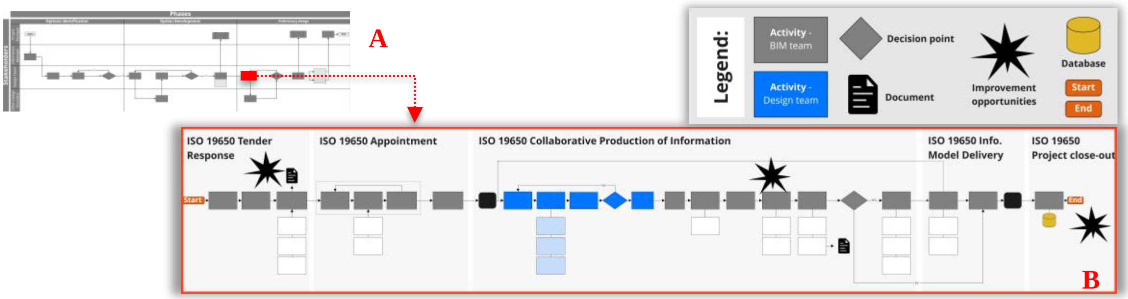

Figure 3. Clash Management process map. Figure 4A represents the BIM subprocess identified within the discipline process map; Figure 4B, clash management map itself.

VSM OF KEY DESIGN PROCESSES

VSM was adopted to capture a ‘current state’ and potential ‘future states’, illustrating opportunities for improvement. A steel bridge design process was value stream mapped as a pilot exercise. The VSM (Figure 4) was developed through workshops in collaboration with the bridge design team, the research team and an external Lean consultant, who led this initiative for the company. The starting point was the development of the current state, or as-is process, illustrating how the bridge is currently designed. The VSM was formed according to the key bridge design elements, such as initial assessment, pile design, beam design, substructure design, superstructure design, and review, represented in different lanes. The key process components contained in the VSM were the activities, resource required (number of stakeholders involved), cycle time, and waiting times in between boxes.

The current state map served as the basis for developing future state maps that would eliminate or reduce unnecessary steps, waiting times and interfaces. Issues and improvement opportunities were identified through discussions with the key discipline team members, supporting the design of the future states. Three different scenarios for future states were defined: (i) improved state (short-term improvements), (ii) ideal state (medium or long-term improvements), and (iii) perfect future state (perfect process with no waste). The team started developing the short-term improvements, following the medium-term improvements, but always aiming for the perfect future state. The challenges of this practice were mostly in implementing the future states, especially the resistance to change, and consequently, the lack of engagement from the designers. Another challenge was associated with the different types of bridges, thus, the VSM of one bridge was not replicable to all the bridge design currently ongoing within the company.

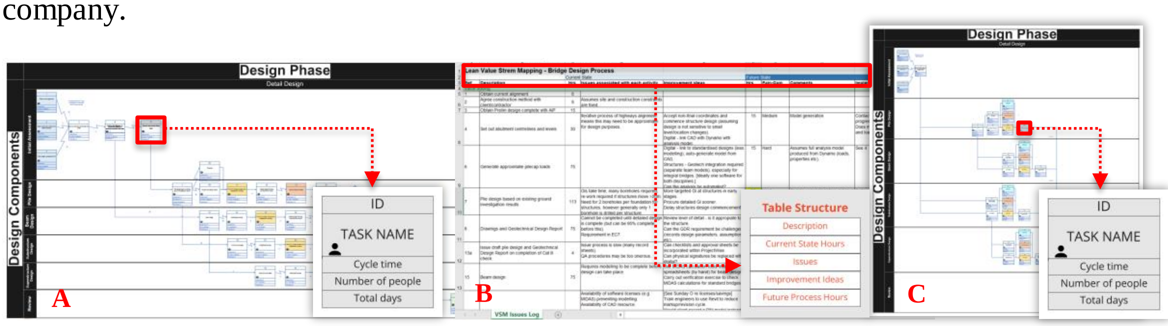

Figure 4. Current state process map for bridge design (5A), identification of issues and improvement opportunities table (5B) and perfect future state process map (5C).

JKK OF KEY DESIGN SUBPROCESSES

Process modelling was a part of the JKK implementation process in the Design Risk Management Process (DRMP). The main aim of the process modelling practice is to have the process work flow ready for the Designers and Principal Designer (PD) to support their understanding of the overall process and individuals’ work activities. The practice required the involvement of the PD and designers with aid from the research team. This practice is believed to support the PD and specialist designers (i) to have a better comprehension of the DRMP, (ii) to acknowledge who is their ‘foremost customers’ within a process, and (iii) to obtain the knowledge of what is needed for the work deployment and whether the products meet the requirements. Figure 5 presents the final DRMP work flowchart and detailed analysis of the two features for each work unit. Although the practice sounds simple, applying it in a real-life context is difficult. The whole practice is a time-consuming task when trying to ensure the team members collaborate. It is difficult to represent the overall DRMP due to the different requirements and perceptions of the design team members.

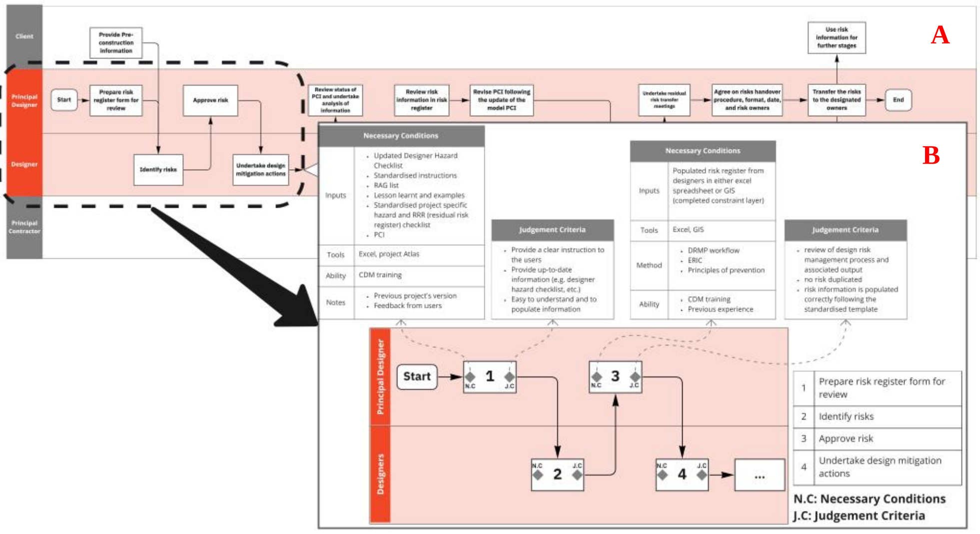

Figure 5. The Design Risk Management Process workflow chart (6A) and the necessary conditions and judgement criteria for each work unit (6B).

DISCUSSION

Table 1 summarises the key process modelling techniques discussed in this paper, when they should be adopted, their purposes, key elements, and the management effort required.

JKK has been recently introduced to the construction context and there are challenges associated with its implementation and adaptation to this new environment. The designers have faced difficulties in identifying tasks and their associated necessary conditions and judgement criteria due to a lack of clear client's requirements and pre-construction information, as also stated in Wynn and Clarkson (2018). There is also a lack of consideration of the JKK as a different approach to support commonly used design process modelling techniques. However, the introduction of JKK concept has partially aid the effort of understanding processes, sharing standard and knowhow between design team members. VSM, likewise, was not applicable in some cases, due to the issues concerning the element or component definition, as suggested by Rosenbaum et al. (2014), as well as the lack of clarity on how the design inventory should be calculated. There were also difficulties in collecting accurate data regarding the leading times and cycle times because of the uniqueness of the projects (Rosenbaum et al. 2014). This was found to be a time-consuming activity, as suggested by Forno et al. (2014), creating issues for continuous use of VSM.

All the different models, particularly the discipline-specific and BIM process modelling, were approached as a learning framework, providing opportunities for improvement and reflection for all the stakeholders involved in the process, corroborating with Tzortzopoulos and Sexton (2007). Other processes models functions were identified as enhancing communication and achieving consistency (Tzortzopoulos et al. 2005; Tzortzopoulos and Sexton 2007) through a common ground and shared understanding among the project participants. Process models can also provide a visual perspective of the full cycle (Martin and Osterling 2014) including different layers of information depending on the technique adopted and the role it performs, and can also formalise hidden processes as described in the clash management case study. Information can be displayed visually in rooms or virtual rooms, enhancing the participants' awareness about the activities, and this was achieved at the company through the adoption of visual management using digital collaborative platforms such as Miro or through the company intranet. A common ground is even more difficult to reach in a BIM-based design process due to the different standards and protocols that need to be followed; and process models seem to help in creating awareness of the steps, responsibilities, and stakeholders' and processes' interdependencies. This can be classified as a Lean contribution to BIM processes (Pedo et al. 2021), in which a Lean technique, i.e. process modelling, can be used to streamline and improve BIM processes.

Table 1. Guidance for process modelling in design.

Findings from the literature		Findings from the practical implementation in the case			
	Purpose and Maturity Level	***Company's Purposes***	***When***	***Key elements***	***Management of Process Models***
Generic swim-lane	**Purpose:** Describe the process (knowledge capture and analysis), and provide an overview of the entire process *(Aguilar-Savén 2004; Cooper and Kagioglou 1998; Tzortzopoulos et al. 2005)* **Level of process maturity:** Defined - documented processes standardised throughout the organisation *(Macintosh 1993)*	Achieve a comprehensive understanding of the design process, interconnection between multiple disciplines, and identify key interfaces	Overall process modelling of all design processes *e.g. 17 disciplines involved in the highways design*	Disciplines, design phases and overall activities.	Support high-level planning and provide a better understanding of interdependencies Standardise overall processes
Detailed swim-lane	**Purpose:** Describe the process (knowledge capture and analysis), and focus on information flow (Aguilar-Savén 2004; Sanvido 1990) **Level of process maturity:** Repeatable *(Macintosh 1993)*	Identify the key stakeholders and its interdependencies, roles and responsibilities, as well as opportunities for improvement, e.g. automation and standardisation opportunities	Discipline-specific processes *e.g. highways, drainage, structure*	Stakeholders (e.g. project manager, information manager, design team, other design disciplines), design phases, activities, decisions points, and key milestones	Top down approach to define the sequence of process to be modelled Support daily work and guide disciplines' schedule definitions (e.g. identifying new activities)
	Purpose: Describe the process (knowledge capture and analysis), and focus on information flow (Aguilar-Savén 2004; Sanvido 1990) **Level of process maturity:** Repeatable *(Macintosh 1993)*	Formalise hidden activities or steps, identifying resources, activity flows, and underlying purposes aligned with international standards	BIM and digital processes *e.g. clash management*	Stakeholders (specialists, e.g. design and BIM teams), activities and sub-activities, decision points, documents, database and connection with ISO or international standards	Top down approach to define the key processes to be mapped Support daily work, and standardise processes Tend to be adopted by specialists due to its high level of detail
Value Stream Mapping (VSM)	**Purpose:** Decision support to monitor and improve processes, and focus on information and materials flow *(Aguilar-Savén 2004; Rother and Shook 2003)* **Level of process maturity:** Managed - measured and controlled process *(Macintosh 1993)*	Create a roadmap for improvements between current and future states. Overall and systematic process improvement and waste elimination	Key design processes that represent large impact in the business *e.g. bridge design / structures*	Subprocesses of key design elements (e.g. beam design), activities, resource (number of people), cycle time, leading time, waiting time	Top down approach to define the processes to be value stream mapped Support a one-off improvement effort (removal of non-value adding activities) and schedule improvements (e.g. adjusting task durations) Future states considering different levels of planning (short-, medium- and long-term improvements)
Ji Koutei Kanketsu	**Purpose:** Decision support to monitor and improve processes, and support individuals in understanding the whole process *(Aguilar-Savén 2004; Manabe and Heller 2014)* **Level of process maturity:** Optimising - continuous process improvement *(Macintosh 1993)*	Improve and standardise individual tasks. Clearly state the input and output required for each activity.	Key process supporting the main design process *e.g. design risk management process*	Stakeholders, work flowchart, activities, necessary conditions, judgement criteria	Top down approach to define the processes to be mapped through JKK Support both the whole process and individual works

As argued by Tzortzopoulos and Sexton (2007), there is a need for meaningful participating and collaboration for a successful implementation, requiring appropriate involvement and engagement. The lack of engagement in designing and implementing the process models was identified as one of the key challenges associated with the stakeholders within the company. A joint effort is required to create process models, which can be currently enabled by virtual collaborative environments; also supporting new approaches for developing process models. The necessity of identifying a process owner and a workshop facilitator with process modelling knowledge was also observed as a significant aspect for process model development and implementation. However, a management effort is also needed for supporting process improvements considering the new digital environment. In addition to this, the management effort should consider different levels of planning (short-, medium- and long-term improvements), and define the management of steps for different needs in design.

CONCLUSIONS AND FURTHER RESEARCH

The complexity associated with the design process and sub-processes reflects in the different types of process models adopted within the company. The process modelling techniques adopted vary according to the different levels of detail required, different purposes and uses, different types of processes, and the elements needed. In addition to this, the management effort is also essential for supporting the design and implementation of process models. The investigation reviewed how process models were used in infrastructure engineering design, by analysing, developing, and implementing various process models' techniques for different purposes and by comparing them with the techniques investigated in the literature. The contribution of this investigation is related to an increased understanding of how process models should be used in civil engineering projects, as well as benefits, limitations, and challenges. This research is limited to the analysis of four process modelling techniques at a single design company, further work should explore a substantial number of process models' techniques and purposes, encouraging a further reflection about the benefits and barriers, as well as refining the recommendations.

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VISUAL MANAGEMENT STANDARD OF THE REINFORCEMENT STEEL PROCESS IN MEXICO.

Fernando Daniel Lazcano Hernández[1], Eugenio Pellicer Armiña[2]and Salvador García Rodríguez[3]

ABSTRACT

The importance of standardizing processes is one of the basic principles of "Lean" practices, it reduces the workload for the Construction Industry. It is important, particularly because of its artisanal process in Mexico. We can ask ourselves, how to adapt the standard with Visual Lean Management of a steel reinforcement work process that is used in Housing in the Construction Industry in Mexico? This attempt is still in its infancy, that is, the vast majority of the processes are not standardized. The studied process is based on the Mexican competency standard ECO-351-Manufacture of structural elements with reinforcing steel, as a spearhead to standardize the processes, of the concepts in general of the construction, to close the entire work cycle of the work, this article aims to highlight the importance and promote standardization, always seeking continuous improvement of the process by the user, but with a visual management approach (VM), so that production workers understand it faster and easier ; it was carried out through the cycle of continuous improvement of Deming (PDCA).

KEYWORDS

Standardization, Visual Management, Lean Construction, Continuous Improvement.

INTRODUCTION

Standardizing a work process with the idea of solving problems, based on the Continuous Improvement methodology, also known as the PDCA cycle, initiated by Shewart and later by Deming, is the main foundation of the Toyota philosophy, and the importance of VM Visual management to make the process transparent.

Two of the most important efforts that have been implemented to improve the construction industry are: construction without losses or "Lean Construction " and construction automation; however, one of the fundamental elements of the lean manufacturing system "Lean Production " is the Visual Management "Visual Management or VM" (Valente C., Brandalise , F., Viana, D. & Formoso C., 2018), which is an intrinsic part of the Toyota production model (Koskela,L ., Tezel , A., &

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Tzortzopoulos , P., 2018). According to Koskela et al., (2018), it is only recently that the academy has started with the creation of theoretical knowledge around visual, management, which until now derived from a practical evolution rather than from a theory. Housing construction in Mexico is one of the sectors with the highest production in the country, as a result of a recognized deficit in housing construction (CMIC, 2018), this construction sector is the fourth economic activity that generates wealth, contributing 7.4% to GDP in 2021 (first quarter) (CMIC, 2021)

Construction in general is noted for its low yields, lack of standardization, safety, high waste, low quality, modularity, high costs, among others, particularly in Mexico the construction industry is listed as the Industry with the most risk of work, established by the Mexican Social Security Institute (IMSS) in the Social Security Law, Work Risks Art. 73 and 74.

It is important to mention that Mexico has a great tendency to continue using labor, that is, building in an artisanal way, depending on the administrative personnel of the work (Corporal, Crew Chief, foreman, construction manager, or first command according to to the Regulation of the Law of Public Works and Related Services, superintendent, construction manager, front manager, resident) internal clients, and taking care of the satisfaction of the external client, which implies a valuable commitment of the people involved in the production, which generate a high impact on quality in execution, safety, cost, likewise, in the flow of processes through planning, continuity and monitoring of activities, to finish in a timely manner to optimize its management.

Construction works generally change from one project to another, with the exception of industrialized works, such as vertical and horizontal massive housing to mention an example, it is common for those in charge of the work (Manager, Administrator, superintendent, resident , etc.) according to their experience, academic degree and personality lead their own works, since companies in general allow them to do so, generating a wide variety of styles and forms in all construction processes, which is why the importance of standardizing work processes within the general construction cycle, seeking systematization and transparency with the lean approach. The ability to measure, understand, and manage variability is essential for effective project and process management (Ballard & Arbulu 2004). If there is no agreed standard, a new way of doing is simply one more version of some individual, and it is just practical (Lander & Liker 2007).

According to (Gadde and Hákansson, 2001; Samuelsson, 2006), a strategy to increase customer satisfaction in construction is to minimize uncertainty and increase the systematization of the construction process. This article answers the research questions:

How to adapt the standard with Visual Lean Management of a Steel Reinforcement work process used in Housing in the Construction Industry in Mexico? How to implement a Steel Reinforcement Standard in structure, as a pilot theoretical process with the Visual Management methodology and continuous improvement PDCA for Real Estate Promoters-Home Builders in Mexico?

The objective is to adapt and implement the standard in an way that is easy and simple to understand by the production personnel on site, supported by Visual Management (VM) of the lean construction methodology, of the standard used in Mexico, ECO-351-Armored elements structures with reinforcing steel", within the city, for residential buildings of up to 10 average levels and systematizing a theoretical pilot standard to promote all the concepts of the work cycle of a construction.

CONTEXT IN MEXICO

If we add to this the lack of some supplies of standardized materials that comply with established standards, in the case of Mexico there are three: **Mexican Official Standard (NOM)** is a technical regulation of mandatory observance, the legal framework that regulates the expedition and its compliance is the *Federal Law on Metrology and Standardization* published on 07/01/1992 in the Official Gazette of the Federation (DOF), the other is the **Mexican Standard (NMX),** a reference instrument to determine the quality of products and services. . They are prepared for public use by a national standardization body or the Ministry of Economy, their objective is to protect and guide consumers, they are not mandatory, their compliance is voluntary, but if it refers to an NMX, it will be mandatory, the third is **Reference Standards (NRF)** are prepared by the public administration. The legal framework is established in the Agreement on Technical Barriers to Trade (AOTC), as well as in the Federal Law of Metrology and Standardization (LFMN) and its Regulations.

A standard of materials and of the proposed process we have the Information References ·NMX-C-407-ONNCCE-2001 Construction Industry-Corrugated Steel Rod from ingot and billet for concrete reinforcement.- Specifications and Test Methods.

A fundamental principle of the 1944 International Labor Organization (ILO) Declaration of Philadelphia is that labor is not a commodity; meaning that workers should not be treated as a factor of production or subject to the same market forces that apply to commodities. The vulnerability of workers and the need to protect their basic rights is reflected in the "Universal Declaration of Human Rights and in the International Covenant on Economic, Social and Cultural Rights".

The National Council for Standardization and Certification of Labor Competencies (CONOCER) recognizes the knowledge, abilities, skills and attitudes of people, acquired at work or throughout their lives, with national and official certifications, is committed to increasing efficiency and effectiveness of the internal operating process; to satisfy the requirements and needs concerning the standardization and certification of labor competencies; In accordance with Mexican laws, the applicable regulations and the continuous improvement of the Quality Management System, there are competency standards (EC) in Construction.

STANDARDIZATION

Currently in Construction of Civil Engineering Works, they are particularly for management and administration processes, in subsector 236 Building there is the **ECO-351 standard** -Assembly of structural elements with steel reinforcement oriented to people who must have knowledge, abilities, skills and attitudes to perform in the assembly of structural elements with reinforcing steel, published on October 5, 2013, and developed by the Mexican Chamber of the Construction Industry, the purpose of the Competence Standard is to serve as a reference for the evaluation and certification of the people who work **assembling structural elements with steel reinforcement** . The **Competence Standard** establishes the critical functions that an iron officer must perform for quality work, these functions are: Carry out work prior to assembly, for which the identification of supplies is carried out to start the assembly work , **enable** the material, and prepare the list of supplies to be used in the **assembly** ; on the other hand, place the reinforcing steel in the structural element; For this, the element is drawn and the respective ties are made to the reinforcing steel rods of the structural element according to what is specified in the project; which will be taken as a basis for the proposed process with a Visual Management approach as a contribution.

PROCESS MAPPING

To identify the correct process and its implementation of the Steel Standard for steel reinforcement in PDCA structure with Visual Management and for Real Estate Promoter-constructor of housing in Mexico, **the process was mapped** with a SIPOC diagram as a tool of the structure or flow of research and documentation, to visually analyze and manage the problem of the standard, with an assertive visual description to achieve the objective, achieving the division of the investigation over time, or the first step for the implementation of a lean construction system, seeking to reduce the variability of the processes, trying to eliminate or reduce inefficiencies or recurring waste.

It is important to mention that visual management is the essential part of the Toyota Production System (TPS) and has a key role in creating transparency (Liker, 1997; Formoso et al., 2002). Generally, communication and transparency problems are evident in the application of planning and control in construction based on Lean concepts, such as the Last planner System (Alarcon & Conte, 2003; AlSehaimi et al., 2009; Kalsaas et al., 2009).

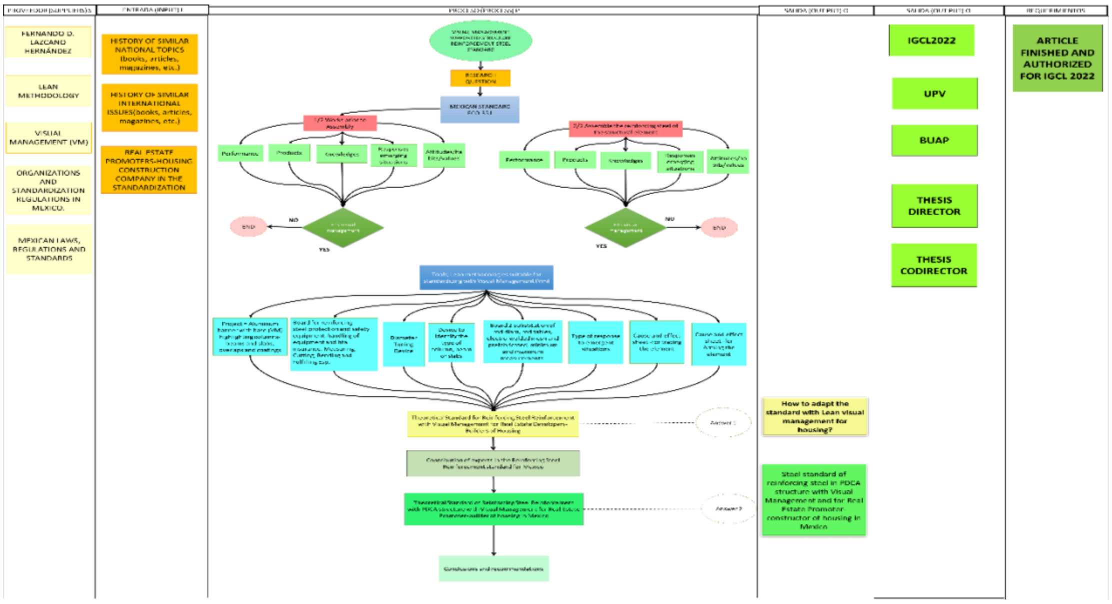


Figure 1 SIPOC Diagram of the Steel Standard for reinforcing steel in PDCA structure with Visual Management. (own source and tabular format Lean-Inn.com)

A common expression at Toyota is “We don't just make cars; we make people”. Every new product development program, every prototype, every quality defect in the factory, every kaizen (Japanese term for continuous improvement) **is an opportunity to develop people** (Liker, 1997).

If there is no transparency of information between planning and execution, it makes it difficult to identify problems before execution (Koskela & Howell, 2001). One of the techniques to implement improvement actions are the Deming cycles or also known as cycles. PDCA (Plan-Do- Check - Act), is a continuous improvement cycle, based on a scientific method, to implement change or standardize a process, to measure and control it, with the main idea of carrying out adjustments, improvements or relevant actions (Pons & Rubio, 2019).

With the support of the process mapping of the following Figure No. 3, the research process was mapped graphically to be competent, it must demonstrate certain criteria such as Performance, Products, Knowledge, response to emerging situations in addition to complying with habits, values and attitudes.

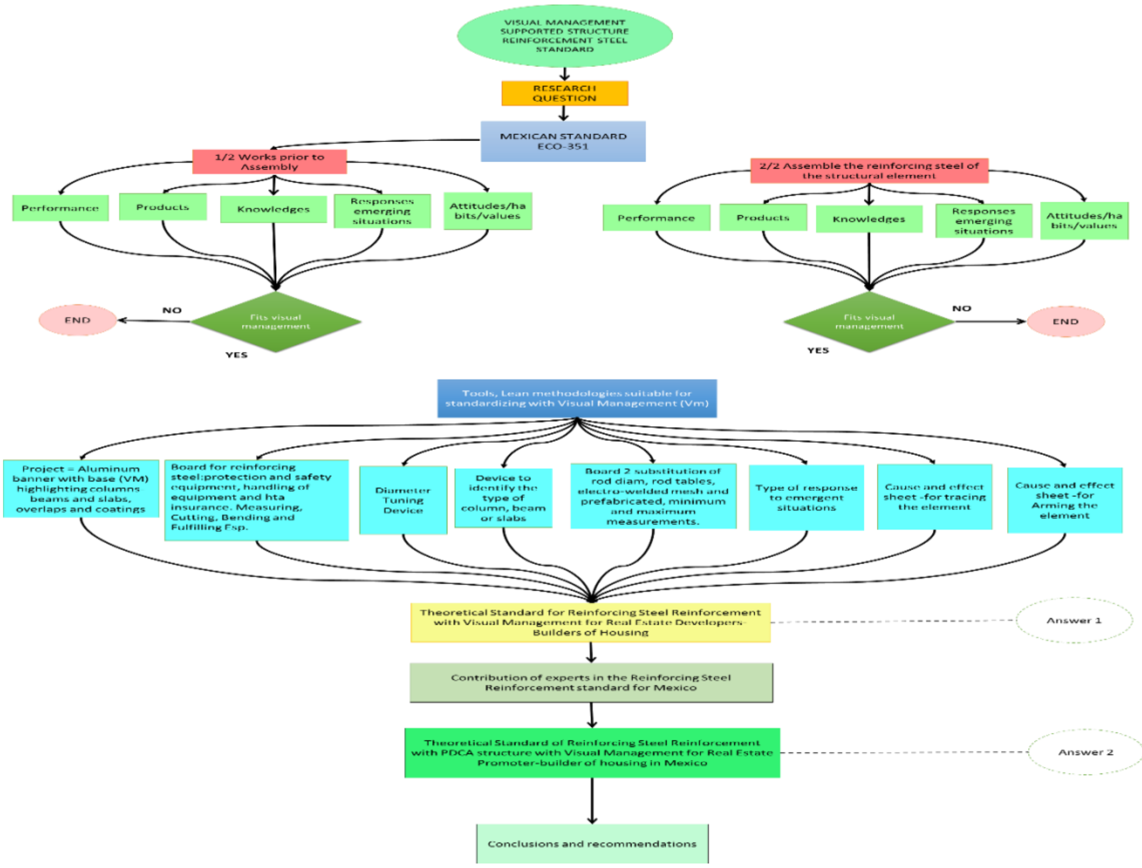


Figure 2 Mapping of the research process in graphic form. (Own source)

Once the competencies of the standard have been determined, we are going to establish the support tool, or Lean Visual Management (VM) methodology, a greater standardization in construction is suggested, to identify the causes of production problems, establishing and systematizing routines greater efficiency and thus easier process control for site administrators (Ungan, 2006).
In addition to Liker, Höök (2008) found that standardizing processes is predictable and essential if a Lean culture is to be pursued. Gibb and Isack, (2001) found that standardization minimizes cost, generating a positive impact on the processes within the general cycle.
Based on the research, we are going to establish the criteria that must be met to be competent in the standard, but with the innovation of being supported with adequate Visual Management tools or methodologies for a better understanding; easily and simply by the staff, from production to work, always seeking the development and growth of people.

In order to be competent in the standard, we are going to develop, in the first instance, the initial PDCA that meets the aforementioned characteristics.

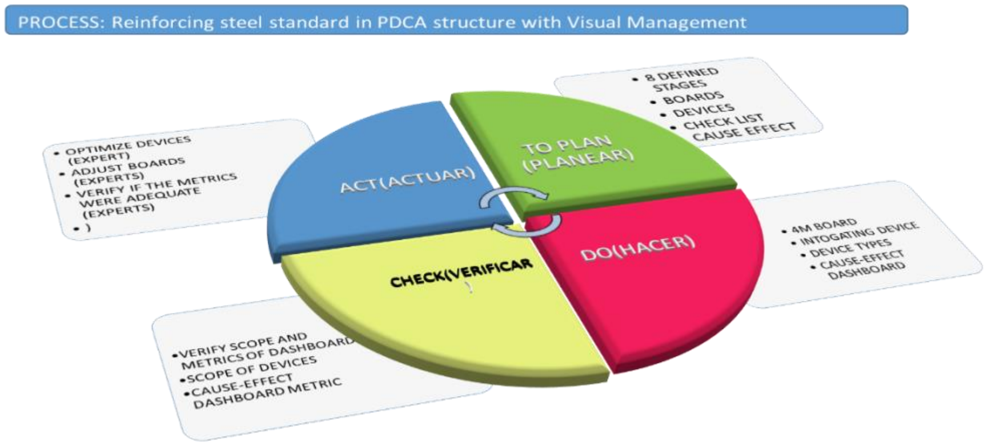


Figure 3 PDCA Continuous Improvement Cycle of the standard research process in graphic form. (Own source)

Seeking continuous improvement and innovation, trying to change the way of thinking, acting and learning collectively and individually with a common goal, think of the cycle of continuous improvement of people as a system:

1.- Standardization as support: Visual management need to create Dashboards, devices and check list.

2.- Create a system of boards, devices and checklist lean visuals that meet the SMART concept, that is, they are specific, measurable, achievable, realistic and timed to generate key metrics.

3.- Verify the scope and metrics of dashboards and devices, Adapt or modify dashboards and devices seeking excellence through continuous improvement.

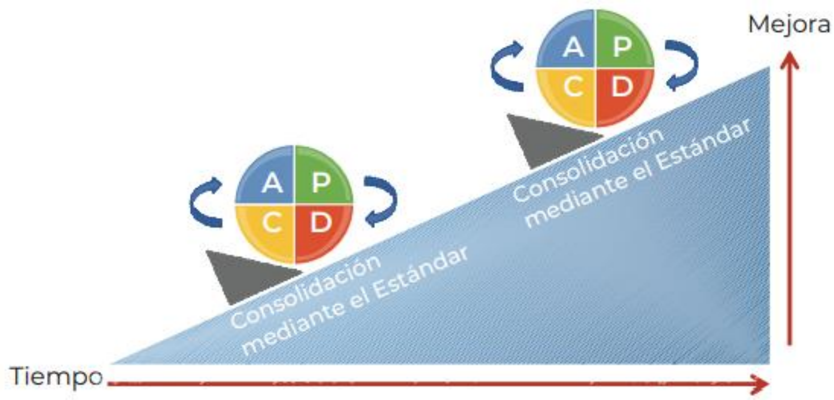


Figure 4 According to the KAIZEN philosophy, each PDCA that we carry out is considered as a starting point to do a better job. Source: (Pons & Rubio, 2019).

The previous figure represents the objective of the process of the improvement cycle flow continues to seek excellence of people and the organization, systematizing and improving processes seeking its practice in lean construction, as a watershed to standardize the entire cycle of improvement processes of work in a construction.

VISUAL MANAGEMENT IN STANDARDIZATION

The information exchange process can be verbal (written or oral communication), nonverbal (eg, body language, facial expression, tone of voice, etc.), or visual (sensory) (Wood, 2009). Let's remember the famous saying: "a picture is worth a thousand words" is not in vain. Or the classic phrases that we say "You have to see it to believe it", or when a person says "It is clear to see", or that Mexican phrase "It is clearer than water", they are expressing that this idea involves reality in an image, transparently. Why does a curve shown on a graph look more real than a departmental memo? (Greif, 1989). The standard is implemented with Visual Lean Management for homes, analyzing in the first instance, the first board that must respond to the following processes:

Evaluation criteria: The person is competent when they demonstrate the following:
With two elements of competency:
Title: **Carry out work prior to assembly - Evaluation criteria**

Devices: 1.-Flag of plans, highlighting: **Identifies the element to be built:** Marking with color on the plan/sketch/work order, also physically locating it in the work front, *by levels and verifying its update by last modification on date, verifying its belonging in situ. 2.- To accommodate the reinforcing steel* by diameter and with the implementation of a quantity control flag.

Figure 5 Device No1. Plan flags identifying the plans, their latest modifications, by levels, floors and sections; Device No2. To accommodate reinforcing steel by diameter and with the implementation of a quantity control flag, source: (Ohra , TodoArt , Own)

Enables the material for reinforcing steel reinforcement: *Board No. 1 previous work: indicating form of accommodation and validating personal protective equipment, with operation safety measures, materials and necessary equipment, and the three* *performances that must be met: measure, cut, fold, in addition to attitudes, habits and values.*

Figure 6 Board No.1: Reinforcement of structural elements with reinforcing steel-Previous Works, source: (OHRA, CISMA and Own)

In addition, it is complemented by Board No.2: Arming of structural elements with reinforcing steel: Organization of equipment and materials; with the objective of identifying and placing the stirrups of all the structural elements, dice, counter beams, columns, beams and others, likewise, the annealed wire cuts for use in the mooring of the different rod diameters.

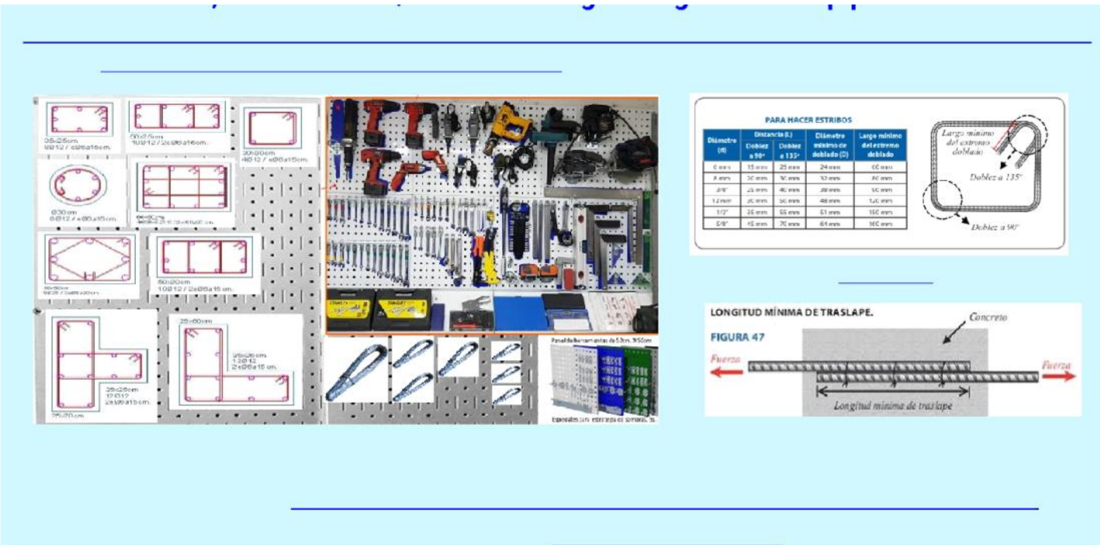
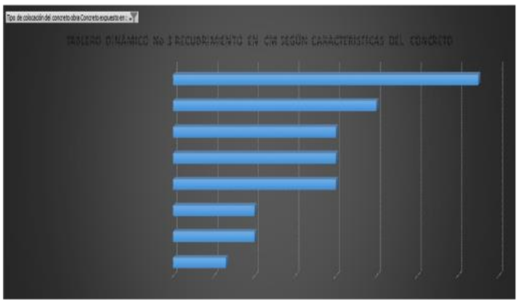


Figure 7 Board No.2: Reinforcement of structural elements with reinforcing steel Organization of equipment and materials, source: (Own with internet images)

The person is competent when he/she obtains the following: Products and Knowledge: *They identify with the device No 1 and Board 1 and 2,* quantities and characteristics, specified of the assembly and the work area, identify materials, tools and necessary equipment and verify in the *DYNAMIC BOARD No 3 COVERING IN CM ACCORDING TO CONCRETE CHARACTERISTICS and elements* , which when identifying the window or button you can select, if it is for concrete made manually or premixed, in the same way in *the DYNAMIC BOARD No. 4 SUBSTITUTION OF RODS*, similarly, it identifies the window and you select the required diameter and it generates the number of rods necessary for the replacement by the steel area, see attached tables.



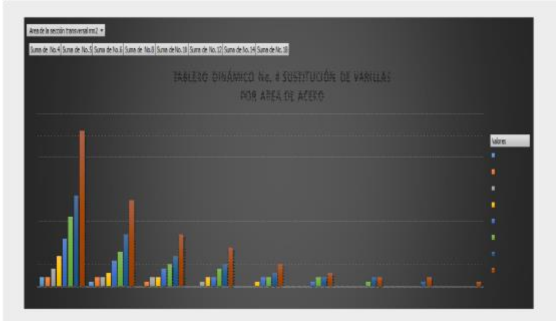


Figure 8 Dynamic Board No 3 Coverage in cm according to the characteristics of the concrete. (source: NMX-C-407-ONNCCE-2001), Dynamic Board No. 4 Substitution of rods per steel area. (source: NMX-C-407-ONNCCE-2001).

Regarding reference 2 **Arm the reinforcing steel of the structural element** , **Evaluation criteria,** With a visual support type check list with metric of whether it complies or not, it is verified before, during and at the end of the standardized process of the sketch in the work (gemba), the trace identifying the element and its setting out in situ (gemba) and times, coatings established according to the project and specifications, what the reinforcement of the steel specified in the project and common practice in the work (gemba) must meet, identifying in a simple and easy visual way what the proposed standard must meet, this is one of the relevance of the investigation.

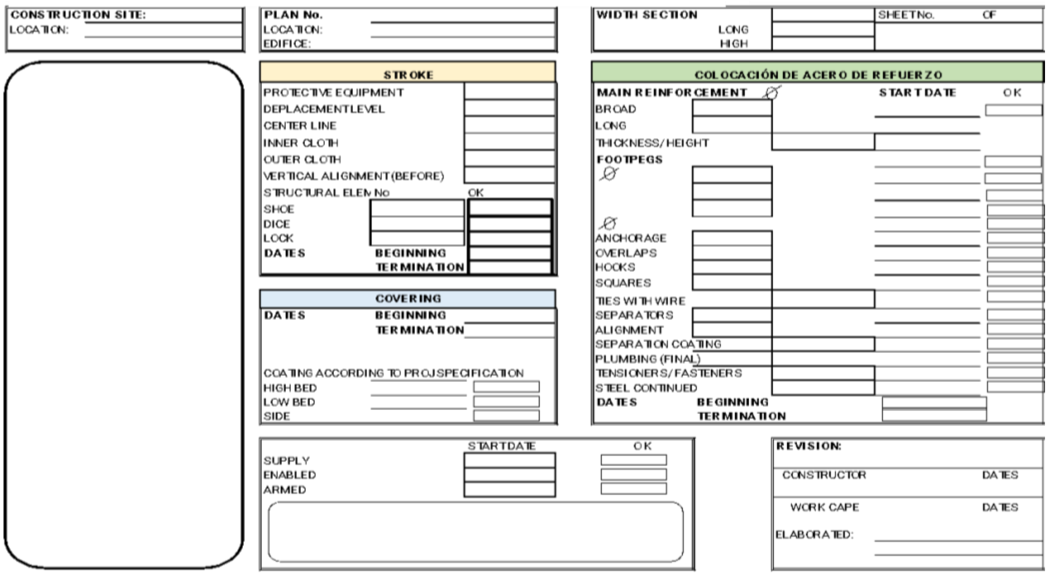


Figure 9 Check list: reinforcement control in reinforcement steel elements

The process was not theoretical when crossing the opinions of two Civil Engineers in charge of Construction Superintendents and a Reinforcing Steel Contractor Industrial

Engineer, generating feedback, in addition to production personnel, a construction manager and two iron officers who gave their points of view, and that they like it visually, currently the standard does not consider this checklist of the real process in the work. In this way we answer the second research question, integrating in 3 Boards the "Standard of reinforcing steel in PDCA structure with Visual Management and for Real Estate Promoter-constructor of housing in Mexico, as shown in the following figures:

Figure 10 "Standard of Reinforcing Steel in PDCA Structure with Visual Management and for Real Estate Promoter-constructor of housing in Mexico.

CONCLUSIONS:

Boards 1 and 2 are for visual support on the construction site, where they normally enable the steel, as well as dynamic boards 3 and 4, with the exception that a device such as an iPod or cell phone that has Excel will be able to select the appropriate coating. and the replacement of rods according to the stock they have on site, or due to a special need, complementing the checklist (check List), according to the "Lean" philosophy, go to the production site called (Gemba) which is the work, as a contribution to the investigation if it is executed and complies, generating a metric that seeks continuous improvement, otherwise what is necessary to comply is executed, which is a great contribution to our field workers, as well as for their personal growth and a visual aid to verify what to consider, as a support to helpers to grow in their knowledge and to shorten their learning curve Even when there are articles as background to the subject, we must highlight the heading of Principle 6 in " The Toyota Way " that states: "Standardized tasks are the basis for continuous improvement and empowerment of employees" (Liker , 2004), no research touches on the subject from the Visual Management approach, some authors stand out as (Rybkowski , 2014), focused on documenting the methods and expected results in a simulation that illustrates the productivity of collective Kaizen , (Polesie , 2009) in interviews identified that it is difficult to implement due to the lack of teamwork between senior management and field management, in the case of (Aapaoja , 2014) reveals the main challenges for process standardization is difficult, processes should be focused on standardizing and modulating them, confirming that this research has a different approach to address the issue. It is a contribution thinking of the production staff, looking for teamwork and for them to take ownership of the process, to find a way to adapt it, to adapt it looking for Continuous Improvement.

Addressing new research questions, such as: In what other construction processes can standardization be generated with Visual Management? Can Visual Management be applied in other countries? generating new research opportunities.

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SUPERIOR CONTRACTOR PERFORMANCE: A BARRIER TO LEAN CONSTRUCTION ADOPTION IN AUSTRALIA

Matt Stevens[1]

ABSTRACT

The Australian construction industry produces twice as much value per dollar while enduring four times the competition than manufacturing. Impressively, this sector outpaces six of nine major industries in the country. However, their quantitative success may dampen Lean Construction's adoption, hurting the industry long-term.

Practices significantly transform the value of the inputs, and contractors do it better than manufacturing. However, the industry is much riskier than manufacturing, so contractors hesitate to change to new ones quickly. It appears that organisations will not rapidly adopt Lean's methodology partially due to the success and risk of the Australian construction Industry.

This paper proposes a survey methodology of practices to convince contractors of Lean Construction's improvement potential. Obviously, they should search wherever there may be promising methods. However, this research outlines a straightforward process to validate valuable practices that can be executed internally in the industry and clarify practices' value and timely completion. The aim is to convince already superior performing contractors to see the LC approach as a competitive opportunity.

KEYWORDS

Construction contracting management, best practice, performance improvement, innovation.

INTRODUCTION

The Australian construction industry produces twice as much value per dollar as manufacturing while facing four times the competition (ABS 2020). Additionally, the sector outpaces six of the nine other major industries. Construction contractors are producing more positive results than the industry they are supposed to learn. The Australian sector achieves more significant levels of efficacy than the exemplar industry (manufacturing), weakening the core argument for LC implementation.

However, the Australian construction industry suffers from many issues that started the LC movement, such as stagnant productivity, time delays, cost overruns, poor quality and client dissatisfaction (Fauzan & Sunindijo 2021).

So, the challenge is to create a strong argument for implementation. However, we know that contractors' practices are difficult to change due to the risk, low margins and hyper-competition. Successful contractors' valuable practices should be shared with the

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rest of the industry. However, due to the risk and hyper-competition, these high-performing organisations do not declare their excellent results nor invite outsiders to observe their operations. There are many reasons, including that this knowledge can leave with the employee separation.

Additionally, that manager may recruit staff to join them. So discovering and documenting effective practices is not easy. So, as a critical intermediate step to LC adoption, we assert that a new principle be added: Ontime adherence to proven practices disproportionately enhances performance. Capturing actionable tasks for clarity with a single performance measurement is an important step. This paper suggests an approach.

LITERATURE REVIEW

Koskela (2011) describes a general decline in management research since 1959. He suggests the focus of researchers is more aligned to social science and that production techniques research has largely gone away. Studies on how to make things more efficiently with higher quality and less cost have been small in number in management research. A common theme in management research is "describing the world" rather than improving it. Lim et al. (2011) assert that the means for achieving construction organisational capability has been lightly explored. Caldas et al. (2009) found that the construction process and the underlying practices have been less studied than those involving the use of technology. There is limited professional research literature about construction contractors' practices even though these firms perform a significant portion of construction (Arditi and Chotibhongs 2005). Additionally, on-site management practice research is "somewhat sparse (Thomas and Horman 2006).

Construction projects are unique and risky; however, the contractors in Australia have produced disproportionate value with greater competition compared to manufacturing (ABS 202). As in many parts of the world, most of these projects require on-site production, are one-of-a-kind, and possess input-output conflicts and interrelatedness complexity. In addition, the uncertainty that occurs before and during the work creates rare risk levels compared to other business sectors (Salem et al. 2006). As a result, construction companies and industry practitioners have created many assessment methods to distil construction project performance. For example, time, cost, and rework are quantitative metrics, while qualitative ones include safety, leadership and sustainability.

CONSTRUCTION INDUSTRY PERFORMANCE

Among the nine major Australian industries, construction's labour productivity as measured by Gross Value Added (GVA) per hour was the third-highest (Leviakangas 2017). Furthermore, current construction industry practices produce more than twice the value per dollar than manufacturing, with four times the competition. See Table 1.

Table 1. Comparison of Australian Construction and Manufacturing (Australian Bureau of Statistics FYE 2020)

Metric	Construction	Manufacturing	Comments
Number of Businesses	394,496	86,226	Construction has four times the competitors
Average Entrants Annually 2016-2020	6.3%	1.9%	Three times the number of new competitors each year
Turnover at Current Prices	$210,659,704,000	$405,091,000,000	Construction has approximately half the turnover
Value Added	$126,293,000,000	$107,479,000,000	Construction adds 59.9% value per turnover dollar, whereas manufacturing contributes 26.4%

Many researchers have provided credible evidence that LC is the answer to many of the industry's ills. However, its implementation has not been fully adopted in Australia. The slow uptake of innovative methods appears to partially cause the lack of improvement in Australia's multifactor productivity over the last two decades (Stevens and Smolders 2021).

The literature has noted several benefits to construction contractors by implementing LC Practices, such as reducing project time, increased asset and labour productivity, improved safety, better cost performance, reduced input waste, and specification adherence (Ghosh and Burghart 2021). However, there is no universal LC definition but rather an interwoven series of concepts from different sources (Koskela 2020). The formal purpose of LC is to deliver more value to Project Owners by reducing variation in workflows. The initially agreed project schedule is highly probable due to the predictability of estimated workdays needed. Ghosh and Burghart (2021) assert that the primary barrier for LC adoption is the need for a new belief system. Babalola et al. (2019) conducted a systematic literature review and found that approximately 20 different economic, social and environmental benefits were linked to implementing LC practices. However, a critical mass uptake of LC's many practices and their sustained implementation is required to attain these goals. With these many benefits available, it is puzzling why significant adoption has not occurred. One assertion is that its broad-based terminologies and principles lack realism and practical application to inspire confidence enough to adopt (Green and May 2005). Leong et al. (2015) echo the same sentiment; the lack of response towards LC is due to an instruction of what workers and managers should be done operationally on the project and in the organisation. The inputs and processes identified by advocates are broad-based and therefore unclear for downstream workers and managers. However, Lean methods in the construction industry are still evolving and have not reached a maturity level compared to the manufacturing sector's adoption history (Babalola et al. 2019).

Construction Contractor Practices

In the 2022 edition of the Oxford American College Dictionary, practice is defined as a noun: 1. the actual application or use of an idea, belief, or method as opposed to theories about such application or use. A process is defined as: 1. a series of actions or operations conducing to an end.

Seymour (2013) asserts that engineers and those around them tend to answer the "what" is to be done ably but not "how" things come to be. These "series of actions or operations" can be interpreted as practices that make up a process. They are "construction design, components and materials, workers, equipment, space, connecting works and external conditions" (Koskela 2000). Construction processes consist of many tasks. Each task may have up to 7 preconditions before it can be completed. These are human-enabled. This set of preconditions and the task itself creates many activities to monitor for the executive. Variations in on-time practice execution is high and thus impact follow-on activities. Delays are common, but early unplanned completions are lost opportunities to advance the schedule. An uncompleted task has a ripple effect to follow on tasks (Liu et al. 2011). Hence, it is critical that they are monitored and, thus, managed and measurable if one is to complete projects efficiently.

Tailoring LC practices to the organisational context is absent in application. London (2008) argued that LC principles do not account for the organisational context. Instead, they appear to suggest that the organisation changes itself to fit the methodology.

What is needed is LC application on project processes and organisational needs. These include many areas such as culture, value streams, development, growth, and human interaction (Koskela 2020). LC Practice definition and implementation are influenced by each industry manager's interpretation of the practical diffusion of concepts within different contexts (Kifokeris 2021). Koskela (2020) examined LC implementation in Swedish Built Environment firms and found widely different interpretations and implementation approaches. Additionally, noting the vast differences in 27 company market services. Hines et al. (2004) suggested LC has been confusing in its definition and, thus, has lacked consensus among practitioners. However, as a starting point, Koskela's (1999) practices should be created and formalised "to do as little of what is unnecessary as possible."

Lessons Learned Programs (LLP) take several forms to capture practices. Charrettes or structured workshops have been held to collect efficacious tasks and have been in use since 1996 (Gibson and Whittington 2010). Several other methods have been used, such as meetings, interviews, electronic means, paper forms, word of mouth and outside consultants (Caldas et al. 2009). Another avenue is general business reading and the distillation of common business practices or policies (Ogunlana et al. 2003).

It is self-evident that the construction industry does not have the same knowledge from company to company. Moreover, construction firms typically do not distribute practice knowledge evenly across the organisation (Caldas et al. 2009). The need is evidenced by quantitative and qualitative data about the construction industry and its performance.

VALIDATION OF PRACTICES

The construction industry relies on informal coordination and decentralised decision-making, which impedes company optimisation and innovation (Brosseau and Rallet 1995). The scientific methodology must be employed if the construction research is to have two critical characteristics for acceptance by academics and practitioners: a) validity and b) reliability (Lucko and Rojas 2010). This type of research is common in other disciplines. However, it must be a focus, and continued good scholarly work is needed to construct academic programs to keep their prominence in elite universities (Halpin 2007). Validation of the promising practices usually follows after selection. Value analysis has been executed by meetings, subject matter experts, electronic surveys, and informal conversations (Caldas et al. 2009). Once a practice is confirmed as "best," the value should be clear, and there is little debate.

Pre-construction planning is a well-accepted beneficial process that contains many steps and has been the subject of several studies. The value of this type of planning is high and, therefore critical (Laufer 1987; Menches et al. 2008; Hanna and Skiffington 2010). Menches et al. (2008) modelled project characteristics, planning and performance in the electrical contracting industry. Each of these factors was quantified, and predictors were discovered. However, project outcomes were limited to self-reported "successful" and "unsuccessful" and did not quantify efficiency in exact percentages or quartiles.

The work acquisition process was examined, including its markup practices, turnover to project management, and resulting financial performance. It was concluded that large deviations in markup affect backlog. This deviation results in an unpredictable workflow, which causes disruptions to the firm's ability to work steadily. When the amount of work is overcapacity, employees rushing to complete their tasks make mistakes and thus cause extra expense. Conversely, when the amount of work is substantially below capacity, the overhead expense percentage of the revenue rises. Both of these situations create a pronounced effect on net profit before tax. A quantified model was proposed (Kim and Reinschmidt 2006).

MEASURING CONSTRUCTION CONTRACTOR PERFORMANCE

Construction companies and industry practitioners have created many assessment methods to distil construction project performance. Time, cost, and rework are quantitative metrics, while qualitative ones include safety, leadership and sustainability (Salem et al. 2006). Some studies have taken a predictive approach to the constructor's future performance. This assessment of the probability of success used a multifactor approach (Waara and Brochner 2006; Hartmann et al. 2009). In other studies, the focus has been on determining a contractor's failure probability. (Suarez 2004; Dikmen et al. 2005; Marsh and Fayek 2010; Mahamid 2012). Others have sought to quantify organisational flexibility. The reason is clear; the ability of the construction business to "flex" allows it to effectively manage the constant change in the industry (Lim et al. 2011). These are based on a generalist view.

Improving operating practices will speed up the work cycle. The work cycle is alike a "flywheel"; the faster it spins; a company will enjoy better business outcomes (Collins 2001). In construction, higher adherence to each step increased speed. Tracking creates an opportunity to coach employees and improve their skills and practice. Tracking can be classified in one of two ways: proactive and reactive (Bassioni 2005). Proactive tracking can be defined as those activities which are behaviours; reactive tracking is monitoring results.

Organisational effectiveness (O.E.) is a relatively new term in construction research. It was widely ignored before the 1990s in construction research (Dikman et al. 2005). Since that time, there have been a few examinations specifically about the organisational effectiveness of construction firms. Some researchers (Maloney and Federle 1993) proposed a model of how superior O.E. should be executed. However, they did not describe specific actions that a firm should undertake, only the approach that should be utilised.

Others such as Sinha and McKim (2000) interwove several common business management approaches, such as total quality management (TQM), business process reengineering and benchmarking to seek a common thread of thought. The "unifying theory" is elusive. This is to be expected. Construction has a complicated value chain of many different stakeholders and a dual challenge of managing projects and the overall firms (Dikman et al. 2005). Construction contractors are rewarded or penalised based on two organisations within their companies: 1) The project organisation 2) The home office organisation. Each has an effect on the overall yearly result. It is this complexity in construction that creates a very fluid environment. Sometimes these two organisations conflict in actions and goals. Examples include sharing of common assets, such as equipment or craft persons. However, a project manager would want the best people on his job; the organisation is building many equally important jobs. This causes conflict and complexity. Peters and Waterman (1982) conclude that the firms that do well "manage ambiguity".

Some studies suggest accomplishments or ratings determine the level of organisational effectiveness. This is a results-oriented methodology characterised by an observational or empirical approach. Project participants either report back, or a third party observes outcomes. At the end of the project, conclusions are made about the project. Examples include construction company performance models (Kim and Reinschmidt 2006; Lim et al. 2011; Ling et al. 2012), conceptual framework (Bassioni et al. 2005), factor analysis (Mahamid 2012), Delphi studies (Yeung et al. 2009) and competitiveness ratings (Tan et al. 2011). These overall models that attempt to guide the contracting community abound in research. Bassioni et al. (2005) attempted to define a general framework of organisational effectiveness with "driving factors and results factors". These can be classified as "before" and "after" factors.

Several studies have advocated a more robust set of critical success factors (Bassioni et al. 2008; Cox et al. 2003; Skibniewski and Ghosh 2009). Critical success factors research lists several dozen areas that prove to be helpful to organisational effectiveness. Some are based on conditions in that the company finds itself. Others are outcome-based and prejudged to be repeatable. Several more are concentrated on processes. However, the void of individual practice or method research is large. Thomas and Ellis (2007) noted: "Unfortunately, there is nothing in print that defines a process that a contractor should follow."

ADHERENCE TO PRACTICES

Martilla and James (1977) created a process for marketing that rated "customer importance" and "company performance" or the Importance-Performance Analysis (IPA).

Abore and Busacca (2011) suggested that IPA's effectiveness is dependent upon identifying key value drivers. It is critical that practices research carefully collect each observable method and test each practice with a limited group of knowledgeable participants. Research also requires objective metrics, such as a financial ratio, to clarify practice effects (s). Platts and Gregory (1990) suggested that there should be a connection when using this approach in operations to tie an audit to strategies that a manufacturer pursues. Slack (1994) asserted that "there seems no reason why it cannot also be used more generally to include service operations". Construction is a service business, and using this approach may be an efficient method to improve contractor operations.

Menches and Hanna (2006) captured and tested 64 management practices. Their methodology judged successful projects by compliance with practices. Each project's grade resulted from what percentage of methods were actually completed. There was no objective, independent variable such as a cost or schedule metric to compare and analyse the effectiveness of compliance.

Ogunlana et al. (2003) studied the performance enhancement of a single company created by implementing generic policies of human resources and financial management at the same time. Using company internal numbers gives an accurate picture. It can show improvement easier by using a trend line over time.

METHODOLOGY

This paper will propose a quantitative process to show the value of Lean Construction to Australian Construction Contractors.

Then design a system to find correlations between a specific set of practices, their importance, their performance and their effect on overhead efficiency of managing direct project cost against peer averages.

Converting LC Practice Language

Practice statements should be created in the language of the targeted country. As part of the research process, further refinement was needed in the wording of each. See Table 2 for suggested restatement of standard LC practices in construction-centric terms.

Table 2: A Suggested Restatement Of LC Practices In Construction-Centric Terms (Stevens 2014)

Lean Construction Practice	**Possible Restatements into Commonly Understood Practices for use with Importance and Performance Assessment (IPA)**
Last Planner® System	"We plan with our project stakeholder group in writing one week or more at a time. The project team uses a complete list of things to consider when ensuring an area and the team are ready for work to be installed."
One-Piece Flow	"Each person in our company executes tasks from beginning to end as practicable."
Heijunka - Levelled Workload	"We look ahead at least 6 weeks to ensure our field and office staff are not overloaded with work."
Standardised Work	"We have one company standardised way to perform each office or field task."
Visual Management	"Our preference is to use visible means (versus written means) to communicate information to all company employees."
Use of Reliable and Proven Technology	"Our software is established and proven; we have few, if any problems with it."
Jidoka – Build In Quality	"We consistently discuss and implement value-adding ideas."

Once finalised, a survey should be given to construction firms that agree to participate. Each statement will be formatted in an IPA survey. The scale used is 1 (low) to 7 (high). This allows practices to identified to be more critical – rated 5, 6, and 7 and to see the implementation opportunity – performance – for these highly-rated practices.

A fictitious practice statement and its response data are shared in Figure 1.

16. We use a proven method to apply overhead costs to each bid.										
Answer Options								Rating Average	Response Count	Disparity
Importance to the Success of our Company	0	0	2	1	2	4	19	6.32	28	0.78
Our Company's Performance	0	1	3	2	2	8	8	5.54	24	

Figure 1. Fictitious Example of Practice Statement Survey Result

The rating of importance and performance provides a) a learning opportunity for survey participants about valuable practices, b) an affirmation to Lean Construction of the perceived value of each of its practices, c) an Implementation assessment across the industry.

Thought was given to using these measures in combination and creating a value or index number based on that combination. Also, several measures were considered to be used alone and be designated as the sole criterion for determining performance. Each concept has benefits and drawbacks. For example, most for-profit firms manage their business to minimise substantial tax liability. This practice creates artificial outcomes such as favorable net worth, owner's equity, and outstanding debt obligations between competitive companies with considerable revenue. Therefore, measurements such as return on net worth or return on assets were less credible.

From this researcher's experience, the Overhead to Direct Cost (OH/DC) ratio fits the goals of this study. This measure attempt to distil an efficiency measure of overhead (office efficacy) in managing direct cost (project expenses). It possesses less overall error; it directly measures any contractor's two largest cost categories. The number size makes these less sensitive to differences between two peer firms' accounting categories. Although, the classification of overhead expenses and direct costs is not standardised. One metric met the efficiency criteria best for the contractor: a construction firm's overhead to direct cost ratio against median Peer Performance.

In summary, overhead expenses are overall, and direct costs are specific and targeted for a specific project. The interaction of these two cost variables can be directly linked to speciality contractor performance. Therefore, the OH/DC ratio was chosen as the dependent variable to measure good operating practice importance and performance.

The OH/DC ratio of participating construction firms was used as an objective measure for company performance against Risk Management Associates data of defined categories of firms.

Accurate outcome measurement is critical when measuring correlation both for the benchmark and the company. Construction Contractor benchmark data was sourced from Risk Management Associates, Philadelphia, Pennsylvania. This banking clearinghouse aggregates information from source documents such as credit line applications, tax returns and business loans.

Participating companies furnished audited Financial reports (Balance Sheet and Profit and Loss statement). These were viewed as the most accurate gauge of a company's financial health available by the researcher.

Table 2. Comparison of Adherence of Company Practices and OH/DC Performance

Organisation	Average Importance Rating of Practices	Average Performance Rating of Practices	Average Disparity Between Importance and Performance	Percentage of Peer OH/DC % Difference
Sample Company A	5.09	4.46	-0.64	+69.60%
Sample Company B	5.77	4.38	-1.40	-17.76%

The importance, performance, disparity and peer comparison distilled the primary operating performance of participating firms. Employees determined the importance and performance ratings. The overhead to direct cost peer comparison provides a relative efficiency.

This paper investigated the correlation between critical practices (ones rated 5,6 and 7), their disparity in performance and Peer OH/DC % Difference. It is logical to assume that timely execution of valued practices results in higher than average efficiency.

This study determined several good operating practices. These are "predictors" according to SPSS software nomenclature. This is an essential part of this research for a couple of reasons: a) for companies in distress, these "best practices" should be the first steps implemented to improve organisational effectiveness; and b) this research proves that there are best practices through a scientific methodology.

In Figure 2, a 40% of Importance-Performance rating disparity correlates to an average Peer OH/DC % for this set of practices. See regression line interception with the percentage of performance. Predictably, increasing adherence to the timely completion of standardised company practices correlated with higher efficiency.

DISCUSSION

Undoubtedly, construction contracting organisations are vigilant for ideas, systems, or practices that increase safety, improve quality, lower costs, and raise multifactor efficiency. Hypercompetition forces them to. However, great credit should be given to the industry and its organic value generation against the significant competition.

The Australian construction industry is producing significantly more value with greater competition than manufacturing. Then the answer may not be a grand transformation but a continuing upgrade and refinement of existing practices. This steady improvement process may involve adopting techniques from other industries, including manufacturing and their Lean Production mastery.

Many metrics have been created to measure efficiency. Projects are problematic to measure due to the many variations, such as size configuration, schedule, location, and stakeholders involved. However, organisations are more uniform when comparing them, such as contractor type and size. To test practice efficacy, a company is a better organism in which to measure.

The objective measure that was determined to yield greater accuracy in measuring financial normality was United States banking data. The source of this information was Risk Management Associates, Philadelphia, Pennsylvania. Many financial measures were considered. The information for cost was also collected to complete accounting and kept separate.

Of course, the industry's practices should be improved; however, there should be more confident that construction organisations have efficacious practices, and many of them should be improved but not replaced.

CONCLUSION

Australian Construction organisations produce more value with greater competition than manufacturers as well as other sectors. Therefore, LC’s insistence on the rapid transformation of construction appears misplaced. Instead, this paper asserts that credible evidence of value that can help adoption should be steady and incremental.

This research did not present the complete list of the LC practices in Australia's construction-centric and native language. Future work could be a starting point for a

Delphi panel to edit, delete, add, and test. Numerous statistical tests can be executed once a statistically significant sample size is attained.

One limitation in this study was using RMA data, mainly from the United States economy. It does not easily translate to Australia's unique construction industry but it the only available source of credible financial content. These areas could further explain practices' relative value for construction contractors.

Improvement is always a challenge for any industry. Construction's stagnant multifactor productivity is a significant problem. Therefore, a refocusing should occur on helping the industry find and test practices wherever they are utilised, including other construction firms. This research proposed a methodology that will test the value of methods. The outline of such a methodology was presented. This approach can be further developed and implemented by sponsoring organisations such as associations or universities.

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IDENTIFYING THE IMPACT ON LABOR PRODUCTIVITY FROM DESIGN CHOICES THROUGH WORK SAMPLING

Jon Lerche[1], Søren Wandahl[2], and Hasse Neve[3]

ABSTRACT

Productivity within construction and production is about the relationship between earned value and input of resource value. Researchers have dominantly focused on measuring how the hours are spent categorically in relation to the total amount of hours spent in order to understand productivity. Little has been done to investigate how the decision before execution affects productivity or process durations. Through a case study investigating assembly of cables at numerous locations with similar configurations, two companies are asked to install and terminate cables between switchgear. Their technical design solutions are compared, as the exterior around these is considered homogenous. This allows an understanding of how two design choices affect productivity and process durations. The results show how the design affects the productivity, where both contractors achieve a 25 % value-adding work, while the durations are significantly different- up to a 94 % difference at times. The results are contributing to the practical understanding of technical solutions and how the processes are thought into the design, The results contribute to the literature by raising the question of whether our quality management systems are adequately attuned to this situation.

KEYWORDS

Process, productivity, time compression, waste, work sampling

INTRODUCTION

For decades, construction has had an interest in understanding labor productivity on the national, project, and individual levels (Neve et al. 2020A; Neve et al. 2020B). As measuring productivity requires data from both earned value as output and the value of resource use as input, it is 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, which is the share of work time that is used for value-adding activities. Neve et al. (2020A) showed that the relationship between direct work and labor productivity on the national level is statistically significant. Neve et al. (2020B) investigated the same relationship on a

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project level and found in detail the relationship between value-adding and non-value-adding activities and how these impact the productivity through the lenses of transformation-flow-value (Koskela 2000). This relates to the understanding of what causes the activities to be delayed or postponed, which Koskela (1999) addresses as preconditions that need to be met for a task to be healthy, and where Sanni-Anibire et al. (2020) see it as delaying factors, which are factors related to material things (tools, equipment, paperwork, materials etc.) and immaterial circumstances (communication, information, weather etc.). Talking about these delays, Hopp and Spearman (1996) saw the delays as flow and process-time variability, where construction has had a tendency to focus on the process time variability as it is what delays a process that has already started (Bertelsen et al. 2007; Lerche et al. 2020). Multiple investigations have tried to understand the delaying factors and productivity on both individual and systemic levels, dominantly utilizing surveys as their primary source of evidence. But limited knowledge exists about what leads to either the process duration or productivity from a design perspective, and even less is known about how design choices impact the productivity.

This research project investigates the impact of systemic decisions on the individual-level performance. The research question to uncover this is how do the design decisions impact project labor performance? To answer this, this paper first provides insights into the relevant literature and presents the productivity measuring methods from the construction domain. The method section describes case selection, how data was obtained, and how analysis provides results. Last, the discussion explains how the results relate to the relevant literature, providing implications to both practitioners and the literature.

DESIGN IN CONSTRUCTION

From the conceptual understanding of transformation, flow, and value (TFV) (Koskela 2000), it becomes evident that the processes are related to the value. It is known how design is part of the value generation but focusing on the cost reveals that little is known about the effects of either design or managerial decisions on construction productivity. In the design process, the value concept relates to effectiveness and can be incorporated by means of value management methodologies (Wandahl 2004). Whereas in the execution phase, the value concept is about efficiency and buildability, which is addressed in Value Engineering methodologies (Wandahl 2004). This can then be seen from various perspectives, and often it becomes an aim of reducing cost and limiting budget overruns, but as addressed by Koskela et al. (1997), there is more to it than just design management. Not limiting quality to the operator's level but understanding that these can also stem from the managerial level as the design decisions occur long before the operators are introduced on the project. There should be a focus on meeting customer requirements in a trade-off with the objective and schedule goals, which aligns with quality management (Koskela et al. 2019). Ballard et al. (2001) add to this, arguing that the design management should also incorporate reductions of, e.g., process times and rework.

MODULAR DESIGN IN CONSTRUCTION

Compared to regular construction, modular construction strategies provide not only investors but also developers and builders with increased standardization (Peltokorpi et al. 2018). Not only does this enable specific sites (O'Connor et al. 2015), but it also provides opportunities for extended off-site productions providing various prefabricated modules (Song et al. 2005). Wind turbine projects in particular rely on these strategies.

From a design perspective Pashaei and Olhager (2019) revealed the impact from design to supply chains and operations, and Salvador et al. (2002) reveal that this interdependence should be managed. McHugh et al. (2019) show how lean methods and BIM designs can improve the productivity for modular projects. While Innella et al. (2019) instead suggested applying lean construction methods to modular, others applied alternative methods, such as location based scheduling (Lerche et al. 2019; Lerche et al. 2019), takt (Lerche et al. 2022) or last planner (Lerche et al. 2020). Besides the obvious opportunities from repetition, like positively impacting the learning curves for technicians (Thomas et al. 1986) it also allows reaping the fruits of repetition and standardized processes, creating construction flow (Lehtovaara et al. 2020). Design constructability seeks to achieve similar benefits (Fischer and Tatum 1997), and having a constructable program is identified to require less resources (Kog et al. 1999). It is evident that neither regular, modular construction, or the constructability discipline have considered work sampling as a method for evaluating the impact on labour productivity from the design specifications.

HOW IS PRODUCTIVITY MEASURED IN CONSTRUCTION

Productivity is the ratio between output and input volume, whether this is quantified in value, time units, or the relationship between planned and completed tasks. Two of the dominant ways for predicting productivity within the lean construction community include Percent-Plan-Complete (PPC) (Ballard 1999; Gonzalez et al. 2008; Liu et al. 2011) from the Last Planner System (Ballard 2000; Ballard and Tommelein 2016; Lerche et al. 2020). Here, the productivity measures are the ratio between planned and completed tasks (Gonzalez et al. 2008; Lindhard and Wandahl 2011), which is indifferent when applied in modular construction (Lerche 2020; Lerche et al. 2020; McHugh et al. 2019) or any other type of construction (Ballard and Tommelein 2016; Ebbs et al. 2018; Olivieri et al. 2019; Power and Taylor 2019). This method was not pursued further in this case study, as neither of the contractors relied on LPS. The other dominate way is measuring direct work (DW) through work sampling (Josephson and Björkman 2013; Neve et al. 2020; Neve et al. 2020; Thomas 1981). In addition to these, some use motion to identify labour productivity (Barnes 1968), while others again use alternative technologies to identify the productivity (Golparvar-Fard et al. 2011; Kim and Cho 2021).

THE WORK SAMPLING METHOD

Work sampling (WS) is a technique first introduced in 1927 by the British industrial engineer Leonard Tippett in which work can be observed and the amount of time spent on various tasks can be determined (Barnes 1968). In the construction industry, the method was introduced in the 1960s, where H. R. Thomas (Thomas 1991) conducted one of the first WS studies. Currently, WS is being used by some larger construction companies to benchmark their projects so that improvements can be made and quantified. Some contractors have productivity departments or process facilitation departments that complete these studies (Gouett et al. 2011). This could also be done through various type of tracking (Teizer et al. 2020) or motion detectors (Ahn et al. 2019).The WS method categorized the amount of conducted work time into various categories, identifying not only what is perceived to be value-adding work for the customer but also what is considered none-value-adding work, which in other terms could be categorized as waste

(Koskela 2000; Ohno 1988) or reasons for delays (Lerche et al. 2022; Sanni-Anibire et al. 2020). All WS studies apply a DW category. However, when it comes to the none-value-adding work category, the picture is not as clear. Some studies categorize all none-DW time as none-value adding, while other studies have a more detailed view of None-Value-Adding Work, including a number of subcategories. Generally speaking, None-Value-Adding Work time in WS can be divided into Indirect Work (IW) and Waste Work (WW), resulting in Work Sampling having three categories of time: DW, IW, and WW. Thomas (1981) and Josephson and Björkman (2013) indicate a weak or no causal relationship between DW and Productivity. This is mainly due to the fact that WS does not consider the output, i.e., how much or how fast work is done. In contrast, a recent review by Neve et al. (2020) does, however, show that many studies have identified a statistically significant correlation and causal relationship between DW and productivity. This study takes the same standpoint – that work sampling can provide an insight into team and project productivity. The literature search also made it evident that work sampling has not been utilized previously to understand the impact of technical design choices.

METHOD

The research project was conducted as a case study (Yin 1994), sampling data from project execution in a modular construction setting. As the opportunity arose, the study was inspired by Brown and Eisenhardt (1997), comparing two different actors in order for the study to provide a more rich knowledge of how their decisions during the project design affected the execution productivity. The case selection follows Voss et al. (2002). Still, to ensure internal validity and reliability, the research mixed the data sampling methods not limited to work sampling, but also using field observations, progress data, and interviews with the actors on both operational and managerial levels. Seven interviews were conducted, along with a process workshop before execution with both companies. The case conditions are outlined in Table 1, allowing individual and combined evaluation of the companies (Gibbert et al. 2008). The external validity was established through discussion in relation to the literature and practically showing the results to the company management actors to gain their view brought forward as well.

BASIC CASE INFORMATION

The case investigated is a cable termination scope of a more significant modular construction site. The contract is awarded based on bids, with a contract sum around 2-3 million EUR each. Both contracts are well-known tier 1 contractors with at least 13 years of experience within the field. But with two different approaches to the management of such a contract, the case was chosen to compare technical and organizational details. Table 1 shows the number of locations each contractor handles, their contractual forms, and their technical solutions for fulfilling their contract.

Table 1. Case conditions.

Category	Contractor A	Contractor B
Number of assembly locations	110	55
Contract form	Lumpsum	Lumpsum
Management	Contracted	Permanent staff
Workforce	Independent contractors	Independent contractors
Progress data capturing	Not in place, established for this project	Daily progress system in place
Cable	Ethylene propylene rubber (EPR)	Cross-linked polyethylene (XLPE)
Cable shielding	Required	Not required
Cable Hang off system	Prototype	Standard
Conductor assembly method. Special requirement.	Water blockage needs removal.	No particular actions are required.

The working methods for preparing, stripping, and terminating the cables are similar between the contractors; their risk and method statements have similar descriptions around tools, equipment, and cable handling.

CASE DATA AND ANALYSIS

The data collection combines three data sources. The first two data sources are the primary data of 1) observations (longitudinal studies) and 2) work sampling, with the third data source consisting of secondary data 3) progress reporting from quarter 2 of 2021 to quarter 1 of 2022. —The paper looks at in-depth work sampling studies of two similar locations—the chosen locations only had the differences outlined in Figure 1 for cabling and its equipment. The routing paths and the environment are identical. The studied teams had completed a minimum of 5 locations each prior to the work sampling; Contractor A had chosen two jointers, a fiber technician, and a cable mate, where Contractor B used one jointer, a fiber technician, and a cable mate. The work sampling method followed similar categories as Lerche et al. (2022); Neve et al. (2020); Wandahl et al. (2021), ensuring that working on a specific part of the cable or its equipment was also coded. This study considers work sampling as a method that can provide insights to productivity, and progress reporting could be regarded as related to this method. As the hourly progress reports offer insights into the contractors' hour consumption, which a customer is paying for, these are considered value related. The limitation with the progress reporting compared to work sampling would be accuracy, which was intended gained through work sampling.

Figure 1. Work process steps. (Step 4 was only required for Contractor A's cable solution, Step 6 included the conductor assembly)

The data analysis is used to illustrate differences between the contractors and the impact of their choices in Table 1. The analytical tools for this are descriptive statistics and percentage calculations. To ensure reliability between the two contractors, we isolated locations with 2-cable ends, which resulted in 90 locations for Contractor A and 40 locations for Contractor B. The additional numbers of locations for Contractor A could be perceived as an advantage from a learning perspective (Thomas et al. 1986) which is seen in Lerche et al. (2019); Lerche et al. (2020).

RESULTS

The results are presented in the following order: first, the work sample study shows the relations between non-value-adding work (WW) and value-adding work (DW) activities. Second, combining both progress data and work sample data to present, 1) location productivity measure, 2) performance comparison: durations of the assembly processes, including specified times for cable preparations, stripping, cable hang-off system, shielding, and conductor assembly (see Table 1) comparing team registrations and work sampling.

PRODUCTIVITY MEASURE WITH WORK SAMPLING STUDY ON LOCATION

Table 3 shows how the two contractors perform on a given location, showing the distribution between the value-adding, non-value-adding, and necessary work performed.

Table 3. Work sampling two identical locations.

Categories	Contractor A	Contractor B
Non-value-adding activities (WW)	118 hrs. (37%)	45 hrs. (28%)
Necessary activities (IW)	114 hrs. (38%)	74 hrs. (47%)
Value-adding activities (DW)	76 hrs. (25%)	39 hrs. (25%)
Number of work shifts	9.3	4.8
Total duration	308 hrs.	158 hrs.

From a productivity perspective, Contractor A and Contractor B have a similar percentage of value adding activities, but Contractor A is almost spending twice the number of hours from a duration perspective. During the work sampling analysis, it became apparent that teams of Contractor A were less prepared for the tasks at hand; there were multiple start-stops for various reasons, like relocating tool parts or waiting for the working space to be free, despite having a management walkthrough of the expected process flow before commencing work. In relation to this, Contractor B had prior to the execution spent time asking the teams to illustrate the sequence of tasks through post-it notes. After a few completed locations, this was followed up by asking the teams for sequence adjustments or sharing of learning across teams.

PERFORMANCE COMPARED

Table 4 presents the full project data view in hours for all the process steps shown earlier in Figure 1, their progress registered duration, and the hours from work sampling as a comparison. The right column shows the difference between the two contractors. Cable preparation was not segregated in the progress data as cable shielding was not included in Contractors B's design, and this is marked. The data monitoring from Contractor B gave them an advantage compared to A, as they (B) constantly reminded their teams of their involvement, questioning progress, and using quality pictures with timestamps as hidden evaluation of the team's performance. Contractor A relied on the customer data interpretations, relying on trust in the teams and their performance reporting without showing greater interest in the progress or durations.

Table 4. Comparison of average process durations, minor delays included. (hrs.)

Process	Registration form	Contractor A	Contractor B	Difference
1. Cable preparation	Progress	Included in routing and termination		
	Work sampling	28:57	42:11	13:14
2. Cable stripping	Progress	26:53	14:45	12:08
	Work sampling	17:04	12:25	4:39
3. Hang off system assembly	Progress	38:36	8:01	30:35
	Work sampling	28:29	6:48	21:41
4. Cable shielding*	Progress	20:16	Not applicable	20:16
	Work sampling	14:00		14:00
5. Cable routing	Progress	82:15	70:41	11:34
	Work sampling	74:34	43:13	31:21
6. Cable termination	Progress	116:20	75:31	40:49
	Work sampling	83:09	38:09	45:00
7. Conductor assembly*	Progress	**	Not applicable	-
	Work sampling	8:10		8:10
7. Finish up	Progress	56:30	9:35	45:55
	Work sampling	53:45	16:17	37:28
Total	Progress	341	177	163
	Work sampling	308	158	150

* Only applicable for Contractor A

**Was reported as part of the termination

The biggest differences are found in the following steps: Step 3- hang-offs systems (30:35 hrs), Step 6 cable termination (40:49hrs), Step 7 finish up (45:55hrs.).

DISCUSSION

To ensure the validity of the results, the results did not rely on the progress data alone, as the understanding came through combining these results with work sampling of randomly selected locations. The differences also allowed the practitioners to question their own team's progress. The difference between progress and work sampling showed an unintended result, raising questions to how supplier and customer relations are handled from a progress reporting perspective. Further research would be required to understand why there is a gap between the two, and whether it intentional or not. The trust and commitment between actors is addressed in LPS, Hämäläinen et al. (2014) for one argues how leadership is also required for performance.

Implications from design

The literature made it evident that construction design has not previously been evaluated through work sampling. The results show that reducing project cost by looking for options which do not require additional on-site assembly or processing, as step 6 for Contractor A shows. This supports that modular construction strategies (McHugh et al. 2019; Peltokorpi et al. 2018) and pre-fabrication can lead to duration reductions (Kog et al. 1999). But as the repetition and standardization should allow construction flow (Lehtovaara et al. 2020), it is peculiar how Contractor A does not deliver massive time reductions. As both contractors have a large number of identical assemblies, the results of Contractor A questions the knowledge of learning curves (Thomas et al. 1986), as these should have been expected to perform better than Contractor B. If not for any other reason, but just through more repetition. It was not possible to isolate the exact reason for this, but the management and the design are seen as key drivers which could be supported by Lerche et al. (2019); Lerche et al. (2020) as they show how increased focus from the management supports the learning curve and its development.

IMPLICATIONS TO INDUSTRY

The results show how the choices during the design phase can relate to durations during the project execution, encouraging one to consider that one solution is to be evaluated at this stage alone, which supports the statements made from a quality perspective by Koskela et al. (2019) and value design perspective by Ballard et al. (2001). But it also raises the question of whether the focus is on the right things with defined productivity measures, as the results show that teams can be productive and have long durations simultaneously. This supports the arguments from Thomas (1981) and Josephson and Björkman (2013), which shows that productivity can have a weak link to output, resulting in 25% value-adding with a duration difference of 94 %, which emphasizes the necessity of focusing on technical solutions and their assembly complexity early in the project development phase.

LIMITATIONS TO THE STUDY

The focus was on understanding the difference between the already chosen technical solutions and how these affected the productivity, meaning that the progress reports from the teams had a focus on hours spent in total within each process steps. As the focus was on overall process times, the waiting times were not further specified during the selfreporting, as seen in Lerche et al. (2022); Lerche et al. (2022). The work sampling studies revealed a broader view on the delays that affected the productivity other than the start-stops it caused. A proposal for future research would be to follow the technical solutions from the design phase to the instalment and later through the service life. In particular, understanding if some end-of-life considerations were made in relation to one technical solution over another.

CONCLUSION

The study showed how the design choices affect productivity, partially if the value-adding activities and necessary work related to these activities are affected. While it showed how the design choices significantly affects the durations of the task, the results also show how it is possible to measure the impact of design choices directly with productivity measures, such as work sampling. The results are seen as way to inspire new questions within both the academic and practical domain, and where else can we use work sampling to measure productivity. Has the method been exploited, or could an expected time per assembly be evaluated through this method, not accepting status quo? Further research would be required to understand other areas of interest from design to execution.

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THE DUAL NATURE OF COMPLEXITY IN CONSTRUCTION MANAGEMENT– CALL FOR A RENEWED DEBATE

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ABSTRACT

The paper is conceptual, with the aim of raising a new debate on complexity and value creation within IGLC. The topic of complexity in construction projects was first raised in the Nineties before it in the early 2000s was introduced on the Lean Construction and IGLC agenda. When facing a complex problem, there are two possible strategies to pursue with reference to the Cynefin framework for complexity. The first is to transform and move the problem into the complicated or even simple domain, thereby making it manageable. The second is to handle the problem within the complex domain. The dominant approach within both Project Management and Lean is the first, namely, to emphasize efficiency, flow, standardization, best practice, planning, reliability, and control. The paper challenges this lop-sidedness by pointing out its potential reductionism and argues that we should also appreciate, exploit, and take advantage of complexity instead of just combatting it. Value creation is reliant upon both strategies and is therefore not a question of either or, but of balance and trade-offs based on an inherent dualism.

KEYWORDS

Complexity, complicated, Cynefin, value creation, design.

INTRODUCTION

In the Lean Construction research community, there is a strong focus on approaches to control the design and production processes to achieve order, e.g., measured by percentage planned completed (PPC) as in Last Planner (Ballard, 2000a), and many of the contributions from IGLC-conferences on complexity are devoted to reduce complexity as a threat to stability and stable flows, see for example Dlouhy et al. (2018); Filho et al. (2016), Larsson and Simonsson (2012) and Al-Sudairi et al. (2000). Bertelsen (2003) took a lead role together with co-authors to publish on complexity in IGLC in the period 2003-2005 (Bertelsen and Emmitt, 2005; Bertelsen and Koskela, 2004). Bertelsen (2003) argues that project management must perceive the project as a complex, dynamic phenomenon in a complex and non-linear setting.

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A motivation for this paper is that we conceive complexity and interdependence also to be a source of value creation. Pennanen and Koskela (2005) are touching upon this idea when they conceive value generation, as in the TFV-model (Koskela, 2000), to address time-independent complexity. The early design processes are seen as inductive by Pennanen and Koskela (op cit.) since there are several correct or good answers. We share this ontological understanding of design, but we also see design as processes that do not just take place prior to the production phase, but often continue in parallel with production. Follow-up design is important in many projects and may be embedded in management styles that pursuit to take advantage of opportunities also in the execution phase (Johansen et al., 2019).

The Cynefin framework (Snowden, 2002) is a central conceptual point of departure for our reasoning on complexity. Snowden differentiates between the domains denoted simple, complicated, complex and chaos, where each domain has different characteristics and requires different management and leadership approaches (Snowden and Boone, 2007). A construction project in the chaos domain would be very demanding (Bertelsen and Koskela, 2003; Vrijhoef, 2004), but in innovation projects that is maybe the domain where we want to be for some period. In the complex domain we don't know the exact effect of actions, the impact emerges.

In construction one may regard the product being produced (the building, bridge, etc.) as being complicated rather than complex, as the parts can be identified and related in a BIM-model. The properties and behavior of the product can however also be complex, e.g., the ability of a bridge to tackle dynamic loads. The contextual conditions related to location, e.g., ground conditions and topography, may also turn a construction project over to the complex side, also conceived as a product. Complicated or complex, the social processes of engineering, design and maybe production, involving internal and external stakeholders, is likely to make it complex or add to the complexity already there.

Project management will typically give priority to order and predictability to deliver on time, cost and scope, especially in fixed price contracts. Also, for the Last Planner System for Production Planning and Control (Ballard, 2000), the aim is to achieve order prior to production (Filho et al., 2016), however in a way that has the capability to deal with uncertainty and emergence on the detailed level. Last Planner addresses the time-dependent complexity (Pennanen and Koskela, 2005) and is an operationalization of the flow model. It does however not have the capability to create customer value based on exploration of the opportunities embedded in complexity or uncertainty (Torp et al. 2016; Klakegg et al. 2020).

When we relate complexity and value, we address customer value, which includes the operation and maintenance phase. By (customer) value creation we mean the construction processes that leads to value for the direct client, the operators, and the end users. We address the value potential which comes in addition to the value identified in the project specification, the potential surplus value.

Our problem statement is to contribute to unpack the duality of complexity, being both a threat to predictability and a possible source of value creation. Increased understanding of this duality has a potential to improve the knowledge underpinning project management practices. Our discussion is focused on complexity related to construction projects. Complexity in manufacturing and in more general terms is only to a very limited degree touched upon.

The structure of the paper is as follows: After this general introduction we first introduce the Cynefin framework, before we present the discussions on complexity within

IGLC/Lean Construction and the broader search on construction projects. With this as input we address and discuss the dual nature of complexity in construction before we conclude.

THE CYNEFIN FRAMEWORK

Cynefin is a framework for sense-making through a distinction between the four domains *simple*, *complicated*, *complex*, and *chaotic* (Snowden 2002). The simple domain is the domain of known, perceivable and predictable cause and effect relations. In the complicated domain things are still (at least in principle) knowable but causes and effects can be hard to comprehend due to quantitative or qualitative reasons. In the complex domain there are still cause and effect relations, but they are only coherent in retrospect and do not repeat. Finally, in the chaotic domain, the cause-and-effect relationships are not perceivable. The simple and complicated domains are characterized by *order*, while the complex and chaotic domains are characterized by *unorder* (Kurtz and Snowden 2003; Snowden and Boone 2007). A complex system is a system composed of interconnected parts that as a whole exhibit one or more properties, which behavior is not obvious from the properties of the individual parts. The system exhibits properties that are not evident from the properties of the single parts (Snowden, 2002).

There is an interconnection between the Cynefin domains, and the three types of interdependencies identified by Thompson (1967). Pooled and sequential interdependencies belong to the simple and complicated domains, while reciprocal interdependencies typically will be part of the complex domain. In reciprocal dependencies there is mutual interdependencies between the elements, creating a feedback situation where the behavior of any element is a precondition for other elements. There is also a relation between the Cynefin framework and the distinction between deductive and inductive systems (Pennanen and Koskela, 2005) and wicked problems (Churchman, 1967). Correct answers can be found to deductive problems. The answers can by easy to find, placing the problem in the simple domain or it can be more difficult to find, placing it in the complicated domain, but they can be found. The answer is in principle a calculation using known elements and therefore actually not producing new knowledge. Inductive problems belong to the complex domain. There might be several (correct) solutions to an inductive problem (no right or wrong) and new knowledge is produced (all information needed for the solution can't be found in the initial information). Churchman (1967) calls these problems wicked and point out that they have no stopping rule and no ultimate best solution. The solutions can be evaluated qualitatively as good or bad but are not true or false.

COMPLEXITY WITHIN IGLC AND LEAN CONSTRUCTION

A search at IGLC.net returned 104 matches on "complexity" and 237 matches on "complex". Especially in the period 2003-2005 there was a focus on complexity encouraged by the work of Bertelsen and co-authors. Bertelsen (2003) called for a new way of understanding and managing construction processes (organizing, planning, and control) based on complexity theory. A complementary contribution by Bertelsen and Koskela (2003) addressed how to avoid chaos in construction projects. They state that construction projects are often very complex and dynamic by their nature, and it is a "well-known fact that such systems exist on the edge of chaos". They explore the forces that may turn projects to cross this "dangerous edge" to chaos. Such forces are rework and parallelism in design. Last Planner, they say, seems to be a useful tool to control chaos-in -the small (firefighting), while it is a more open question of how to control chaos-in-the-large, chaos which is a threat to the whole project. Bertelsen and Koskela (2004) explain more in detail their work from 2003. Bertelsen and Emmit (2005) address the client as a complex system. They suggest a research agenda to improve understanding by applying value management alongside contract management and production management.

Kenley (2005) characterizes complexity in construction as a myth and criticizes the referred work by Bertelsen and Koskela. He argues that it is the activity-based planning (CPM) that leads to chaos, and that the problem and solution is one of mathematic. Kenley's solution is to pre-plan location-based and to establish a factory production set up on site. He argues that control systems of late intervention such as Last Planner are then not necessary.

Vrijhoef and Tong (2004) argue that construction environment should be understood as complex adaptive systems, which need to be adaptive to changes from both inside and outside the system. The management challenge of adaptive networks is to balance a minimum level of predictability and controllability and a maximum level of flexibility and emergence.

Bertelsen (2003), Bertelsen and Koskela (2003, 2004), Bertelsen and Emmit (2005) and Kenley (2005) do not differentiate between design and production. Lima et al. (2011) discuss complexity in design related to BIM. The authors argue that despite the complexity of design processes, simplistic thinking like BIM is needed. To support this, they refer to the distinction of Pennanen and Koskela (2005) between necessary and unnecessary complexity in construction.

Pikas et al. (2015) differentiate between production (construction) and design regarding process complexity, as design problems are inductive in nature and that there is no single best answer or "best way", while production is deductive and a "best way" is possible (Pennanen and Koskela, 2005). Theoretically, it is argued, construction can be developed with sequential or concurrent tasks. From this they deduce that complexity is rather self-inflicted and caused by organizational structures and people, an argument that is strengthened by reference to Tommelein (2015). The Design Structure Matrix is applied for mapping and modelling purposes. What makes design complex is that tasks are coupled (Wynn, 2007), simultaneously needing input from each other. Moreover, they discuss how process and organizational complexity can be reduced using concurrent engineering in organizational settings known as "big rooms", "extreme collaboration" (Chachere et al., 2003) and "Obeya room" (Morgan and Liker, 2006). Pikas et al.'s ontological understanding of design gives resonance to wicked problems in design, which is addressed by Whelton and Ballard (2002), Kalsaas (2020) and Lane and Woodman (2000).

Most of the papers reviewed so far see complexity as a threat to the construction processes. Other examples of this line are Ramírez-Valenzuela et al. (2021); Al-Sudairi et al. (2020); Dolphy et al. (2018); Filho et al. (2016); and Larsson and Simonsson (2012). Several contributions use the term complexity as a self-evident term (e.g., Al-Sudairi et al., 2020). Intuitively we understand and accept that a hospital project is more complex than a housing project. Pikas et al. (2015) characterize complexity as a vague term. Filho et al. (2016) refer to the Cynefin framework and make a distinction between complicated and complex. Biton and Howell (2013) argue that the Cynefin framework can be highly useful for people working in construction projects and that it should be taken on board as one of the theoretical foundations of Lean Construction. Their argument has this far only been followed up in a few IGLC papers.

OTHER LITERATURE ON COMPLEXITY IN PROJECTS

Pennanen and Koskela (2005) referred to above, arguing that to create value and manage time and cost, project management should promote complexity when needed, and reduce complexity, when it is unnecessary. They relate necessary complexity to the commitment making process among the whole variety of stakeholders. Unnecessary complexity is exemplified by the separation of programming and sketch design to eliminate complexity. Design is understood as an inductive process, and it is differentiated between inductive and deductive complexity. Regarding design for production (detailed design) they claim that the "right answer" is known (from pre-design), and that complexity therefore switches to become deductive.[4]

Baccarini (1996) is recognized to be an early contributor on complexity related to projects (Rolstadås and Schiefloe, 2017; Bertelsen, 2003). He differentiates between organizational and technological complexity analysed from the perspectives of differentiation and interdependencies. When it comes to technological complexity the differentiation is seen as a function of the number and diversity of inputs/outputs, tasks to be produced and the number of specialties involved necessary to design and build the artefact, when relate to construction. The interdependencies in technological complexity can be related to the interdependency terms developed by Thompson (1967) where reciprocal interdependencies between tasks, technologies and stakeholders create uncertainty and call for iterations in design (Kalsaas, 2020). Organizational complexity is defined by the number of organizational units, relations between these and the kind of tasks the units are handling. Williams (1999, 2002) introduces structural complexity by combining Baccarini's technological and organizational complexity and adds uncertainty as a second main component, in which uncertainty in goals and methods are addressed.

Hass (2009) understands complexity in term of characteristics that make a project unpredictable and dynamic. Brady and Davies (2014) conceive dynamic complexity in projects to be a function of changing relationships between system components and between the project and its environment and has to do with unpredictable situations and emergent events that occur over time. They make a distinction between dynamic and structural complexity. Structural is seen as the arrangement of components and subsystems in the overall systems architecture, which comprises the system produced, the producing system and the wider system. The system produced is the delivery of the product. The producing system contains a technological (the process of producing) and an organizational part (the project organization), whereas the wider system includes the owners and the users of the produced system. A project can have a degree of structural complexity with a low level of dynamic complexity and the other way around. Hence the two complexity dimensions may occur independently. Whitty and Mayor (2009) relate complexity in projects to system thinking and define a complex system to be a system formed out of many components whose behavior is emergent.

Luo et al. (2017) address research trends regarding complexity in construction project. They identify influencing factors contributing to project complexity, the impact of project complexity, complexity measurement methods, and considerations for managing project

[4] Pennanen and Koskela (2005) do not distinguish between complicated and complex. Parts of their reasoning on "complexity" can be read as what is in the Cynefin framework called "complicated".

complexity. They argue that future research should concentrate on specific factors that drive complexity throughout the lifecycle for different types of construction projects, and to develop management guidelines for handling the complexity.

There is a direction in project complexity research which aims to establish a model to assess project complexity and to align the project organization to handle the complexity at hand. Rolstadås and Schiefloe (2017) have developed such a model, and argue that project complexity is a function of project characteristics and the organization managing it. Their model operates with generic drivers and surroundings (contextual factors) which may influence the drivers and complexity factors, which are conceived to be project specific. The identified drivers based on literature research are ambiguity, uncertainty, unpredictability, and pace. The surroundings are categorized into socio-political, economic, technological, and nature. Nature represents a source of uncertainty in any project. It may lead to complexity in execution and has impact on the project organization. The complexity factors include the project context of internal and external stakeholders, the project organization, production technology (the producing system) and the system produced, confer Brady and Davis (2014). The social and cultural dimensions are embedded in the project organization.

DISCUSSION

While Cynefin makes a distinction between complicated and complex, much of the literature on “complexity” does not. It can therefore be observed that when discussing “complexity”, parts of literature is in fact addressing the Cynefin domain of the complicated. What is in literature referred to as technological complexity often belongs to the complicated domain in Cynefin. However, if the levels of innovation are high, it can also be complex. What is referred to as dynamic complexity certainly belongs to the complex domain also in Cynefin.

The literature addressing complexity in construction projects is mainly focusing on complexity as a threat to predictability and successful execution. It focuses on procurement models, execution models and tools that can enhance the project’s ability to identify, reduce and handle complexity.

Pennanen and Koskela (2005) differentiate between necessary and unnecessary complexity. They do not conceive complexity as a possible source of value generation. Instead, they promote the importance of resolving programming prior to sketch design. This is an approach to reduce complexity and may be counterproductive for value generation, confer our discussion below about the dual nature of complexity.

Pikas et al. (2015) address process complexity, applying the Design Structure Matrix (DSM) for mapping and modelling. DSM is instrumental to reveal interdependencies ex ante, but we claim that this mainly belongs to technological and product complexity. Processes also include the social dimensions and therefore the world of emergency. It might be possible deductively to design processes ex ante, but design is best understood to be ontological inductive as argued above with reference to Pennanen and Koskela (2005). Hence, some important aspects of complexity in projects are difficult to identify ex ante because people are important contributors to complexity. It is however possible to predict complexity through analysis and experience, using approaches like the model developed by Rolstadås and Schiefloe (op cit.). Such predictions can be useful when designing project organizations. Moreover, if complexity is well understood by management and the project organization, they can better reflect on which decisions and behaviours are likely to increase complexity, making them able to make a trade-offs between predictability and order on the one hand and possible value creating potentials and costs on the other. We address this duality below.

THE DUAL NATURE OF COMPLEXITY

A central dimension of duality we address in this paper is that between complexity as a threat to predictability and complexity as a source to value creation. The threat argument is apparent from the literature review above. In IGLC papers and in the broader literature search in the construction literature we have not identified the idea that complexity may be applied as a source of value creation.

The value creating argument needs to be developed, especially in relation to design. Koskela, et al. (2013, p. 9) see "the design-production-use process as a chain where the value is created as a potential in design, is embodied in production and is realized in the intended use by the client". Hines et al. (2004) argues that most of the potential for value creation is found in design, and that in fact all changes of design, even if they are initiated from production, will account as value creation in design or development of customer value.

When it comes to complexity and value creation, we will take the point of departure in the tradeoff between the drive to freeze solutions in design to create order and predictability versus the drive to postpone (Yang et al., 2004) the decision to explore alternatives as in set-based design (Ward et al., 1995) with the aim of creating surplus customer value. However, postponement and set-based design strategies are likely to increase structural complexity (Williams, 1996) as the number of interdependent variables and issues increase. Zinn (2019) argues that set-based design decisions normally decrease uncertainty (Yang et al 2004), due to higher maturity, understanding, and the involvement of more trades in the decision.

The idea of postponement is related to the concept of the Last Responsible Moment (LRM)., defined as "the instant in which the cost of the delay of a decision surpasses the benefit of delay" (Senior, 2012). Ballard (2000b) argues that customer value might be increased by deferring design decisions until the LRM. The mechanisms underpinning this are learning and gradually increased understanding of what is being created. Working with different sets of alternatives is likely to encourage and increase the learning by the client and end-users if they are involved in the decision-making process. We prefer, however, to apply the postponement term instead of LRM, as we regard it to be practical impossible to identify a specific LRM.

As the project proceeds the customers will learn and increase their understanding of the project and its impact and their plans for usage may change, leading to changed needs and priorities (Boyd and Chinyio, 2006). Eikeland (1998) uses the well-known increase in accumulated cost and decrease in uncertainty during the execution of the projects due to freezed design and work completed to demonstrate that this creates an increasing gap between the needed/wanted and available freedom of action, limiting the ability to make changes. We have identified uncertainty as an important driver of complexity and can therefore replace uncertainty with product complexity in this model, demonstrating that as complexity decreases, so does the ability to make needed/wanted changes. Set based design and postponement of decisions are strategies to reduce this gap.

We apply the term product complexity, which in our conceptualization is the same as technological complexity. When the design develops and matures it becomes less complicated as the number of interfaces and interdependencies between disciplines and other actors is reduced. However, design is at its hart people creating something new. (If nothing is new, there was nothing to design.) Design will therefore always have an element of emergence, handling reciprocal interdependencies, possible ambiguity, unpredictability, uncertainty, and pace (Rolstadås and Schiefloe, 2017). It will therefore also always have at least a degree of complexity. Size also matters. It is e.g., far more challenging and potential complex to coordinate or lead the work of 100 engineers and architects compared to 10.

To avoid the domain of chaos, all decisions in design can of course not be delayed. The project needs to identify certain strategic decision to be object of set-based design, e.g., the decision of when to freeze the room schedule of a building. When the room schedule is frozen, the product complexity is reduced. But the freedom to explore new opportunities for value creation is also restricted. As an example, an evaluation study of a new world class animal hospital project with significant cost overruns, indicates that late decisions of the room schedule contributed to chaos in design (Kalsaas et al., 2020). The delay was mainly caused by late decisions by the end-users who wanted to take advantage of world class equipment and facilities for the hospital. It may make a huge difference for the design processes if postponement and delay is planned or if it just emerges.

The strategy of increasing complexity to enhance value creation can also be related to uncertainty management (Klakegg et al. 2020). Uncertainty comes with both upsides (opportunities) and downsides (risks or threats). While risk management has a sole focus on avoiding downsides, uncertainty management advocates a balanced focus on exploiting upsides and avoiding downsides. The first is an often-unexploited potential in both the design and execution phase (Johansen et al., 2019). The opportunity part of uncertainty represents a potential to harvest surplus value. In the hunt for opportunities, it may be worth the risk to increase complexity, e.g., by postponing design decisions. Malvik et al., (2021) relate the concept of uncertainty and opportunity management to the concept of Target Value Design/Delivery (TVD) (Ballard, 2020). In TVD the approach is to maximize value delivery within a cost constraint. This in contrast to traditional bidding where the approach is the opposite, to minimize the cost of a predefined value delivery.

Relational construction contracts seem to gain ground in replacing transactional contracts as design-bid-build and design-build. Integrated Project Delivery (IPD) is one of several relational contract models (Lahdenperä, 2012; Mesa, 2019) well known in the Lean Construction community. The aim of IPD is to improve collaboration and remove sub-optimalisation by aligning the interests of the parties. This is done through a multiparty contract between the client, the designers and one or more construction companies. Central elements of the contract are open books, limited liability for the parties, sharing of profit and risk, and joint decision making. These are all elements that increase complexity. E.g., Kalsaas et al. (2020) studied an IPD hospital project and found that the project organization were struggling with the decision making. IPD projects are usually founded on a TVD approach where the parties in the initial phase collaborate on design and cost estimation to agree the target price as a precondition for signing the final contract of execution. This initial phase is complex due the nature of design and the number of decision makers, but also because the economic interests of the parties are not yet aligned (Kalsaas et al., op cit.). The client may want a low target price, while the construction companies want a high target price to reduce their risk. Even if the economic risk for the contractors is limited in IPD it is a severe blow for companies to be working on a major project for several years without any return on capital.

Closing this discussion of IPD and complexity we summarize that in IPD projects complexity is increased to create surplus value. At the same time the project organization is designed to, or should be designed to, cope with the complexity created.

CONCLUSION

Literature on complexity in construction projects is focused on how to diagnose levels and types of complexity and which strategies to apply to cope with it. Several complexity terms and models have been developed, e.g., technological complexity, product complexity, dynamic complexity, and organizational complexity. Complex system may exhibit properties that are not evident from the properties of the single parts and a central aspect of complexity is emergence. Something emerging can only be identified ex post. In contrast to the Cynefin framework, parts of literature do not distinguish between complicated and complex.

The Cynefin framework differentiates between the four domains, simple, complicated, complex and chaos and represents a breakthrough when it comes to understanding complexity and how to approach it. Taking the Cynefin terms as point of departure, we have in this paper discussed aspects of complexity that are central to design and production in construction in general and to value creation.

Our literature review demonstrated that the debate on complexity in IGLC in the early 2000s conceived complexity as a threat and construction as being at the edge of chaos. When facing a complex problem, there are two possible strategies to pursue. The first is to transform and move the problem into the complicated or even simple domain, thereby making it manageable. The second is to handle the problem within the complex domain. The dominant approach within both Project Management, generic Lean and Lean Construction has been the first, namely, to emphasize efficiency, flow, standardization, best practice, planning, reliability, and control. One of the most recognized products of Lean Construction, the Last Planner System (LPS), can act as an example: LPS is designed to create predictable flows, mainly by reducing complexity (e.g., through phase scheduling and look-ahead planning), partly by handling it (through collaboration and short-term planning).

We have argued that the dominating approach to complexity as a threat is somewhat lopsided and potentially reductionistic. We therefore call for a renewed debate within Lean Construction on how we could also appreciate, exploit, and take advantage of complexity instead of just combatting it. Humans and cultures are complex by nature and learning, understanding and the creation of something new (that is design) are complex phenomena. Value creation is reliant upon both strategies and is therefore not a question of either or, but of balance and tradeoffs based on an inherent dualism.

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APPLYING A DFMA APPROACH IN THE REDESIGN OF STEEL BRACKET -A CASE STUDY IN POST AND BEAM SYSTEM

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ABSTRACT

Design for manufacturing and assembly (DfMA) has gained increased attention in the construction industry as the process has been industrialized and shifting towards a combination of factory prefabrication and assembly on site. The aim of this study is two-fold. Firstly, to apply the DfMA approach in the redesign of a steel bracket from a post and beam building system to simplify the design for reducing the cost and improving manufacturability. Secondly, to experimentally evaluate the mechanical properties of the redesigned bracket for implementation. An experimental case study has been conducted in a multistorey post and beam building system. The empirical data were collected from five semi-structured interviews and two workshops.

The result shows that the DfMA approach has the potential to improve the manufacturability and cost of building components in Industrialized house building (IHB) and is comparable to lean design. Moreover, the proposed steel bracket offers satisfactory load-bearing capacities and shows an improvement with a reduction of cost by 15%, lead time by 50%, and material efficiency by 25%. DFMA can be used as a promising approach for aligning the design phases of IHB with the production and assembly by improving cross-functional collaboration.

KEYWORDS

Off-site construction, Design management, design for manufacturing, design for assembly, lean construction.

INTRODUCTION

IHB companies are challenged to improve their productivity as the demand for housing in the market has increased dramatically (Uusitalo & Lavikka, 2021). The companies must be able to respond quickly to changing market demands and unique customer requirements (Grenzfurtner et al., 2021). This has triggered them to consider means to improve the cost and lead times in both design development and production process to

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become competitive in the housing market (Jansson et al., 2014). The design phase contributes significantly to the performance of a project and has been considered the crucial stage of the IHB life cycle with uncertainties and iterations (Lidelöw & Jansson, 2017). Besides, the design phase is the most suitable stage in the whole life cycle of an IHB project to establish new solutions that can have a high impact (Vaz-Serra et al., 2021). The knowledge exchange between design and production leads to continuous improvement (Gao et al., 2020; Lessing & Brege, 2015). Thus, placing more consideration on production knowledge early in the process is a proven strategy to reduce cost and bring efficiency.

The post and beam system is one of the oldest building systems built mostly on concrete and steel but has been using timber structures in the past decades (Tlustochowicz, 2011). Steel brackets are used to connect the post and beam where brackets are a key component of the building system due to their custom-oriented nature (Thajudeen et al., 2018). The production of customised building components generates several new knowledge and experiences, and it is important to integrate those into the design process (Gerth et al., 2013; Tillmann et al., 2015). There are several approaches by which the design phase of IHB can be efficient, thereby improving the overall productivity (Grenzfurtner et al., 2021). One way to improve the IHB design is by adopting an integrated method supporting the decision-making process for designers.

The Design for Manufacturing and Assembly (DfMA) approach has been widely used for decades in several industries for the development and rationalizing of products, such as the aerospace, automotive other manufacturing industries (Vaz-Serra et al., 2021). The potential of the DfMA approach has increased by industrialising the construction activities where the building components are manufactured in the factory (Tan et al., 2020). The design for manufacturing (DFM) and design for assembly (DFA) concepts are more essential than ever in the IHB industry (Tan et al., 2020), particularly for companies offering customised buildings (Yuan et al., 2018). The implementation of DfA and DfM has the potential to bring considerable benefits, including reducing costs for manufacturing and assembly, enhancing product quality, and shortening production time by simplifying products (Boothroyd et al., 2010; Lu et al., 2021).

Several researchers have studied the possibilities of incorporating DfMA in the IHB process and provided an overview of the application at the industry level (Gao et al., 2020; Langston & Zhang, 2021). This is evident from the literature review on DfMA and its application in prefabricated construction by Wasim et al. (2020) where most studies are performed in recent years. However, existing practices in construction generally follow the DfMA approaches established in a manufacturing setting without sufficiently considering the critical aspects of IHB (Lu et al., 2021). Moreover, demonstration of the practical application of DfMA approaches in IHB is limited (Tan et al., 2020) and no studies have been performed in the post and beam IHB system. Therefore, the aim of this study is two-fold. Firstly, to apply the DfMA approach in the redesign of a steel bracket from a post and beam building system to simplify the design for reducing the cost and improving manufacturability. Secondly, to experimentally evaluate the mechanical properties of the redesigned bracket for implementation.

THEORETICAL BACKGROUND

IHB involves the prefabrication of components and modules in factory settings and the efficient use of technical systems and components with different levels of standardization, that are combined to form unique buildings (Lessing & Brege, 2015). The management of IHB design is crucial as it involves either modifying existing solutions according to new requirements, configuring a product's modules or designing a new version of a product (Thajudeen et al., 2018). The design phase of IHB plays a crucial role in determining the resources, costs, time and others for the production and assembly process. Ensuring improved quality and minimizing the production cost is key to an optimised design (Ulrich and Eppinger, 2008). One way to evaluate the design of a product is with the DfMA approach (Wasim, 2020).

DfMA is a design philosophy and method that originated in the manufacturing industry (Tan et al., 2020). It consists of two parts where DfM is mainly concerned with the enhancements in the manufacturing of individual parts and DfA addresses the means of assembling them efficiently (Bogue, 2012). DfMA strategies have evolved from the manufacturing industry and are widely used to improve productivity in construction with the primary aim of optimising the cost, quality, and lead time (Lu et al., 2021). The typical stages of the DfMA approach presented by Boothroyd (2005) have been used for this study. According to the author, DfA should consider in the beginning, leading to a simplification of the product structure. The economical selection of materials and processes and early cost estimates is the next step to comparing the cost and material utilisation of old and new designs. This is followed by the analysis of DfM aspects to reduce total manufacturing costs and operations involved.

Lean construction is a method which adapts the concept of lean production to maximize the value-adding activities and minimize waste (Koskela, 1992). The principles of lean construction and DfMA are interrelated and mutually supportive (Lu et al., 2021). Several methods and tools such as the last planner system, target value design, set-based design, and design structure matrix have been introduced to support lean application (Uusitalo et al., 2017). Design management methods such as lean design, last planner in design and agile management in construction have been discussed by Lidelöw & Jansson (2017). Lean construction and DfMA share the same principles as both ensure improved product quality while minimizing waste and manufacturing costs (Gerth et al.,2013). They introduced an approach named Design for Construction (DfC) based on DfMA and shows the importance of experience feedback in the design phase for enhancing productivity. Ng & Hall, (2019) identified the common practices shared to demonstrate their potential synergies of them in the construction industry. As dominant factors of DfMA adoption, they identified just-in-time, reduction of speed and improvement of site management and concurrent engineering (CE) from a lean perspective. However, these two principles are viewed differently where lean aims to eliminate construction waste and DFMA works on improving ease of manufacturing and assembly from the early stage of design (Gao et al., 2020).

The production knowledge supports the designers to evaluate product characteristics (Gao et al., 2020). Tillmann et al (2015) investigated the topic of managing the production of custom components on a complex project and discussed the importance of integration of design and production. By considering the downstream processes of manufacturing and assembly, DfMA offers a method for evaluating and improving product design (Boothroyd et al.,2010; Lu et al., 2021). Here, the optimisation achieved through DfMA at the early design phase can substantially contribute to best practices, reduce time and delays, improve safety, and thereby enhance the overall productivity of the prefabricated construction project (Wasim, 2020).

Over the last few decades, several studies have highlighted the importance of DfMA in the design stage, presenting different approaches to facilitate improvement. However, there is a lack of practical studies in the IHB sector showing how companies can benefit from the DfMA approach. The literature reviews show that the traditional approach is still used in construction and there is a need to develop affordable technologies for better adopting DfMA strategies for the IHB industry to improve efficiency (Langston & Zhang, 2021). Moreover, a coherent description of DfMA specifically for IHB is needed for successful development. By acknowledging the current gap, this paper intends to demonstrate the adoption of the DfMA approach in the house building industry.

RESEARCH METHODOLOGY

An experimental case study has been conducted in a Swedish company offering multistorey buildings using the post and beam system (Karlsson, 2016). A case study method allows to focus on a particular issue within a real-life context and is often jointly used with other qualitative methods to enhance robustness (Yin, 2018). The primary data for this study has been collected from multiple sources by triangulating methods such as workshops, in-depth interviews, document analysis and literature reviews. The unit of analysis was the design and manufacturing process of steel brackets in the building system, which is a suitable case from the DfMA perspective. Empirical data were gathered from two workshops and five semi-structured interviews by including experienced participants from the case company and supplier of the bracket. The participants were: the design manager, senior structural engineer, CAD engineer, structural engineer, and production engineer from the supplier. The selection was based on their experience in bracket design and knowledge about the production process. The questions were mainly focused on the challenges in the existing component design from a process perspective and the opportunities of the bracket redesign from a DFMA perspective.

A review of DfMA approaches was conducted as the first step to understanding key concepts and practical applications in construction and more specifically in IHB. The different stages of the DfMA approach presented by Boothroyd et al. (2010), have been followed and used for analyzing the study. DFMA approach has been chosen for redesigning the bracket as the production and assembly aspects were significant for this study. The knowledge of the design and production process of steel brackets gathered from workshops and interviews were mapped and related to the DfMA approach. The first workshop focused on the existing old design and its challenges whereas the second one aimed at the new design, its benefits and evaluation to implement in projects. The suggestions for improving the current design of the bracket were taken into consideration.

The work has been carried out in close collaboration with the supplier of steel brackets. A factory visit to the supplier was undertaken to deepen the understanding of how components are produced and create a process map for analysis. This mapping aided to compare the lead time for the old design and the new design of the bracket while the prototype was produced during the visit. Moreover, document analysis for three previously finished projects was conducted including detailed drawings of brackets, assembly drawings, BOM list, and invoices for performing the cost analysis. The prototype fabricated with the new design has been tested at the test rig located at the case company with the support of structural engineers from the case company. This was mainly to analyse the mechanical behaviour of brackets as part of the evaluation and to support the final decision for implementation in future projects. Finally, the collected empirical data including the experimental findings have been analysed using the procedures recommended by Miles et al., (2014) and reported.

CASE STUDY

A leading manufacturer of Glulam (Glued laminated wood) based multistorey house building system to the Swedish market has been selected as the case company. The building system is named Trä 8 which means that it can be used for up to eight meters of free span enabling flexibility for architectural designs. The fundamental part of the system is the idea of "Big Size Pre-Cut", where a high level of prefabrication of large building components and sets of material is developed through efficient production. The main components of the building system and the assembly view of the steel bracket are shown in figure 1.

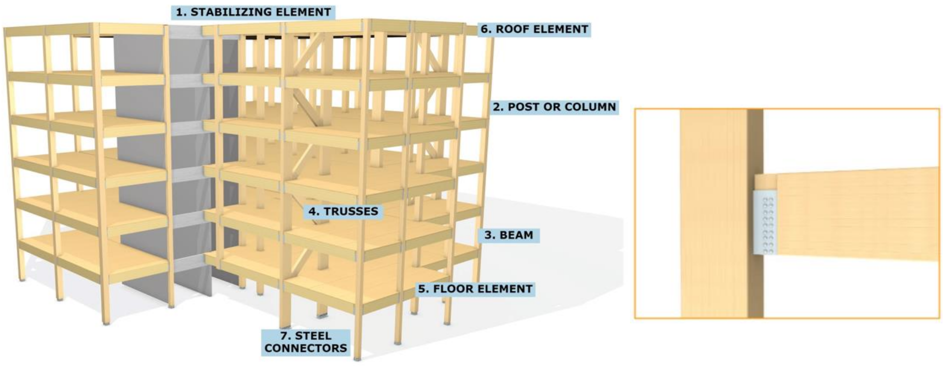

Figure 1: Trä 8 building system and assembly view of steel bracket

REDESIGN OF STEEL BRACKET

In a post and beam building system, vertical post and horizontal beams are connected to form a structural frame where steel connections play a vital role in structural stability when subjected to lateral loadings (Thajudeen et al., 2018). Steel brackets are engineered components used to transfer loads from the beam (secondary member) to the post (primary member). In the Trä 8 system, brackets are designed to transfer different magnitudes of loads from several floors to the foundation through the vertical post.

The load transmission between the secondary and the brackets takes place mainly by contact pressure, while the load transmission between the brackets and the primary beam takes place by means of nails, through screws. Moreover, by transferring the horizontal loads to the wooden trusses, they function as stabilizing elements for the building. They are folded from a piece of sheet metal "S355J0" with a required thickness of 5mm, screwed to the members with 8mm screws. The variety of the brackets depends on the size of the beam, the number of screws in the primary & secondary objects and the required load capacity. This generates an increased number of variants after every project. Thus, the reuse of brackets is limited creating difficulties in standardisation. Therefore, design support is essential for designers from a process perspective as a solution for managing the challenges due to the customization.

Design and production process of steel brackets

The findings from the production visit and interviews with the case company and suppliers are reported. The design process of steel brackets generally includes structural design, modelling and detailed drawings for production and assembly. The structural design identifies different types of loads acting on the building and the dimension of the primary and secondary members. Math CAD is used to design the brackets where the vertical load, horizontal load, the dimension of the beam and the size of screws that insert into the post are required for calculating the brackets. The following step is the modelling of the building and detailing of different variants of bracket components. Tekla structure is used as the tool for both modellings of building and detailing of components in 2D format for production and assembly. Finally, all these drawings and requirements are forwarded to the suppliers who produce the brackets.

The case company has long-term cooperation with the suppliers and has been involved in the development activities. The process mapping of old bracket production is shown in figure 2. The order from the case company includes the detailed drawings of brackets with all individual assembly details prepared by designers. These drawings are then prepared for production by the suppliers in a way that maximum yield can be achieved during the operation.

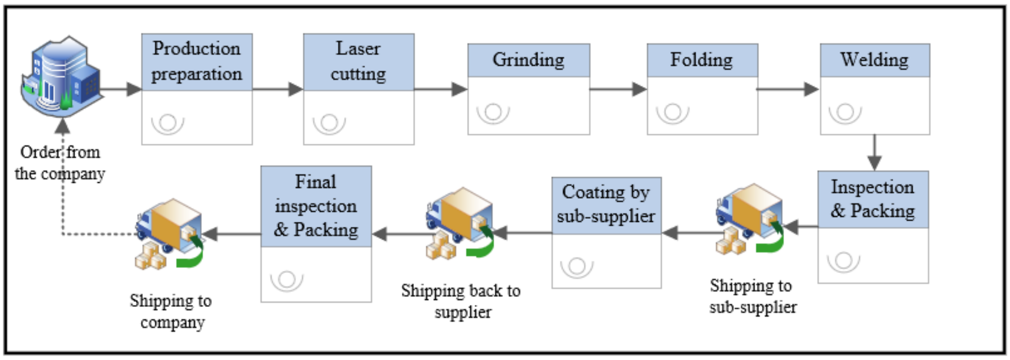

Figure 2: Process mapping of the old design

The first operation is cutting smaller sheet components from sheet metal into the necessary shapes and dimensions with the help of a laser cutting machine. The holes required for screws are also punched during this operation. The next step in the fabrication process is the grinding of sheet metals to smoothen the surfaces and edges. These smoothed components are then folded into a bracket. The following step is the welding of the bottom edges of these brackets. A random inspection and packing are carried out after the operations and transported to the sub-supplier for performing the electric galvanised coating on the bracket. This process usually takes a week, and the components will be shipped back to suppliers again. The final inspection and packing are performed before transporting the coated brackets to the company directly or building site depending on requirements. This is because brackets are welded at the site, in some projects where the coating needs to be done at the site.

There are several challenges involved in the production of old bracket which is important to consider while designing. The existing challenges were discussed in the first workshop. The most highlighted challenge of the old design was the lead time as it utilizes extended time with the process such as welding and galvanised coating on brackets by sub-suppliers. The process mapping shows that one and half weeks is required for the coating process from sub-suppliers. Moreover, the time requires for folding operation is high for the old design. The higher cost is another problem as it involves a lot of operations as shown in the figure. Moreover, this design uses more materials for the bottom part which is welded to the adjacent side. Here, the welding requires more time and energy which is not sustainable. Another challenge is that the old design generates a lot of scraps on the sheet metal from which the brackets are cut out. Any change in bracket size creates a lot of scraps when the sheet metal is prepared for production.

New design of bracket and its benefits

A new design and production process for the bracket is proposed as shown in figure 3. Here, the welding operation has been avoided by folding the bottom plates at the supplier level. Additionally, the coating operation by the sub-supplier including transportation is eliminated from the process. Therefore, the overall lead time can be reduced as the whole process has been reduced in half. The coating process can be avoided as the brackets are produced from pre-coated plates with magnelis which is a metallic coating that offers high corrosion resistance and protection against long-term wear. The time taken for folding operation is less for the new design. The new design is more sustainable as the energy can be saved by avoiding the welding operation and transportation can be reduced.

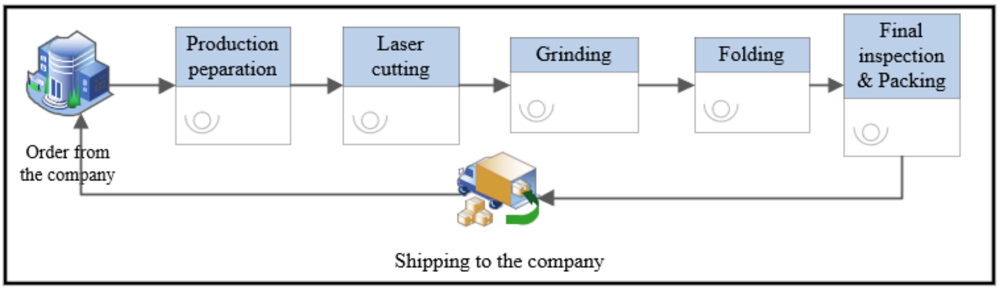

Figure 3: Process mapping of new design

As shown in figure 4, one advantage of the new design is the utilisation of material as the maximum number of brackets can be accommodated in the sheet metal depending on the size of the bracket. According to the production engineer, 25 folded type brackets can be produced from sheet metal whereas only 20 can be produced with an old design. The main reason is that the bottom neck part can be avoided which saves a quite amount of material. The tolerance generates when folding is manageable while tightening the screws. In other words, there is no need for the base plate as the screws can take the loads from the building. Yet the new design has this extra safety to support the load from the beam. The bottom plate is required during the assembly of beams as a support member. The advantage is that the brackets can be aligned in a different direction to reduce the scrap generated. The analysis shows about 25% of material efficiency when compared to the old design.

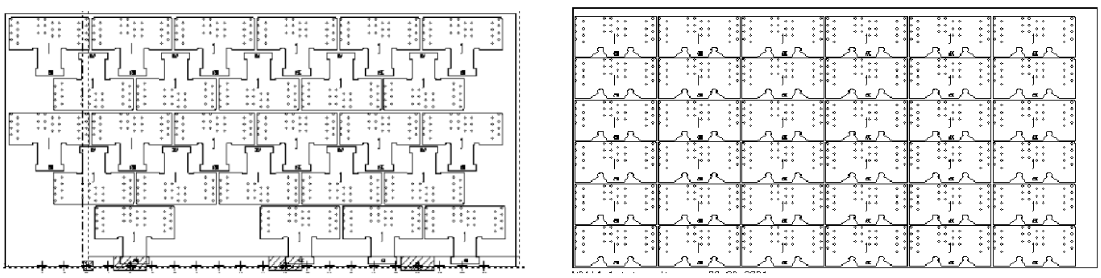

Figure 4: Process mapping of new design

Additionally, a cost comparison has been performed with brackets produced from old and new designs as shown in table 1. A document analysis of two previously completed projects was carried out. The total number of brackets produced including all variants used in these projects was taken to compare the cost. Table 1 shows the comparison between the cost of the new and old design. The analysis shows that the production cost can be reduced to 15 to 20% and this was also verified by the suppliers from interviews. Moreover, there is no additional investment needed for producing the new bracket as the operations are the same and few processes were omitted.

Table 1: Cost comparison of old and new brackets from selected projects

Project	Variant s used	Numbers of brackets used	Total price with old design (SEK)	Total price with the new design (SEK)	Cost difference
Project 1	**2**	**206**	**75850**	**64473**	**11377**
Project 2	**3**	**759**	**682736**	**580324**	**102412**
Project 3	**18**	**207**	**73521**	**62493**	**11028**
				Cost-saving of 15%	

EXPERIMENTAL PROCEDURE AND ANALYSIS

As part of the evaluation, the newly designed bracket has been tested in the test rig located at the case company. The main purpose was to experimentally assess the behaviour and load-bearing capability of the newly designed steel bracket when subjected to dynamic loads. The test specimen includes a column and beam connected with a bracket and a hydraulic device that pulls down the specimen. The load on the bracket has been adjusted with the help of a hydraulic hand pump. Four draw wire type transducers were used for this experiment which accurately measure the position or change in position of members when applying the load. The transducers are connected to the workstation to observe the behaviour and to measure the load and deflection.

In total, there were two setups for testing the behaviour of brackets loaded from the vertical and horizontal directions. Three trials were performed from the first setup including the testing of one old and two new brackets for horizontal loads and two trials from the second setup with two new brackets on vertical loads. The conditions for failure were considered at the point of deformation of bracket or screws on primary and secondary or screw withdrawals.

The first setup is performed by placing the column and beam at an angle of 5 degrees. The load was increased uniformly, and screw withdrawal from the primary member occurred at the load of 54 KN for the first trial, 68.6 KN for the second trial and 69KN for the third trial. Here, similar deformation has been noticed on the steel brackets and screws from three trails where screw withdrawals were the reason for failure. The final breakdown occurred due to tension perpendicular to the grains of the primary member.

In the second setup, the testing was performed by only screwing the brackets to the column with a dimension of 165X225 mm. This setup was mainly to analyse the behaviour of the bracket under vertical load. Therefore, the secondary members were not screwed. Also, to verify the stability of the folded bottom part of the newly designed bracket. The post and beam connection is designed in such a way that the screws are load-bearing components holding the designed load after the assembly at the site. Here, the main purpose of the folded part was to hold the load from the beam before screwing.

The deformation in the bottom folded part has been observed with an increased load of 86 KN for the first trial and 96 KN for the second trial. The final failure of the bracket happened at the total load of 96 KN applied on the beam which is distributed to the two supports. However, the position of the applied load was close to the bracket where the most load was taken in this case. Therefore, the failure load is estimated to be 75.6 KN. The reason for the failure was due to the combination of crushing and tension perpendicular to the grains where the friction generated in the bracket damaged the folded part of the bracket. The measured load-mid-deflection behaviour of the specimen from setup 1 and setup 2 is shown in Figure 5.

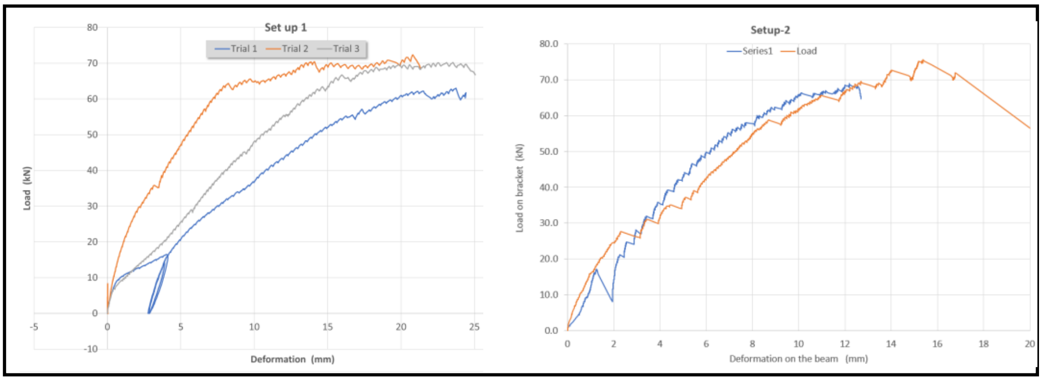

Figure 5: Load-deflection behaviour of the test specimens from setup 1 and setup 2.

DISCUSSION

This paper reports a case study of a successful application of DfMA in the redesign of a building component. The outcome of this study highlights the use and positioning of DFMA in the context of lean construction (Ng & Hall, 2019). IHB companies are generally following the same routine and use similar methods or tools where they put extended effort on sub optimising those to gain efficiency in the process. However, optimising these existing solutions might be a short-term goal. Another way to handle this situation could be to take a holistic approach and apply or test different methods and tools to achieve a long-term goal (Jansson et al., 2014). The lean principles are commonly applied to improve the production process although they can create value across the process from a holistic view. The point here to emphasise is to extend the process and include the lean way of working in the engineering design, thereby identifying value-adding activities in the whole chain (Lidelöw & Jansson, 2017).

From a process perspective, one remarkable finding is that DFMA can be considered as a method that can foster a lean culture in daily engineering work (Tan et al., 2020). Lean design can be used to standardise the process and optimise the whole process from quotation to the assembly at the site (Uusitalo et al., 2017). The opportunities for asset reuse have been increased in IHB, unlike traditional construction where standardisation of processes and components can be achieved with DFMA guidelines and checklist (Jansson et al., 2014). Here, DFMA complements lean design by providing relevant knowledge and experience from production and assembly available for designers in a set of predefined guidelines (Ulrich and Eppinger, 2008).

Another finding is that the term DFMA approach is not explicitly discussed in the lean construction community. However, several methods introduced as part of lean design share the same outcome. Applying DFMA can be a potential way to standardise the process of bracket design which promotes a lean design. The finding shows several improvements in the new design of bracket using the DfMA approach, resulting in significant cost savings and easy manufacturing due to a reduction in the number of parts and involved operations (Vaz-Serra et al., 2021). The results add value by reducing the waste in the process and indicating that DfMA and lean construction share common grounds (Gerth et al.,2013; Ng & Hall.,2019).

The steps presented by Boothroyd (2005) in the DFMA method have been followed in the redesign process and evaluation of the bracket. The finding from the study shows that this approach can be similarly followed in construction as in manufacturing to gain competitive advantages (Lu et al., 2021). However, some aspects need detailed descriptions and support in the IHB process. The method is mainly developed within other domains and the application area is mostly the manufacturing industry. In IHB, the assembly process has two parts i.e., component assembly at the site and assembly at the production facility. Therefore, DfA has to be classified into the design for assembly at the site (DfAs) and design for assembly at production (DfAp) and should be considered independently. Designers should be aware of the process and challenges of both stages. Here, assembly guidelines can be developed for both stages to support sufficient review and assessment of component variants available and how to use them, which also guides workers in the process (Bogue, 2012).

The study shows that companies are more familiar with management tools such as lean principles, agility, product platform etc. and are not fully aware of how to use the DfMA approach. This was evident from both the case company and supplier, where an explicitly defined or formalised method and guidelines were missing. However, the analyse of data shows that the companies are trying to design by making sure that components are easy to manufacture and assemble. DfMA aspects are considered a high priority during the design of components in IHB, and the designers are always considering aspects of the assembly process upfront in the process. However, the knowledge and experience from the production and assembly phase are not properly aligned with the design phase. According to the design engineer "*DfMA is something company should take into account as the study has resulted in getting a simpler and cheaper component design*".

The cross-functional collaboration to transfer gained knowledge from production and assembly and consistent information flow are necessary to implement DfMA and create it as a part of the company's culture (Gao et al., 2020; Tan et al., 2020). Documenting production and assembly knowledge is one of the most vital parts of company assets and the way to collect it and make it available for designers needs support methods and guidelines (Boothroyd et al.,2010). Hence, a good alignment can be achieved with production and assembly that provides an idea about what kind of asset can be built and used in different projects. There is a need for integrated support for designers and the analysis of empirical data put forward the possibilities for integrating a platform-based design approach to the traditional DfMA. However, detailed studies are required to show how this approach can be realized when dealing with components having different production strategies and can be considered a future study.

CONCLUSIONS

A novel beam-to-column connection with a steel bracket is proposed and experimentally tested the mechanical behaviour as part of the evaluation. The results show that the DfMA approach can be used as a promising tool for redesigning an existing building component and aligning the design phase of IHB with the production and assembly. Moreover, the contribution of this study to the IHB industry pointed to the importance of adopting DfMA as an integrated tool supporting decision-making for designers to facilitate lean design. Based on the analysis and experimental results, the following conclusions can be drawn:

- DfMA can be equated to lean principles in several aspects and has the potential in IHB to reduce waste and add value to the process.
- This study has resulted in an improvement in efficiency and the overall cost has been reduced to 15%, material efficiency by 25% and total delivery lead time of components by 50%. Moreover, the results of the experimental study indicate that the proposed steel bracket offers satisfactory stiffness and load-carrying capacities.
- In the IHB sector, the DFA has to be considered and evaluated separately, i.e., DFA for site and DFA for production.

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A CONCEPTUAL FRAMEWORK FOR LEAN CONSTRUCTION AND BLOCKCHAIN SYNERGY

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ABSTRACT

Blockchain is a distributed ledger technology referring to decentralized databases existing across multiple locations and participants, in which the need for intermediaries to process, validate or authenticate transactions is reduced or eliminated. Such transactions are synchronously held by computer nodes in distributed copies, with cryptographic signatures validated through consensus protocols and transparency achieved through peer-to-peer transactional access among the nodes. Blockchain-based applications can be preferred over centralized databases on the basis of high levels of trust, data security, immutability, transparency, and multi-user consensus protocols. There is growing interest in blockchain in the built environment, with a focus on procurement, the management of supply chain project-life cycle, smart cities, intelligent systems, sustainability, and decentralized organizations. However, there is little discussion on whether and how blockchain will affect the advances in lean construction (LC) and vice versa. This paper therefore proposes a framework that establishes interactions between blockchain and lean construction, which can potentially facilitate the implementation of both. It is based on a synthetic literature review. The results indicate that blockchain can facilitate the implementation of LC (e.g., recording and retrieving of Last Planner data), and vice versa (e.g., value stream mapping guiding the integration of blockchain with processes).

KEYWORDS

Lean construction, distributed ledger technology, blockchain, smart contracts, framework, synergy.

INTRODUCTION

Distributed ledger technology (DLT) refers to a database decentralized across multiple locations and participants, reducing or eliminating the need for a central authority to

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process, validate or authenticate transactions (i.e., data exchange between multiple parties for different purposes) (Li et al., 2019). Fundamentally, DLT transactions are synchronously held by computer nodes in distributed copies with cryptographic signatures validated through a consensus protocol, with peer-to-peer (P2P) transaction access (transparency) between the nodes (Li et al., 2019).

When high levels of trust, data security, immutability, transparency, and a multi-user consensus are sought, DLT applications can be preferred over centralized databases. Typical examples of these applications are smart (automated) contracts, or digital tokens denoting a value or ownership (Scott et al., 2021). A popular type of DLT is blockchain, introduced with the cryptocurrency Bitcoin by pseudonymous author Satoshi Nakamoto (2008) – where transactions are recorded as a chain of data blocks linked with one another. The cryptocurrency is the token used to keep the system running and does not equate to blockchain (Nakamoto 2008). Key blockchain features are: (i) decentralization across a P2P network of computers (nodes), (ii) data immutability once the blocks are chained, (iii) reliability due to all nodes having the same copy that is checked through an algorithm, and (iv) a proof-of-work procedure that is applied to authenticate the transaction and uses a mathematical currency (Bitcoin) to reward the miners (nodes) (Nakamoto 2008). Since the initial Bitcoin blockchain, other algorithmic procedures have also been developed to tackle the authentication issue such as the proof-of-work, proof-of-stake, proof-of-authority, ripple protocol consensus, delegated proof of stake, stellar consensus protocol, and proof-of-importance (Wadhwa 2022). Since around 2015, blockchain-based applications have been intensively discussed from the built environment (BE) perspective (Xu et al. 2022), including the following topics: contract management, information management, project-life cycle management, stakeholder management, integration with other technologies (e.g., BIM and Internet of Things (IoT)), procurement and supply chain management, smart cities, sustainability, and decentralized organizations.

Lean construction (LC) refers to managerial principles and techniques adapting lean management from automotive manufacturing into construction (Tzortzopoulos et al., 2020). This is guided by key principles (e.g., waste reduction, variability continuous flow), and facilitated by certain tools (e.g., the Last Planner System (LPS), visual management) and management and procurement practices (e.g., relational contracts) alongside digital technologies (e.g., BIM) (Tezel et al., 2018). LC research and application have been expanding through research and practitioner communities since coining the term in the early 1990s, the most active being the International Group for Lean Construction (IGLC).

There are some common themes in LC discussions such as improving trust between stakeholders (Howell, 1999), enabling process transparency as a key LC principle (Sacks et al., 2009), automating non-value adding activities (Akinci et al., 1998), instilling continuous improvement through effective record keeping (Koskela et al., 2019), BIM and LC integration (Sacks et al., 2010), and adopting prefabricated systems (Bjornfort and Sarden, 2006), which as discussed in this paper, could potentially be facilitated by DLT. With LC's increasing adoption, LC's potential impact on DLT implementations in the BE is also worth exploring.

Despite the surging interest in DLT in BE, there is scarcely any discussion on the synergies between DLT and LC. This paper therefore aims at proposing a framework of interactions between DLT (and specifically, blockchain) and LC, and outlining its synergistic elements as the initial outcome of a broader research effort aiming at mapping and expanding on those interactions. Similar conceptualizations in different technology domains have proven beneficial in the past in terms of setting the research agenda (e.g., see Sacks et al. (2010) for BIM, or Rosin et al. (2020) for Industry 4.0 technologies).

LITERATURE REVIEW

Blockchain-related research started being contextualized within the BE context in 2015 (Cardeira 2015). Ever since, there has been a surging research interest focusing on the role of blockchain applications in the BE. However, up until 2018, such studies were mostly speculative and mainly featured high-level conceptualizations (Xu et al. 2022). It is primarily since 2019 that relevant studies have become more concrete, featuring more detailed concepts, developed frameworks, prototypes (Kifokeris & Koch 2020; Tezel et al. 2021; Xu et al. 2022), and some rare use cases (Kifokeris & Koch 2021).

Based on that evolution, the literature review was limited to the period between 2019 and 2022, being focused almost exclusively on journal articles. Given those criteria and considering the categorizations offered by key publications in the field, the main foci of blockchain applications within the BE are on contract management, information management, project lifecycle management, stakeholder management, intelligent systems and integrating blockchain with other technologies (Xu et al. 2022), procurement and supply chain management (Kifokeris & Koch 2020; Scott et al. 2021; Tezel et al. 2021; Xu et al. 2022, Yoon & Pishdad-Bozorgi 2022), smart cities (Scott et al. 2021; Samuel et al. 2022), sustainability (Shojaei et al. 2019), and decentralized organizations (Scott et al. 2021, Tezel et al. 2022). Moreover, the industry report produced by Arup (Nguyen et al. 2019) divided the construction sector into five markets (cities, energy, property, transport, and water), and then presented the potential of blockchain in five subcategories in each market – e.g., smart cities integrated with the IoT (cities), energy microgrids (energy), sale and asset transactions (property), material passports (transport), and utility contracts and billing (water). In the same report, a technology readiness level for the development of blockchain applications corresponding to those subcategories was stated: almost all applications were at the level of concept or early prototype development, and commercialization were generally not thought to be achieved before 2025.

The common denominator of those studies is that the core properties of blockchain can add value to relevant business models, stakeholders' roles, organizations, and projects. These properties are: peer-to-peer transactions, process streamlining, and integration of the economic, material, and information flows through automation, smart contracts, record immutability, security through decentralization, consensus protocols, and reduction of the intermediaries' role (customized per case of implementation). Moreover, across the studies, the blockchain-related attributes are clustered around five epicenters: features (e.g., smart contracts), algorithms (e.g., proof-of-authority), permission levels (e.g., consortium), application fields (e.g., supply chain management), and technology integration (e.g., with BIM) – see Fig. 3. While concerns about the technology have been raised (e.g., its interoperability with other digital and cloud technologies, the available margins for a return on investment, long-term technology implications and needs, and a lack of legal and business frameworks) (Li et al., 2019), the potential of blockchain renders the predictions for commercialized systems for the BE feasible by 2025, with new implementation pilots reported at an increasing pace by practitioners and researchers.

Notably, some studies (e.g., Li et al., 2019; Kifokeris & Koch 2020; Tezel et al., 2022) have indicated the importance of properly contextualizing blockchain for addressing key contemporary issues faced by the BE (e.g., sustainability, affordable housing, trust, transparency), as well as potentially integrating the technology with other frameworks and domains in order to meet long-standing industry needs. In this study, the context and potential for integration is set on the interactions with LC, which can act as a project management backbone in improving construction productivity, quality, and delivery of value to clients and end-users in the BE (Tzortzopoulos et al. 2020). However, studies on integrating blockchain and LC are scarce and fragmented. In that vein, Alonso et al. (2019) proposed a digital twin platform where smart contracts (automation of contract execution) could be used for reducing production time based on lean management concepts and principles. Dakhli et al. (2019) postulated that LC tenets can aid in precisely defining construction production tasks needed for the correct development of smart contracts. Di Giuda et al. (2020), and McNamara and Sepasgozar (2021) explored the use of blockchain for an LC-induced reduction of process fragmentation while executing contracts. Li et al. (2021a,b), designed a framework for a blockchain- and IoT-based smart product-service system tailored for prefabricated construction and off-site manufacturing. Sbiti et al. (2021) conceptualized a blockchain-streamlined information transaction within a framework integrating BIM and LPS. Finally, Bolpagni et al. (2022) mentioned that blockchain properties can be integrated with LC principles to aid nonlinear project management and integrated project delivery. To outline those connections, LC is conceptualized here over four dimensions (see Fig. 2 later): (i) principles, (ii) managerial practices, (iii) procurement practices, and (iv) tools and techniques.

RESEARCH METHOD

The literature on LC and blockchain in the BE was reviewed to synthesize a novel, conceptual LC-blockchain interaction framework (Webster & Watson 2002). The main concepts were "lean construction", "digital ledger technology", and "blockchain". Units of analysis emerged along the literature review, including, indicatively, "project lifecycle" and "construction supply chains". Filters and Boolean operators were applied to seek the search terms throughout each publication.

To develop the framework, the insights gained from the literature review were utilized according to the abductive reasoning of qualitative research, in which conceptualizations are developed iteratively between theory and data (in the current study, data as research content) (Bell et al. 2019). Through abduction, critical reflections and insights were gradually developed in a cyclic way (Bell et al. 2019). In the same vein, the authors evaluated the conceptual framework elements based on the expected benefits and return impact of an interaction point that can inform LC-blockchain applications in the future.

CONCEPTUALIZATION: INTERACTION FRAMEWORK

The framework of interactions between LC and blockchain (Fig. 1) combines LC elements (Fig. 2), and potential attributes of blockchain implementation in construction (Fig. 3), into a schema of interaction elements (Fig. 1 and Table 1). Fig. 1 shows the two-way (from LC to blockchain and vice versa) synergy framework dimensions.

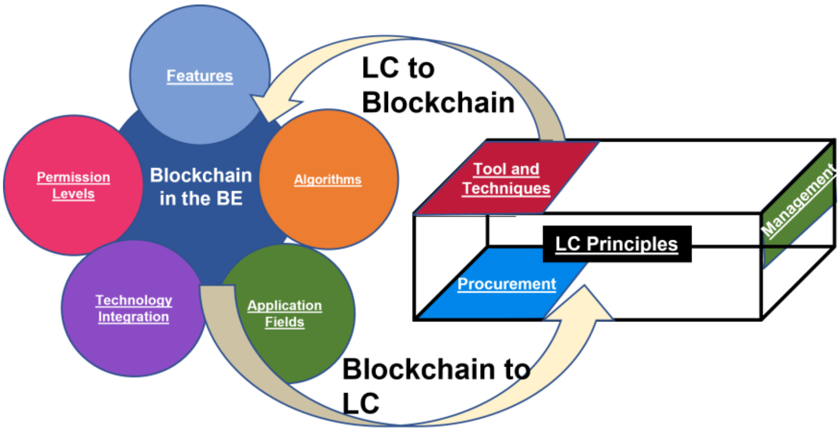

Figure 1: LC and blockchain synergy analysis framework

The cubic schema in Fig. 2 is expanded on and inspired by Thomsen et al. (2009). There are four types of elements, broadly covering the LC domain (Tzortzopoulos et al. 2020), having the LC principles in the middle surrounded by the supporting tools and techniques, managerial and procurement practices:

- LC principles, i.e., the core tenets and fundamental properties of LC. Those include a focus on customer value and the technology adding such value, reduction of waste, variability, batch size, cycle-time, and inventory, a push/pull-based control, increased transparency and flexibility, continuous improvement, standardized work, and others (Sacks et al. 2010).
- LC implications for construction management, incl. a modular and prefabricated systems strategy, supply chain management practices, engagement and investment in LC, Gemba walks, and Hoshin management (Dombrowski & Mielke, 2013).
- LC implications for procurement, incl. integrated project delivery, long-term relations, relational contracts, team- and trust-building and others (Ghassemi & Becerik-Gerber, 2011).
- LC tools and techniques, incl. LPS, visual management, 5S, TQM, BIM, Just-in-Time production, location- and Takt-based planning, PCDA and A3, value stream mapping, choosing by advantages, set-based design, and others (Tezel et al. 2018).

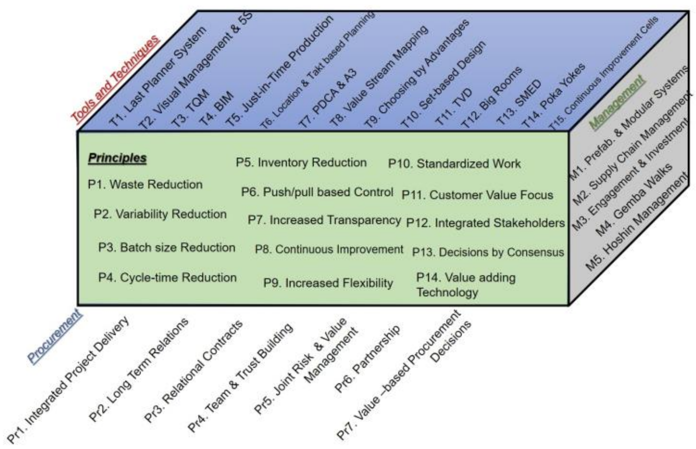

Figure 2: Cubic conceptualization of LC over Principles, Tools and Techniques, Management, and Procurement

Accordingly, the mapping in Fig. 3 is based on the content and insights offered by the reviewed blockchain-related studies. The potential attributes of blockchain implementation in construction are clustered around the following epicenters:

- Features, i.e., the core attributes of the technology. Those include digital distributed ledgers, crypto assets (incl. cryptocurrencies), throughput (processing rate), data storage and sequencing, interoperability and application programming interfaces (APIs), non-fungible tokens (NFTs), smart contracts and others.
- The algorithmic structure of the consensus protocols. Those include the proof-of-work, proof-of-stake, delegated proof of stake, proof-of-authority, proof-of-importance, ripple protocol consensus, and stellar consensus protocol algorithms.
- The permission levels indicating the blockchain's privacy settings. Sorted from the most open to the most demarcated systems, those include public, consortium, hybrid, and private blockchains.
- The construction sector fields where blockchain can be applied, including the management of contracts, information, design, production, project lifecycle, stakeholders, procurement and supply chains, energy, and water and others.
- Technologies that can be potentially integrated with blockchain such as BIM, IoT, intelligent systems, digital twin, digital building logbooks (DBL) and others.

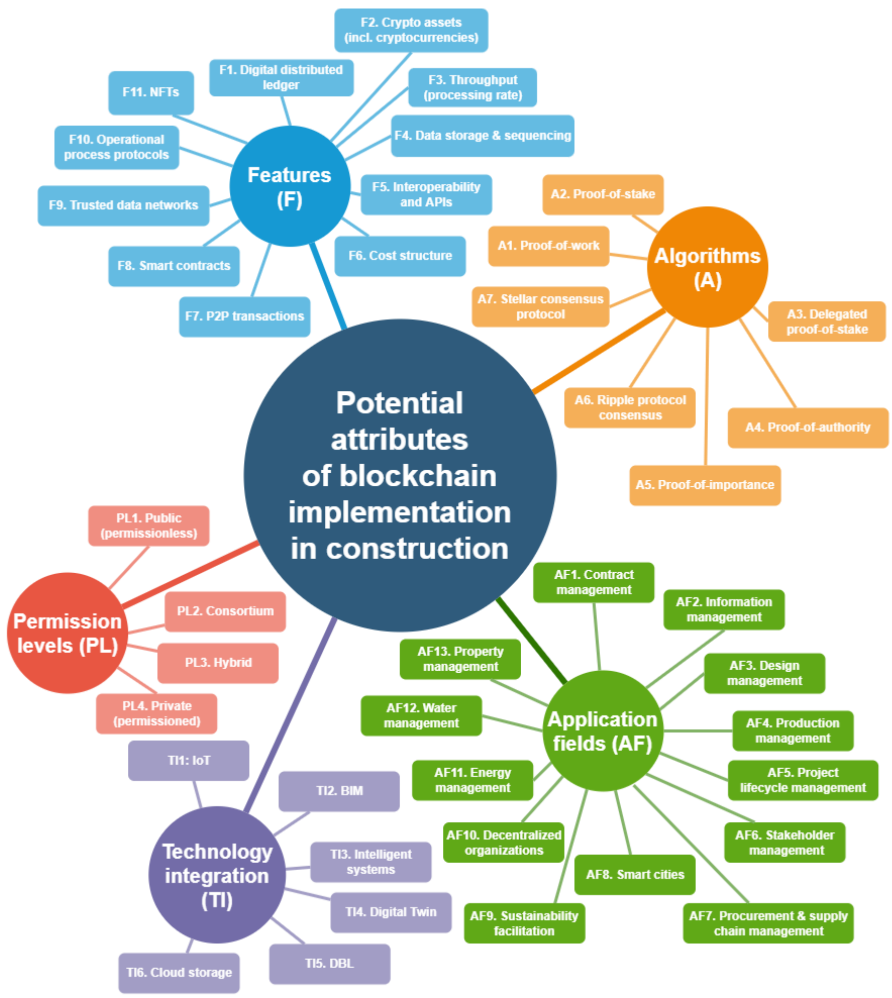

Figure 3: Potential attributes of blockchain implementation in construction

Table 1 explains the interaction between blockchain, and LC shown in Fig. 1, based on the alphanumeric coding used in Figs. 2 and 3. There are two main sections in the table; blockchain's potential contributions to LC, and LC's potential impact on blockchain. Some elements map against specific components (e.g., AF1) on Figs. 2 and 3, and some more general attributes (e.g., AF) covering all the corresponding subcomponents. Color coding was used to display the envisioned impact potential with explanations.

Table 1. Interaction between LC and blockchain

Blockchain to Lean Construction			
No	***Explanation***	***Blockchain element***	***LC element***
1	Multi-attribute and multi-stakeholder contractual agreements supporting LC, such as IPD, relational contracts, and partnerships, can be facilitated through a trusted and decentralized blockchain network.	F1; F5; F7; F8; F9; A4; A7; PL2; PL3; PL4; AF1; AF6; AF7; AF10	Pr1; Pr3; Pr5; Pr6; P7; P12; P13
2	Blockchain can streamline platform processes in industrialized and modular construction, which feature a mode of production supporting LC. Prefab. material logistics, provenance, certification, manufacturing and sourcing related data could be recorded on blockchain	F4; F10; A2; PL4; AF2; AF3; AF4; AF7; TI3; TI6	M1
3	A blockchain-powered network of relevant stakeholders can be implemented across the supply chain, helping in its streamlining and waste reduction. Supplier certification, performance, guarantees, payment, approvals, and contract data could be recorded	F1; F4; F5; F7; F8; F9; F11; A2; A4; PL3; PL4; AF7; TI1; TI6	M2
4	Key hoshin targets and performance metrics for departments and teams could be recorded on blockchain.	F9; A3; PL4; AF2; AF5; AF10; TI3; TI5; TI6	M5
5	Key Last Planner data (e.g., PPC, constraint logs, phase, lookahead and weekly plan) for critical projects with multiple parties could be recorded on blockchain.	F1; F4; F5; F9; A4; A5; PL3; PL4; AF2; AF3; AF4; AF5; AF6; TI6	T1
6	Quality logs, documentation, certificates, and performance data for critical projects with multiple parties could be recorded on blockchain.	F4; F8; F9; A4; PL4; AF2; AF6; AF13; TI5	T3
7	BIM is an important enabler for LC. Some BIM management data (e.g., clash records, approval history, handover data, ownership, IoT sensor data and IFC code) could be recorded on blockchain.	F4; F5; A4; A6; AF2; AF3; AF4; TI1; TI2; TI4; TI5	T4
8	Data for logistic scheduled dates, responsibilities and material/component manufacturers could be recorded on blockchain for key materials/components.	F4; F5; F9; F10; A4; A5; PL3; PL4; AF4; AF5; AF7; TI1; TI3	T5
9	Continuous improvement data, such as responsibilities and targets for important efforts, could be immutably recorded on a blockchain.	F4; F5; F9; A5; PL4; AF2; AF5; TI3	T7; T15; P8
10	Critical CbA options and decisions could be recorded on a blockchain.	F4; F5; F9; A5; PL4; AF2; TI3	T9
11	Set-based-design development progress and decision-making points could be recorded on a blockchain.	F4; F5; F9; A5; PL4; AF2; AF3; TI3	T10
12	Adopting smart contracts on blockchain will partially automate contract execution, reducing mistakes, waste, and cycle times in those activities.	F8; A4; PL4; AF1; AF2; AF6; TI6	P1; P2; P4; T14
Lean Construction to Blockchain			
No	***Explanation***	***LC element***	***Blockchain element***
1	Core LC principles and procurement-related tenets can inform the development of smart contracts, for an optimized value delivery to the contracted stakeholders.	P7; P9; P11; P12; P13; P14; Pr3; Pr4; Pr5; Pr6; Pr7; T5	F8
2	Core LC principles and procurement-related tenets can set a benchmark for data trust requirements when designing the blockchain framework.	P7; P13; M3; Pr2; Pr4	F9
3	Core LC principles and procurement-related tenets can inform the customization of the consensus algorithms, which will most probably support (quasi-) permissioned architectures.	P13; M3; Pr6; Pr7	A4; A5; PL3; PL4
4	Core LC principles and procurement-related tenets can inform a blockchain-powered contract management (e.g., in the consensus privileges held by the stakeholders in the network).	P12; Pr1; Pr2; Pr3; Pr4; Pr5; Pr6; Pr7	AF1
5	LC-inspired tools and techniques for design optimization can inform a blockchain-powered design management (e.g., on the choice of the design data to be stored in the blockchain).	T2; T4; T10; T11; T12	AF3
6	LC-inspired tools and techniques for production optimization can inform a blockchain-powered production management (e.g., on the choice of the production data to be stored in the blockchain).	T1; T5; T6; T8; T11; T15; P1; P2; P3; P4; P5; P6; P7; P8; P9; P10; P11; P12; P13; P14	AF4
7	Core LC principles and procurement-related tenets can inform a blockchain-powered stakeholder management (e.g., on the choice of the permission levels and implemented data security protocols in the blockchain architecture).	P11; P12; P13; M5; Pr2; Pr4; Pr6; Pr7	AF6
8	Core LC principles, procurement-related tenets, and procurement and supply chain-related tools and techniques, can inform a blockchain-powered procurement and supply chain management (e.g., when writing smart contract clauses).	T5; T9; P3; P4; P5; P6; P11; M2; Pr1; Pr2; Pr3; Pr4; Pr5; Pr6; Pr7	AF7
9	VSM could facilitate an effective blockchain technology and application integration with existing processes.	T8	TI; AF
10	CbA could be adopted to select blockchain technology integration, application, and permission levels for a project	T9	TI; AF; PL

Synergy Impact	***Higher***	***Medium***	***Lower***

DISCUSSION

The literature on LC is mature and diverse, and the academic output is also supported by information and accounts of best practices that are featured in, e.g., the Lean Construction Institute (LCI) websites or practitioner events around the world. As such, the content of the referred studies was aligned with the dimensions of the cubic LC framework (Fig. 2) in the most concise manner possible. By contrast, the literature on blockchain for the BE is nascent (though rapidly expanding, especially after 2019), and several related perspectives and aspects have not been fully investigated yet – let alone in connection to LC. Thus, while the blockchain mapping framework attempts to crosscut through the relevant studies by showing the connection between the depicted elements, it is evident that most attributes revolve around technological aspects that may only influence the BE tangentially – which indicates that the direction of blockchain research for the BE, which is presently technology-focused, should take a more pronounced sociotechnical, and even sociomaterial, turn.

When it comes to the interaction framework, it can be observed that its two mirrored dimensions (from blockchain to LC, and from LC to blockchain) are quite heterogeneous in terms of the quantity, content, and interconnections of the synergistic elements.

Considering quantity, there are quite a few recurring elements in both dimensions of the framework. Core LC principles and procurement tenets, blockchain features of data storage and retrieval, blockchain algorithms and permission levels pointing to more private (but still partially decentralized) structures with an established level of control, and a technology integration with more commercialized (e.g., BIM, IoT), rather than nascent (e.g., DBL), technologies are found in most instances of the interaction framework. This shows that the synergy between LC and blockchain can have specific elements in its core. As such, non-recurring elements that appear only on specific instances show a particularization of the two-way LC-blockchain interaction. Nonetheless, it is evident that more blockchain elements are generally matched to the respective LC elements in the “Blockchain to LC” dimension, rather than LC elements matched to blockchain elements in the inverse case. This may show a certain contextual “flexibility” of the blockchain elements, as well as their “materiality” as technology components, in their potential to facilitate LC. In comparison, the LC elements have a higher specificity.

Moving on from quantity, the analysis of the content of the synergies shows that blockchain can inform and facilitate LC on a largely technical basis – i.e., streamlining, digitizing, and decentralizing LC-supported tools, techniques, tasks, and processes in procurement, contract, and supply chain management in particular. As such, the theoretical and methodological contribution of blockchain to LC seems to be minimal, with the challenge placed mostly on properly fitting LC elements into specific blockchain architectures. On the other hand, LC can inform blockchain with the provision of core principles and tenets (mostly related to procurement), and in aspects such as design, customization, and appropriation of the blockchain attributes. This insight is aligned with the understanding of blockchain as a general-purpose technology (Kifokeris & Koch 2020) and its characterization as a contextually “empty cup” that needs to be filled – also in connection with construction. It is shown that some LC tools, such as CbA and VSM, can be practically used for, respectively, decision making and the integration of blockchain elements in existing processes.

Regarding the interconnections of the synergistic elements, it can be observed that some are bilateral (e.g., core LC principles, permissioned blockchain algorithms structures, and blockchain features mainly connected to data provenance, storage, and retrieval), while others are connected one-way. This shows that not all points of interaction between LC and blockchain are fully unambiguous and is probably connected to the aforementioned content analysis of the synergy – the nature of the elements' interaction is necessarily influenced by the content of their synergy.

For a more tangible LC and blockchain interaction discussion, a more dedicated contextual focus should be sought. Considering the global challenges that point to more resource-economic perspectives, such a contextual focus could be placed on the facilitation of circular construction – i.e., the contextualization of the circular economy concept towards sustainable construction (Ogunmakinde et al. 2022). This contextualization must address the key contemporary issues of the sector, while also accounting for meeting long-standing industry needs. As such, the circularity context can be provided by the UN sustainable development goals and the relevant problematization on how construction can become more circular (Ogunmakinde et al. 2022). As such, while the potential for interaction between blockchain and LC can be conceived to act as a fundamental factor in improving construction productivity, quality, and delivery of value to clients and end-users of the BE (Tzortzopoulos et al. 2020), this can also be taken up a notch by considering sustainability and circularity through a resource-economic lens.

The discrepancy between the maturity of LC research and implementation, and the nascency of blockchain perspectives and application for the BE, cannot be overstated. For a more streamlined synergy with LC, concerns, issues, hindrances, and barriers faced by blockchain implementation within the BE should be tackled – including its interoperability with other digital and cloud technologies, the available margins for a return on investment, and a lack of legal and business frameworks. In line with this, it is advised that the suitability of the opportunities identified in this paper should be justified by using a DLT decision-making framework – for example the framework developed by the World Economic Forum (WEF) (Mulligan et al., 2018) to avoid unnecessary implementations.

CONCLUSIONS

In simple terms, blockchain is a decentralized database and a form of DLT existing across multiple locations and participants, reducing the need for a central authority or intermediary to process, validate or authenticate transactions. The interest in blockchain in the BE has been soaring with many application opportunities identified recently. However, despite such an interest, to the authors' knowledge, there is no specific discussion of its potential interaction with LC. The objective of this paper was therefore to present and outline an initial effort for creating a detailed conceptual interaction framework between blockchain and LC.

Alongside the automation-related process benefits where necessary non-value activities such as contract control and execution, payment arrangements, validation of transactions and data records by external parties, blockchain holds the potential to support the required trust and transparency in LC applications in multiparty arrangements (e.g., IPD), which in the current narrative are more relational through contractual and social dynamics, with technology-induced trust and transparency. This does not however mean that it should replace the social and relational aspects of LC arrangements. LC on the other hand will help the technology to become more relevant for the needs of project management in the BE by shaping its features.

More specifically, the interaction framework shows that its two mirrored dimensions are quite heterogeneous in terms of the quantity, content, and interconnections of the synergistic elements. With the materiality of being a disruptive technology, it is evident that more blockchain elements are matched to the respective LC elements as facilitators. On the other hand, with respect to the content, LC can shape the blockchain elements by its principles, management and procurement dimensions and tools. Moreover, the interconnections of blockchain and LC in the framework of interaction show that not all synergy points are fully unambiguous with some being two-way and some one-way. To strengthen and operationalize the synergy between the two concepts, it is deemed useful to frame this synergy within a key contemporary challenge facing the BE. Sustainability, with a narrow definition around environmental sustainability or a broader definition containing social and economic elements, seems to be a suitable candidate for future efforts in that regard. Nevertheless, it is deemed necessary to further define and explore the two-way synergy between DLTs/blockchain and LC for the sake of Lean Construction 4.0, in which DLTs can be an important data recording layer.

This study's limitations are connected to its highly targeted rather than extended review of the literature, and the nature of the framework's conceptualization, which at this point is based only on the authors' understanding and synthesis. As such, recommendations for future work can include conducting a more detailed literature review, involving expert practitioners in not only expanding and updating the interaction framework empirically – but also in validating the framework itself through surveys and case studies. Moreover, we recommend commencing the development of blockchain architectures informed by LC, as well as LC implementation cases that include the utilization of blockchain. Establishing priorities among the multiple interactions on Table 1 presents another research opportunity. Exploring the LC-blockchain interactions from a TFV (Transformation-Flow-Value) perspective will be also useful.

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DEFINING MORE SUSTAINABLE AND INNOVATIVE SOLUTIONS THROUGH CHOOSING BY ADVANTAGES

Randi Christensen[1]

ABSTRACT

The nature, characteristics and traditions of the Architect, Engineer and Construction (AEC) Industry can be a challenge for enabling innovations and development. As projects are limited in time and scope and often under cost pressure, it can be difficult to prioritize time to innovate. However, as we recognize the negative impact our industry has on e.g., climate changes, loss of biodiversity and social inequalities, the industry needs to change and develop at a higher pace. If we want to be part of the solution and not the problem, we need to ask some very important questions on e.g., the methods we work by, the solutions we design, and the materials we use. Lean methods like Choosing by Advantages (CBA) have proven to enable cross disciplinary and collaborative decision making. But CBA could also set the framework for targeted innovation and development within a project setting. This paper presents the idea of how CBA could support targeted innovation within project constraints. The method was tested on a case, where the client was seeking improvements within specific areas compared to a 'standard' solution.

KEYWORDS

Sustainability, Choosing by Advantages (CBA), Learning, Action Research, Innovation

INTRODUCTION

Many look to the AEC industry for changes these years. Our industry has an enormous impact on our society, and while the industry will deliver many solutions for us to deal with climate change and support an increased standard of living for billions, we also slowly realize the significant negative impact the industry has on the planet and the climate.

A NEED FOR CHANGE

The build environment has a significant role to play in reaching the national and regional goals set around the world to reduce carbon emissions. 11% of the global carbon emissions stems from materials manufacturing, transportation, construction and end of life handling of materials in the construction industry (World Green Building Council, 2021). At the same time, the industry right now holds some golden opportunities. To recover from the COVID pandemic governments across the globe seek to stimulate the economy through investments in the construction industry. The EU has launched investment opportunities in Deep Renovation in Europe (United Nations Environment

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Programme, 2020), and the Biden Administration in the US have launched a $1.2 trillion Infrastructure Framework as part of the Build Back Better (The White House, Briefing Room, 2021). These investments can intensify the green transition of the AEC industry, if the industry actively seeks to make real changes and embrace the green transition.

Engineers are perceived to hold the tools and knowledge to support this green transition of the industry (Danish Association of Consulting Engineers FRI, 2018). But the engineering companies need to take this responsibility, integrate core skills and disciplines, set up the right framework for collaboration and innovation, and challenge clients and societies to become more sustainable (The World Federation of Engineering Organizations (WFEO), 2002).

With this in mind, we need to develop new solutions, materials, and technologies to support the growing population, help raise the standard of living, while at the same time reducing the negative impacts like the carbon emissions in relation to construction activities. Best Practice develops rapidly, hence we need to adapt quickly and integrate new knowledge and technologies into our designs and by this supporting a culture for innovation in the industry.

MORE INNOVATIVE METHODS ARE NEEDED

Freeman defines innovation as the use of nontrivial change and improvement in a process, product or system that is novel to the institution developing the change (Freeman & Soete, 2017). Innovation therefore includes both incremental and more radical changes and can be ideas and technologies known elsewhere but adapted to a new context. But innovation is more than just a change, the change also needs to provide value (Tidd & Bessant, 2014). Innovation is hence a term for everything from incremental changes to radical changes, both on a component and systematic level.

The AEC industry has for long been perceived as lagging other industries when it comes to the rate of innovation (Renz & Zafra Solas, 2016). Some of this is due to the characteristics of the industry like: temporary organisations (Bresnen & Marshall, 2000), one-of-a-kind production (Koskela & Vrijhoef, 2001), a conservative mindset (Renz & Zafra Solas, 2016), separation of responsibility and division of powers (Scarbrough et al., 2004; Winch, 1998). This also means that innovation models invented elsewhere might not apply to the AEC industry (Winch, 1998). Where some research focuses on how to bring innovation into best practice (Koch-Ørvad, 2019), this paper will focus on innovation culture and processes within a project setting.

If we want to support innovation in the AEC industry, we need to consider the characteristics of the industry as well as remember that we can't rely on normal management processes when it comes to managing an innovation process (C. M. Christensen, 1997). If innovation is tied up in a project setting with a paying client, there will be a constant tension between delivery towards the expected outcome (incl. time, resources and risks), versus the free, risky and innovative thinking (C. M. Christensen, 1997). While this tension between innovative thinking and time and resource constraints might not be ideal for blue-sky thinking of how to make radical innovations to e.g., reduce carbon footprint of a project, it is the reality for most projects in the AEC industry. Therefore, this paper will focus on how to best utilise innovative thinking within a design team. The focus will be on the processes behind enabling innovation within a project setting through a project case. Therefore, the process and not the specific product is in focus.

METHOD

The idea of using Choosing by Advantages (CBA) as a driver for structured innovation came from the authors' combined experiences in training CBA (Arroyo et al., 2019) and using CBA as an integrated decision and value engineering method, where the project team systematically used CBA to choose from design alternatives in preliminary design as described in (Schöttle et al., 2018a). The structured process and cross-disciplinary collaboration led to optimised solutions and ideas for improvements as a 'bi-product' of the decision process on previous projects. This sparked the interest to investigate how CBA could support innovation and development within a project setting.

The study is based on a case, where a client specifically asked for innovative thinking on a desk study, where a known and already completed construction project, should act as baseline and a team of engineers should come up with new ideas for a solution. The author was brought into the team to support the innovation process through application of CBA. Therefore, this study qualified as action research (Dickens & Watkins, 1999), bearing in mind that the key focus was to deliver towards the client's expectations not to conduct research. Being part of the project allowed for situated learning through integration with the team (Sense, 2007). Literature review and discussions within a Community of Practice (Wenger, 2004) focusing on Choosing by Advantages (Collabdecisions.com) have enabled reflections on the topic and elimination of some of the potential bias from being actively part of the case.

As the team wasn't familiar with the CBA process, it was decided to evaluate the process for internal learning. A survey was carried out within the consultant team, asking open questions with a Plus/Delta format: What went well? Ideas for Improvements? Data from the survey (5 out of 9 responses) formed a basis for a semi-structured interview with the senior responsible from the client's side to understand their perspective on the process. The purpose here was also to examine the teams' perception of innovation and how well CBA supported this process. An interview with the project manager from the consultant side was finally carried out to get insights and clarification. Both interviewees and the team members have had the opportunity to read and comment on this paper.

CASE: INPUT TO AN INNOVATION STRATEGY

The case was a project for a public client, managing the development, operation, and maintenance of major urban transportation infrastructure in Europe. The client was in the process of developing a standard internal innovation process to give input to ideas to be tested out in desk studies. See draft sketch of the innovation process below based on (Interview with Russel Saltmarsh, 2022).

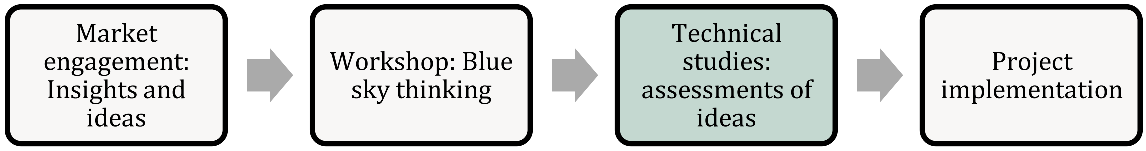

Figure 1: Innovation process of the client

The market engagement gave input to internal workshops. In the workshops blue sky thinking resulted in ideas for further clarification e.g., change in design. These ideas should then be further assessed through technical studies. COWI, an international engineering company with headquarter based in Denmark, was in this case requested to come up with alternatives to design for a typical project for the client and assess these on certain parameters. The client brought some ideas on how to reduce CO2 footprint and wanted an assessment of the ideas and input on how to mitigate potential risk and challenges. This paper focuses on this technical study, here carried out as a desktop study.

The study considered a holistic approach reviewing reduction of CO_2 emissions. It assessed changes in the structural elements, materials, and construction methods, whilst the architectural functionality, look-and-feel and finishes were unchanged. The design of an existing project was selected as baseline, and suggested alternatives should maintain the same boundary conditions e.g., geology, space constraints, O&M requirements, M&E requirements, neighbouring buildings typology, etc.

The engineering team consisted of experienced senior specialists within underground structures, geotechnic, concrete, sustainability, metro station and tunnel design. The team selected 8 reference projects as inspiration and as background for new technologies and ideas within the specific context, and as input selection of factors and criteria and the risk assessment. In summary: the task was to come up with innovative design ideas for a metro station, leading to a 'greener' solution with less CO_2 footprint compared to an existing station. As the project was unusual in nature, having no specific project brief – but with expectations to be innovative, some time was used discussing the baseline, criteria, and what process to use, and it was suggested to use CBA as a framework for this discussion.

CBA FOR IMPROVEMENTS

Choosing by Advantages was developed by Jim Suhr (Suhr, 1999) to support his work in the U.S. Forest Service. Through the work of many Lean practitioners, but for this study in particular referring to Paz Arroyo, the method was made operational for the AEC industry in Europe (Arroyo, 2014), (Arroyo et al., 2019). The method is a multi-criteria decision method to facilitate assessment between two or more alternatives based on the perceived advantages of the alternatives. This is particularly relevant when the different alternatives have advantages within different parameters not directly comparable. For example, a decision could be between two design alternatives of a tunnel design where one would result in a lower carbon footprint, while another design alternative might preserve more biodiversity. For decisions like this, it is important to have a structured and transparent method that enables collaboration and inclusion, while also enabling consistent documentation of the outcome and the related risks and presumptions (Schöttle et al., 2018b).

CBA include a range of different tools all based on the same principles, but from the tabular method follows the below steps (Arroyo, 2014):

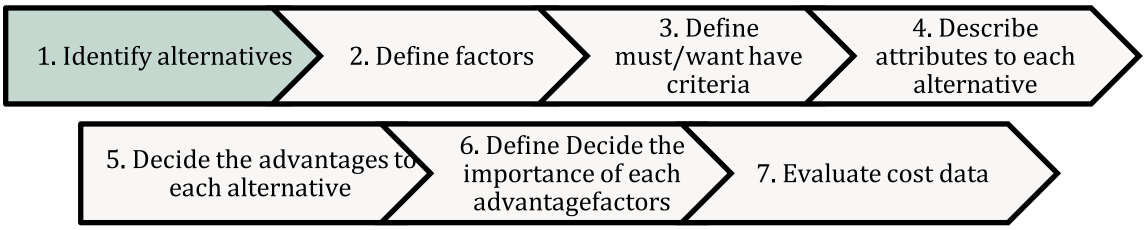

Figure 2: CBA process

1. **Choose the alternatives**. What is the decision? What design alternatives could be chosen?
    a. For example: two different station designs.
2. **Define factors**. What are the expected main factors for the decision?
    a. For example: carbon footprint or low risk.
3. **Define criteria** and select must have/ want to have criteria for each factor. For example:
    a. Want to have criteria: lower CO2E including phase A1-A5 in a Life Cycle Assessment is better
    b. Must have/Want to have criteria: Technology Readiness Level (TRL) needs to be 7 or above, higher is better.
4. **Define attributes** for each alternative. For example:
    a. 12 kg CO2E per functional unit
    b. TRL: 8
5. **Describe the advantages**. For each criterion, there will be one or more least preferred alternative, and one or more alternatives that are better. For example:
    a. 1.2 kg CO2E less per functional unit is better
    b. One level higher on TRL scale is better
6. **Decide on Importance of Advantages (IoA)**. What advantages are perceived more important?
    a. For example: discussion on whether 1.2 kg less CO2E per functional unit is more important than 1 level on the TRL scale to reduce risk?
7. **Cost evaluation**. Weigh the accumulated extra benefits against potential extra capital cost.

As CBA had previously inspired project teams to innovative thinking, it was decided to test the method out on a project case, where the client asked for innovative thinking and a holistic assessment of one or more alternatives. But the project context made it necessary to modify the method.

MODIFIED CBA TO CREATE ALTERNATIVES

This wasn't a 'normal' CBA as there were no defined alternatives. Instead, there were some loosely defined success criteria and a baseline. It was therefore decided to design and follow a process to first create alternatives. Hence, step 1 in a 'normal' CBA process "Identify Alternatives" was extended with the following sub-steps:

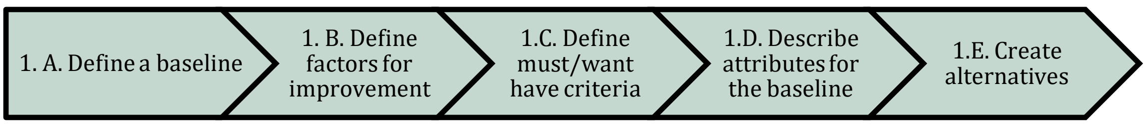

Figure 3: Identifying Alternatives

1.A. **Define a baseline.** A comparable existing project was selected as the basis for the project. A metro station previously designed by the team for the client was selected.

1.B. **Define factors for improvement.** It was discussed with the client within what factors advantages were expected compared to the baseline.

1.C. **Define criteria.** The team defined minimum criteria for the new alternatives and in what areas success should be measured.

1.D. **Define the attributes for the baseline:** By testing out the criteria on the baseline, the criteria were constantly refined by the team.

1.E. **Create alternatives.** Through an iterative process, 6 alternatives were created based on desired attributes with regards to success criteria.

The above steps were iterated over a few weeks during regular progress meetings. The team used a virtual whiteboard with a CBA table to define factors, criteria, and attributes. The alternatives were defined by bringing ideas from reference projects, where these had advantages on some of the success criteria. For example, designs on similar projects have been used in other parts of the world, where less concrete were needed. Some of the ideas were combined in new ways or scale. Based on the constraints and the areas for desired optimisations (success criteria) the team constructed 6 alternatives using a mix of different technologies, to allow for a lower CO_2 footprint. When the alternatives were defined, a 'normal' CBA was facilitated to assess the baseline and the newly defined alternatives including a cost indication. All 6 alternatives were presented to the client in a CBA tabular method, to get the client's assessment on what advantages were more important.

EVALUATION OF THE PROCESS

To learn from the process an evaluation was carried out and through analysing the interviews using heuristic text analysis, some key findings were identified as key takeaways from the team to improve the process:

1. Tension between 'open' project scope and lump sum contract
2. Some team members found the early phase inefficient
3. The team was well organised with reg. to technical competencies
4. Lack in innovation management competencies
5. Collaboration with Client is needed

TENSION BETWEEN AN 'OPEN' PROJECT SCOPE AND LUMP SUM CONTRACT

The team has been used to having a specific problem, or project at hand – defined by the client - where *a* solution needs to be defined within given constraints. This time, the team was asked to challenge the constraints while at the same time drafting solutions within constraints. The word 'innovation' was also frequently used in the beginning, which might have meant something different for the participants. This gave, for some, too many moving parts in the project, while at the same time there was a pressure to deliver on time and budget.

Some of the team members found it frustrating that the scope of the project wasn't clear so they could start defining solutions. They felt they wasted time in the early meetings, which was also a clear concern of the project manager: "*We started with a blank page, with no clear expectations of the outcome…. As a project manager I was concerned about the budget*" (Project manager). This tension between project delivery and creating new solutions was difficult to navigate for both the team, the project manager, and the client.

SOME FOUND THE EARLY PHASE IN-EFFICIENT

Both the project manager and the client felt that both sides weren't clear on how to manage expectations within the context of a project in a continuum of innovation and project delivery. Both parties stated that this was a new way of working and that learning was a part of the process. "*The team were very enthusiastic, often ending in long discussions, disciplines to focus on specific tasks would reduce the hours spent, and still maintain the innovative process*" (Team member)."*We are trying to formalise the process, but it's definitely a learning experience because we haven't gone through anything like this before.*" (Client)

The team was primed to use technical expertise and come up with solutions to known issues, the client was focused on getting challenged on solutions while also getting value for the money spent on the innovation project, and the project manager was focused on delivery within constraints. Communication and hence the understanding of the project scope was challenged by differences in the team and among the partners when it came to syntactic (language), semantic (meaning) and pragmatic (motivation) (Carlile, 2004). Where some were very focused on the product and details, others were focused on the business case and risk mitigation. Therefore, the parties could benefit from a shared evaluation, not only on the project delivery but also on the process and collaboration, to ensure more efficient use of time in the future.

THE TEAM WAS WELL ORGANISED WITH REGARDS TO TECHNICAL COMPETENCIES

This project was of high importance to both the client and the engineering team, and therefore very experienced specialists were allocated to the project. "*The team delivered on the technical aspects of the study, from design to constructability, identifying areas of improvement to the current specs*"(Team member). The team members all had +15 years of experience within the field and could therefore include many significant reference projects from all over the world and bring these experiences into the specific context. They also included knowledge of challenges with existing assets owned by the client and knowledge of the client. As some of this knowledge was deeply context dependent it was unclear what should be included in the study and how possible constraints should be mitigated.

LACK IN INNOVATION MANAGEMENT COMPETENCIES

It was the first time the team was asked to think innovative and deliver a solution where the outcome shouldn't lead directly to delivery of a project. Because of the importance, the consultant selected the most experienced and competent technical experts, and very early the team started to focus on the details without having agreed on the overall framework. This was partly because of the time pressure, but also because the team quickly confined itself to known work processes. "*More training to leaders about innovation processes, not all seemed to know (the) project was about innovation*", (Team member). Also, the client acknowledged the project was a learning experience and that they too need to adapt to a new way of working to allow for innovative thinking. "*We* *didn't even think about innovations to start with, but we know we wanted to somehow bring the UN SDGs*[2] *in*" (Client).

It became clear that while the team was experienced and skilled in some areas, they were beginners and inexperienced when it came to contributing and leading such a process. We learn from childhood that it is important to be competent, and when being put in an uncertain situation people react in different ways (Flores, 2016). This inner conflict between being a beginner and at the same time an expert was uncomfortable for the team.

COLLABORATION WITH CLIENT IS NEEDED

During the process interim meetings were held to inform the client and get feedback on the process. Also, the client was guided to make the final assessment of the Importance of Advantages (step 6), but the client wasn't formally introduced to CBA. The client found certain aspects of the results in the final report interesting, and some ideas were clearly new to the context. It is the authors' perception, that the communication with the client was centred around technical issues and solutions, whereas the process and way of collaboration was less defined and discussed. It was subsequently recognised that closer collaboration would have been beneficial for all. As the expectations for the level of innovative thinking in the project were unclear at the beginning, it was also perceived by the project team that the level of details and assessments wanted by the client changed as everyone became more knowledgeable.

CBA CAN SUPPORT INNOVATIVE THINKING

CBA was introduced as a method to structure the process and allow specialists to contribute with their technical skills while also thinking creatively. With more clear constraints of the solution space, it was expected that creativity could be channelled to areas where the client was looking for improvement. In the beginning where few unclear constraints were put on the creative process, the team ended up forming solutions based on their knowledge and experiences. The constraints from the process provided focus and creative challenge to come up with improvement in very specific areas (Acar et al., 2019).

Also, by addressing the project as a decision, the team could present their technical knowledge in a structured way and then allow for the client to assess what mattered. The client would then get information with consistent data and uncertainties outlined and based on this get a more informed basis for decisions (Mullan, 2018). This was also the perspective from the team. The method helped them focus and align while also setting the area for innovation and improvements compared to the baseline.

However, as this was the first time for many of the team members, the project didn't get the full benefit. Also inviting the client into the process might have been useful. As one team member put it in the survey:

"*A systematic approach to decision making was good, as we normally just go ahead and design what we think is needed and then hope it would fit into a decision, instead of aiming at the start on something that would matter to the client. A clear process and a clear goal (provide basis for evaluating*)", (Team member).

Using CBA for this type of assessment, however, might bias the members of the team to look for advantages but overlook the challenges and how to deal with these. The client had expected a more thorough assessment of the alternatives including a more balanced

[2] Red: United Nations Sustainability Development Goals

assessment of negative and positive impacts by the ideas proposed. The client expected the team to focus more on mitigations to remove some of the perceived constraints. For example, it was expected that instead of dismissing an idea that wasn't aligned with codes and standards, they would have liked to know what a diversion would be demanded.

However, by continuously using CBA as a driver for innovation on more projects, the terminology and process can become more familiar for the participants and the process of reaching a shared view on a decision becomes more efficient (Arroyo et al., 2019). This could compensate for the loose scope in the beginning of the project and set a framework to channel the knowledge and skills for the technical experts into innovative thinking within a project setting.

CONCLUSION

The AEC Industry needs to change, and we need radical innovations to be able to reach national and regional climate targets and ambitions (Koch-Ørvad, 2019). We also need to foster an innovation culture within our industry and our project delivery context. As learning and innovation is context dependent (R. Christensen, 2008), we therefore need to apply methods within our project context to utilise the full capabilities from our specialists to come up with innovative solutions.

In our industry, innovation and implementation goes hand in hand and cannot be separated (Winch, 1998). One challenge is therefore, to support innovative thinking within a project setting with constraints on time, scope, and resources. We need to apply efficient methods that allow our technical specialists to contribute to making sustainable solutions efficiently. Another challenge is that our industry lacks competencies to manage the creative phase of innovation, where communication across different disciplines is key.

In the case we showed, Choosing by Advantages could be used to create new alternatives based on desired areas of improvement. The methods directed the creative energy of the specialists to areas within their profession and therefore allowed them to contribute while still being able to see the bigger picture. The structured way to handle uncertainties in developing alternatives and to assess the alternatives, made the process more effective and the experience can be used also on future projects.

Design and problem solving shouldn't be considered alone from the technical domain, both need to be multidisciplinary and get input from all stakeholders and experts to solve the issues we face. Our industry is one of the most fragmented, and we need to focus on how we support a seamless collaboration across the value chain (World Economic Forum, 2012).

By training our teams in thinking in alternatives and criteria, we train our teams in applying innovative thinking and come up with new and more sustainable solutions within an agreed framework suited for a project delivery context. This study was based on a single study but should be tested on more projects to test the validity of the conclusion, and I therefore encourage more studies of applied CBA where focus is on innovative thinking and added value.

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PROJECT PULL PLANNING BASED ON LOCATION: FROM CONSTRUCTION TO DESIGN

Clarissa Biotto[1], Mike Kagioglou[2], Lauri Koskela[3], Patricia Tzortzopoulos[4] and Sheyla Serra[5]

ABSTRACT

Construction project management is known for being fragmented and disconnected between the stages of design, supply and construction. Lean construction has a variety of well known production planning and control methods that may be used to integrate and improve the information flow between these stages. These methods and techniques include location-based tools and the Last Planner System (LPS). However, the combined use of location-based tools with the LPS to allow an entire project, including the design, supply and construction, to be pull planned, has not been described in the literature.

This paper presents results of one study in which location-based planning tools were deployed to pull the project planning from construction to design. The study is part of a doctoral thesis which used the design science research as a mode to produce new knowledge. The main contribution of the paper is the model to develop a location-based project management including the use of the LPS in construction, supply and design. The model enables project managers to have a holistic view of the project plan, and structure it as a pull flow from construction to design, reducing work-in-progress and batch sizes between stages, and improving the information flow among project stakeholders.

KEYWORDS

Project management, pull planning, location-based schedule, design, construction.

INTRODUCTION

It is known that construction projects face delays and cost overruns all around the world. The traditional management of projects no longer meet construction demands (Formoso et al., 2002; Moura, 2005). This may be explained by the architectural, engineering and construction (AEC) industry fragmentation and how construction projects are managed. As design and construction phases are conceived separately (Alarcón & Mardones, 1998), it is more difficult to integrate information in the construction industry (Alshawi & Ingirige, 2003 as cited in Dave et al. (2008)). As consequence, there are disconnections

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at the interface design-construction, such as different production sequences and priorities for design and construction, which create delays, rework and waiting for the project's participants, namely, designers, suppliers and builders.

A possible solution is proposed by Dave et al. (2015) who mention that "a better interface between production and design schedule should lead to the release of design information with a pull from the master schedule". Some authors have already applied the pull flow to integrate planning between construction and design from the point of view of a construction company (Bolviken et al., 2010); an engineering-to-order (ETO) enterprise (Viana, 2015); an ETO company in a project with overlap between design and construction phases (Sivaraman & Varghese, 2016); and a construction project also with overlap (Holm, 2014). However, none of these research shed light to the holistic construction projects planning and control using location-based tools and pull flow including the stages of design, supply and construction.

The idea of applying a pull planning from construction to design was put in practice through one case study, in which the approach used to plan construction was the location, by means of the line of balance and takt-time planning. The results suggest that location-based planning might be used for project pull planning, however, in order to maintain the information flow from downstream to upstream activities, it is necessary to plan and control production using the Last Planner System collaboratively.

LITERATURE REVIEW

JUST IN TIME (JIT)

One of the two pillars of the Toyota Production System (TPS) is the Just-In-Time (JIT). A production system in which JIT is applied "makes and delivers just what is needed, just when it is needed, and just in the amount needed" (Marchwinski & Shook, 2003). A JIT production system eliminates overproduction, inventories and wastes.

The JIT pillar is based on three operating elements: continuous flow, takt time and pull system, namely (Marchwinski & Shook, 2003):

1. Continuous flow: also known as one-piece flow, it is the production and moving of "one item at a time through a series of processes", at which each process makes just what is requested by the next one as continuously as possible.
2. Takt time: is the rate at which products are made in a process to meet customer demand or "the available production time divided by the customer demand".
3. Pull system: is a production system where the downstream process signals its needs to upstream process, eliminating overproduction.

Tommelein (1998) applied the pull production, i.e. the downstream process (construction site) sends real-time progress status to upstream process, for the pipes installation. It forced a resequencing of manufacturer's production, which reduced buffers, enabled time for project completion, and increased the productivity.

Viana et al. (2013) implemented pull production in an integrated planning and control system in an ETO company which was responsible for designing, prefabricating components and assembling on-site. The authors used the assembly process on-site to pull the prefabrication of components.

However, in order to develop a pull system in construction it is necessary to master plan the whole production system in a wider point of view: plan beyond construction stage activities. It means that project managers should consider the upstream activities such as the construction supply chain and design, and structure the work in a manner that the pull production method may be applied.

PULL PLANNING

The Pull Planning was incorporated to the Last Planner System to structure the work of a project phase collaboratively among stakeholders (Ballard, 2008). It bridges the master and lookahead planning. The construction phase's milestones that were set up at the project's master plan are pushed to the phase planning. Next, the phase's activities are broken down into tasks and handoffs. A network and duration of tasks are defined by the contractors of the phase using sticky notes (among other means) on a wall (or other physical and digital media). Then, a reverse plan of the phase's tasks is devised, pulling the tasks from the phase deadline towards the phase start date (Alarcon et al., 2004). The contractors define the handoffs collaboratively between the crews and project phases, insert buffers, and guarantee the completion of the work on time (Alarcon et al., 2004; Ballard, 2008; Ballard & Howell, 2003).

The pull plan can be scheduled using traditional tools, such as a Gantt chart (Knapp et al., 2006), or Location-Based Schedule (LBS) techniques, such as Line of Balance (LOB) (O'Brien et al., 1985), flowline (Kenley & Seppänen, 2010) and Takt Time Planning (Fiallo C & Howell, 2012).

The authors of this paper suggest the use of a LBS to prepare the whole project's planning (from construction to design) in a reverse manner.

LOCATION-BASED PLANNING

The term location-based schedule was proposed by Kenley (2004) to designate the techniques that use the location or unit as a basis for the production planning and control. The aim of using LBS is to design a production system with continuous workflow and uninterrupted flow for crews throughout the location units (Moura et al., 2014). To make the workflow smoother and reduce the work in progress, the activities should be planned at only one rate, i.e. in parallel lines (Mendez & Heineck, 1998).

Takt Time Planning

The takt-time planning (TTP) in construction is derived from the takt time used in lean manufacturing. In construction, it started to be used in the Phase Scheduling or Pull Planning (Frandson et al., 2013; Linnik et al., 2013).

To develop a production plan using TTP, it is necessary to define zones and takt time, the trades sequence and duration, and balance their workflow (Frandson et al., 2013). All these steps are devised with the participation of trades and general contractor in an iterative fashion, and the decision is made collaboratively by communicating and exploring production systems alternatives.

So far, in the literature, the LBS techniques are used specifically for the construction stage, ignoring the procurement and design stages.

RESEARCH METHOD

For this investigation, the authors used Design Science Research (DSR) to iteratively develop an artefact (designed solution) based on its usefulness to the organizations and contribution to existing knowledge; and to apply and develop the theoretical knowledge throughout the studies (Lukka, 2003). In this paper, the artefact is a model for project pull planning based on location.

DSR aims to fill the gap between the theory and practice through the development of an artefact (Rocha et al., 2012). This middle ground between practice and theory is necessary in order to develop valid and reliable knowledge to support practitioners in organisational/business to devise solutions to problems (van Aken, 2005).

DSRs might be evaluated in different manners: 1) Internally – made by the researcher through reflections on practice and connections with theory; 2) Externally – carried out by the studies' participants and scholar experts; and 3) Field-testing – through the instantiation of the artefact in an organization.

The study is a case that presents a whole project reverse master plan, which embedded the construction, procurement and design stages. The researcher was an observer of the construction company management practice that deployed the takt time planning to pull production from construction to design stage. It is characterized in Table 1.

Table 1: Case study characterization

	Case Study
Type of Project	Residential – block of apartments
Period of the Project	January 2016 to December 2018
Area	31 residential units totalizing 2,535 sqm
Type of Study	Case study
Time Horizon	Cross-section study
Location	Trondheim - Norway
Design Stages	Developed and technical/detailed
Construction Stage	Foundations and Concrete Structure
Evidence Sources	Direct observation, documents, interviews and focus group
Research activities and participants' roles	2 workshops and 8 interviews with Project Manager; Design Manager; Site Manager; Architects; Structural Engineer; Project Manager
Companies involved	Construction Company; Architecture Office; Engineering Office; Client
Evaluation	Internal and external evaluation with study' participants through focus group
Activities	Project Pull Planning using Takt-Time Planning; Design and Construction Planning and Control using Last Planner System

The study was evaluated internal and externally according to the utility of the model. It was composed by five criteria selected from the literature as reference as best project management characteristics of collaboration, integration and flow; the criteria were broken-down into eight measurable sub-criteria, as depicted in Figure 1. To see the interview questions, access the thesis (Biotto, 2019). It is noteworthy that this paper is focused, mostly, on presenting the last phase of the DSR, namely, the model evaluation.

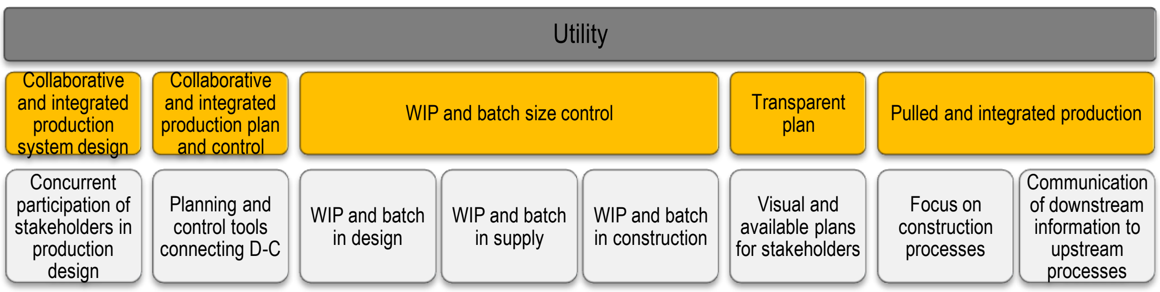

Figure 1: Criteria for the model evaluation.

CASE STUDY

In case study, the project development comprised of three stages: 1) Pre-design; 2) Delivery Stage; and 3) Facility Management. The first stage encompassed a) Idea Phase and b) Concept Phase, whereas the second stage comprised a) Design; b) Detail/Engineering Design; c) Construction; and d) Commissioning. The third stage is Operation and Maintenance. The study observed the project management of the detailed design phase and construction.

The Project Planning and Control System deployed had six levels of planning and control, as depicted in Figure 2:

1. **Level 0 - Project Master Planning**: developed by the Project Manager, Construction Manager, Design Manager and Owner presents the strategical decisions made for the whole product development process, its major phases and deliverables. It is the basis for further planning.
2. **Level 1 - Construction Plan and Purchasing Plan**: represented strategical decisions about construction, procurement and supply, respectively:
    - Construction plan is generated using developed design documentation in MS Project by the Project Manager and Construction Manager. It is the most important plan to pull detailed design plan and supply acquisition;
    - Purchasing Plan is derived from the Construction Plan and contains the majors milestones for supply acquisition.
3. **Level 2 – Detailed Design Plan and Construction Takt Time Plan**:
    - Detailed Design Plan: developed collaboratively by the Owner, Consultants, Design Manager, Project Manager, Construction Manager, Foreman and Designers at the kick-off meeting (see Figure 3). Project Master Plan and Construction Plan milestones are used as reference to pull planning design deliverables. The result is transferred to a MS Excel spreadsheet and used in the lookahead planning;
    - Takt-Time Plan: the construction team studied the workflow, the crew size, buffers and the takt-time for production.
4. **Level 3 - Decision Plan and Design and Construction Lookahead Plans**:
    - Design Lookahead Plan: design project team removed six types of constraints related to 1) client's expectations and requirements; 2) dialogue and share understanding among stakeholders; 3) decisions needed; 4) team capacity and autonomy for decision making; 5) methods and tools; and 6) previous design task according to the required quality;
    - Construction Lookahead Plans: the project had different lookahead planning involving different professionals and different planning horizons; namely, a 8 to 12 weeks plan developed by the Site Manager, Design Manager and Project Manager; a 4 to 8 weeks plan developed by the Operations Manager, and; a 2 to 4 weeks plan developed by the Operations Manager and Foreman. The different planning horizons and meetings are related to the responsibility and power of decision of each sort of professional in removing constraints.

5. **Level 4 – Design and Construction Weekly Plans**:
    - Design weekly plan: tactical and operational levels of planning were developed and controlled in the weekly meetings at the site office. The Design Manager was responsible for drawing up a set of activities to prepare the meetings, and to distribute the information to designers and set the future actions. Figure 4 is the plan used in the meetings that shows the design milestones, detailed design deadlines in accordance to construction batches and sequence, and basic design packages deadlines;
    - Construction weekly plan: the team leaders devise the weekly plan, revising which activities were concluded in the current week, and predicting the next work week according to crew's production capacity.
6. **Level 5** – Daily Plan: occurs every working day on site. The crew's members gathered in the first hour of work to draw over the floor plan what should be executed on the day, considering the previous tasks executed. The researchers did not collect data about daily meetings within the designers' offices.

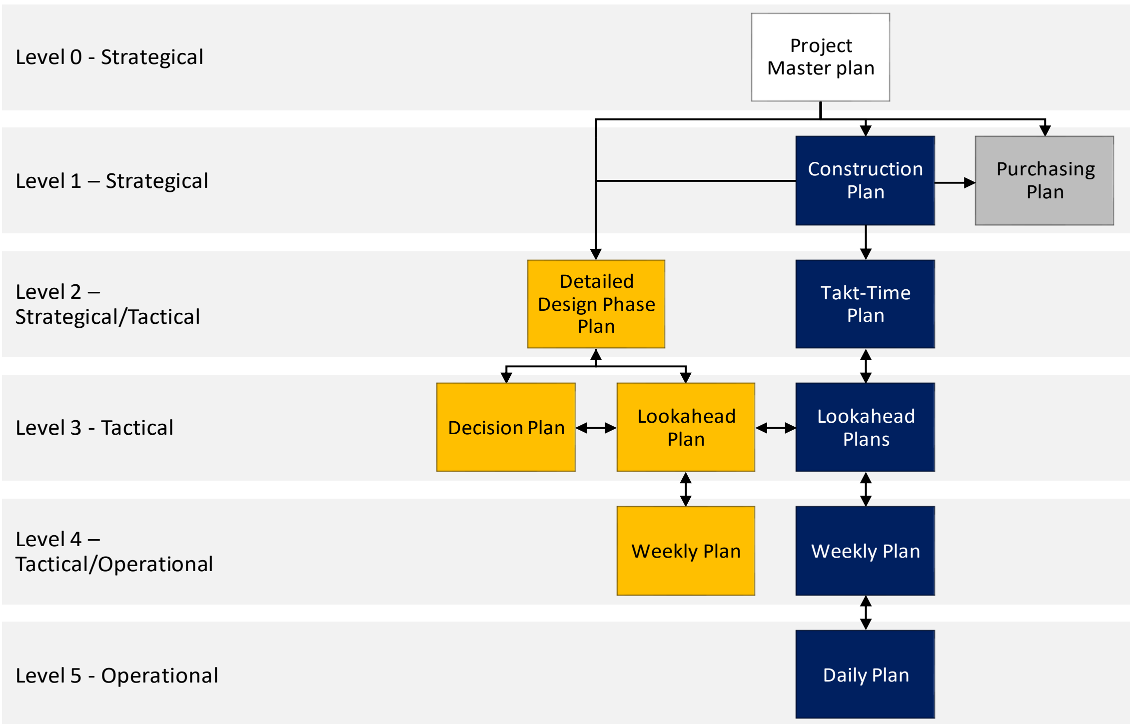

Figure 2: Levels of the project planning and control system deployed.

Figure 3: Strategical Collaborative Planning for Design. Source: Courtesy of Construction Company.

In order to keep the communication flowing smoothly and rapidly, weekly meetings occurred among designers, construction teams, managers and owner. In figure 5, the light grey arrows demonstrate the flow of information from the operational meetings on Mondays until the progression status meetings on Fridays. The blue arrows represented the communication flow from construction, designers to the owner and client of the project. The flow of information had a short update cycle time of only one week. For this reason, the communication of changes, decisions and other information was rapidly transmitted between stakeholders and in a transparent manner.

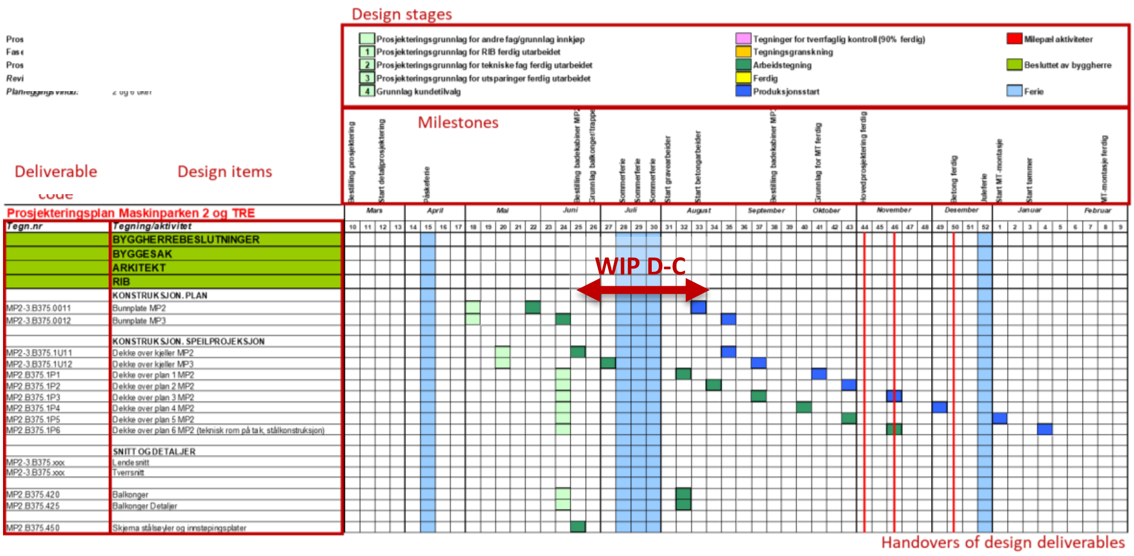

Figure 4: Example of using location-based from construction to pull design. In blue: construction activities from the takt time plan. In dark green: deadline for detailed design delivery. In light green: deadline for design package delivery. Source: Courtesy of Construction Company.

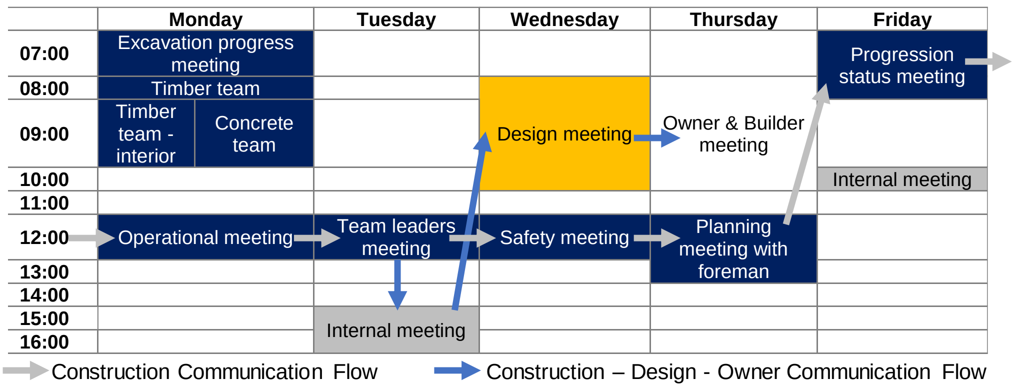

Figure 5: Project meetings structure and the weekly communication flows.

Case Study Evaluation

Case study project planning was characterized by the early participation of stakeholders from design, manufacturers, suppliers and builders in the production system structuring. The project used the takt-time planning as a location-based tool for work structuring the construction, which used the developed design as input information, and prepared the reverse design and supply/purchasing. The internal evaluation of the study is detailed in Table 2, following the criteria specified in the method section of the paper.

Table 2: Case study evaluation

	Case Study
Collaborative and integrated production system design	At the beginning of the detailed design stage, the organizational structure of the design and construction stages is presented to all participants. It defined the planning responsibilities of Design Manager, Designers, Project Manager, Site Manager, Operation Manager, Foreman, crews' leaders and workers.
Collaborative and integrated production plan and control	The Collaborative production planning and control promoted the ownership of plans by its stakeholders, which was boosted by the high transparency of planning.
Work in Progress (WIP) and batch size controls	The WIP between design and construction was small because detailed design batch was the same than construction. WIP was controlled in the design meetings.
Transparent plan	The available plans and weekly meetings stimulated transparency of people's responsibilities, tasks, dependencies, decisions, planning and project goals. In design, it was intrinsically connected with the BIM model's development and construction.
Pulled and integrated production	The developed design was pushed and inputted to the construction master planning. The latter was pulled by the design planning to set delivery milestones. Both design and construction lookahead planning were connected and communicated through the weekly meetings.

It is worth noting that the "WIP and batch size controls", and pull flow were easier to implement in detailed design rather than in earlier design phases. In case study, the construction and detailed design shared the same production batch size, enabling the pulled flow between them. However, when analysing an earlier design stage, its production batch was composed by a set/kit of drawings/models/documents, i.e. a large batch, which was delivered to the next design phase for detailing. Earlier design stages experience constant changes due to clients and designers negotiations and conflicts/clashes solutions, i.e., higher interdependency among stakeholders. As soon as design matures and clashes are solved, the design development focuses on detailing the models; an action that might occur with higher independency among stakeholders. The latter enables the adoption of same size batch between design and construction, thus the pull flow.

MODEL FOR PROJECT PULL PLANNING BASED ON LOCATION

The model presents a project planning and control system composed by construction, supply and design, as shown in Figure 6. The pull production system guarantees the integration of information in the design-construction interface. The model might be implemented by the Project Manager.

The first step to implement the model is to identify the construction demand. In the stream design-supply-construction, the latter is the final internal client. To define construction demand is important to structure the work of designers and suppliers. For that, the construction work structuring should start early in the project development using design documentation and a location-based planning tool. The Construction Manager, or the General Contractor Manager should be responsible for gathering all people and information necessary. As soon as design becomes more mature, it should be pushed to the construction system for decision and planning review.

Consequently, construction location-based plan might be the reference to pull reverse plans for suppliers that will pull a reverse plan for designers. Both Project Manager and Construction Manager might gather the main manufactures and suppliers to participate in the collaborative planning, providing information about duration of installation, fabrication, designing the items. The supply reverse plan sets the milestones based on the same location breakdown structure used in the construction plan. The design deadlines in the suppliers' plan will pull the designers' reverse plan. The Design Manager is the responsible to gather the main design offices' leaders of the project for that.

The idea of using the construction location breakdown structure (batch) for suppliers and designers is to allow the alignment of plans and facilitate the pull flow. Moreover, the LBS might be a facilitator for batch size reduction in construction projects. Suppliers are stimulated to deliver the material/components to construction following the construction batch and sequence in order to avoid waiting, inventory and space interferences on site. However, the manufacturers might find difficult to produce and deliver components defined by construction needs. In this situation, they should resize their batches in agreement with construction managers considering construction site space, logistics and plans.

The same is valid for designers, who should produce the detailed design following the suppliers or construction production batch and sequence. This idea enables a new way of assembling work, and support the continuous flow by pulling only the necessary information, when necessary, which are concepts of the just-in-time (JIT) production system. Thus, the design packages will be composed by a combination of drawings/models of a certain location necessary to be released to the next supplier. The supplier will use this pack of drawings to engineering design (if applicable), and plan the fabrication of components necessary to be delivered to a particular construction location.

The progressive design fixity concept is also behind the model. At the first design phases (conceptual and developed), the design production flow is pushed. At the detailed phase, there occurs the decoupling point, which is the interface between push and pull (PP) flows (Kiiras & Kruus, 2005). It also points to the interface between transdisciplinary and interdisciplinary design production. The interface push and pull was explained by Hopp and Spearman (2011).

However, as construction projects suffers with uncertainty and variability, the whole production planning and control system should be connected. It is suggested that the Last Planner System should be used by builders, suppliers and designers. Through the lookahead planning, the project participants should focus on removing the constraints, updating the reverse plans and, when necessary, replan. The use of LPS is critical in order to confirm with designers and suppliers the right priority of production based on construction status. This idea of confirmation points was suggested by Viana (2015) in her work regarding integrating the planning and control system in ETO companies. However, the integration of the LPS adopted by designers and builders was suggested by Bolviken et al. (2010).

The model enables the articulation of the project production planning and control to integrate decisions and information between participants at the interface design and construction (D-C). The plans are connected vertically and horizontally. In each phase of design and construction, the hierarchy of plans (strategical, tactical and operational) provides information from the upstream plan to the downstream and feedback in the opposite direction. The horizontal integration between the phases D-C occurs at the strategical levels, properly from the construction master plan reversely towards the design master plan. The updates for confirmation of production occurs at the tactical levels, which receive updates from the operational plans in their respective stages.

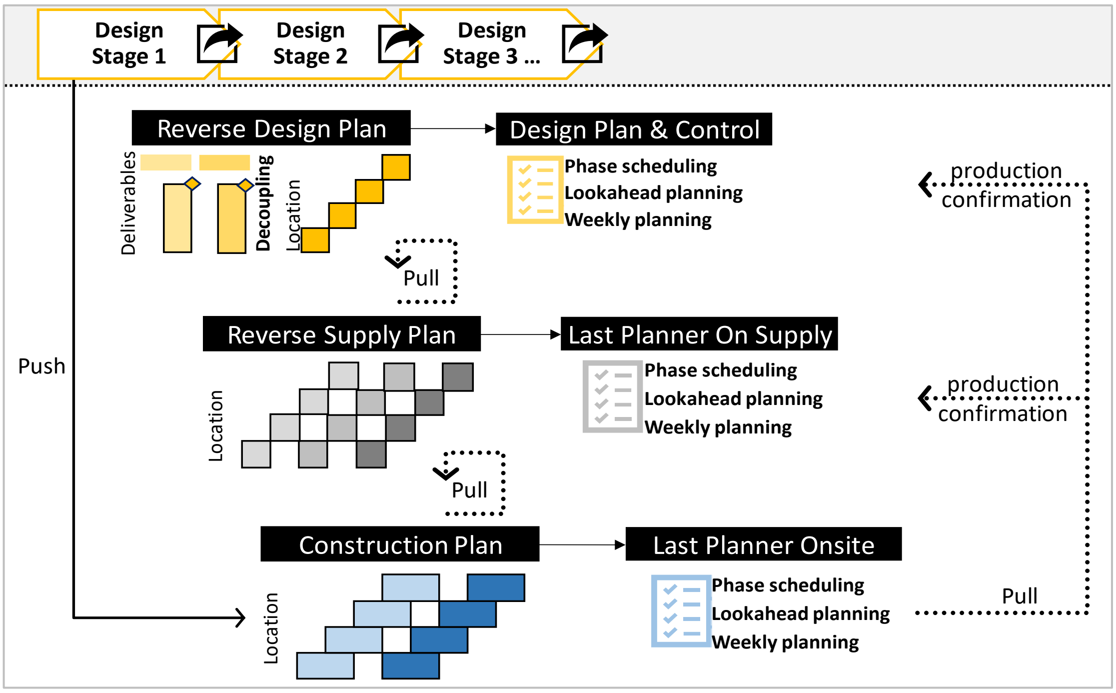

Figure 6: Model to implement project pull planning based on location.

Figure 7 demonstrates the vertical and horizontal connections between hierarchical plans in the D-C interface. This contribution suggests an integrated use of the LPS (Ballard, 2000) to plan and control the stages of design and construction. It also expands the collaborative planning model of Bolviken et al. (2010) to include the suppliers' planning activities.

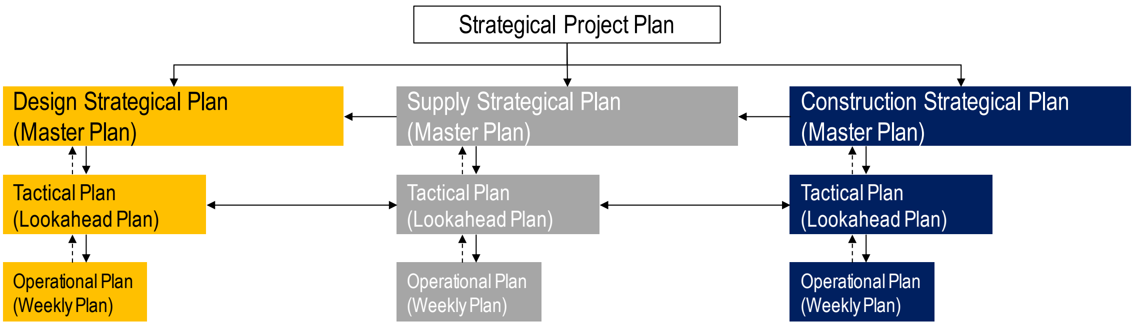

Figure 7: Vertical and horizontal connections in construction, supply and design plans.

CONCLUSIONS

The paper presented a case study in which construction location-based plan were used to pull plan the whole project production, including supply and design. Results were internally evaluated and a model proposed for Project Managers apply pull production at the design-construction interface using a location-based planning and the Last Planner System. The model integrate a variety of lean concepts and tools in different levels of construction project management, i.e., from strategical to operational. It also shed light to the push and pull flows in design production, that must be understood by Design Manager in order to preserve the transdisciplinary development of design solution. The model implicates in reducing WIP and batch sizes in the D-C interfaces when applying a unique LBS.

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THE SYNERGIES BETWEEN LEAN AND BIM: A PRACTICAL AND THEORETICAL COMPARISON

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ABSTRACT

Lean and BIM combined have proven to positively impact productivity in the construction sector. This paper aims to identify how the synergies between Lean and BIM have been happening in practical and real-life applications and compare them with the Sacks et al. (2010) matrix, using the information on processes of Brazilian construction companies that work with Lean and BIM. We carried out semi-structured interviews with three construction companies to identify the interactions between Lean and BIM in their processes. As a result, we identified synergies in both Sacks et al. (2010) and the construction companies' practices; other synergies were identified only in Sacks et al. (2010), while others were identified only in the companies interviewed. These new interactions may be due to the technological advances during the last decade that made possible new uses of BIM or the level of implementation of Lean and BIM by companies, amongst other factors. This work contributes to technical and scientific knowledge since it brings a practical view of a topic that has a more theoretical approach. With the results, we can indicate the more common interactions to be implemented by companies, creating a safer way to be followed by companies seeking to implement Lean and BIM.

KEYWORDS

Building Information Modeling, Lean Construction, BIM and Lean Interaction Matrix, synergy.

INTRODUCTION

Compared to other industries, the civil construction industry has low productivity (Heigermoser *et al.*, 2019). Even though it is still considered an industry not technologically advanced, scholars have studied topics such as waste reduction, processes improvement, and information virtual flow in the past decades.

Among these topics, two essential concepts have been developing since the ’90s and have significant impacts when delivering construction projects. The first topic is Lean Construction, a production management philosophy adapted to construction and derived from the Toyota Production System (TPS) (Comelli, 2017). The second topic is Building

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Information Modelling (BIM), which has the potential to transform the use of information technology in the construction industry (Tezel et al., 2020; Greenwood et al., 2017).

According to Dave et al. (2011), there are two types of problems associated with construction: a) construction processes problems; and b) product representation problems. Lean Construction offers an effective way to solve construction processes problems, while BIM help to solve many of the problems related to projects (products) by providing visualization tools and intelligent product models based on a virtual platform. Because of that, these topics have been more developed and studied.

Oskouie et al. (2012) indicate the necessity to explore the interactions between Lean and BIM through practical and real-life application of such synergies. Seeking to supply the absence of data on how these synergies have been applied in real life, this paper aims to identify the synergies that happen in construction companies that already use Lean and BIM but do not necessarily use them in an integrative way.

Thus, this study sought to compare the findings of Sacks et al. (2010) with Brazilian construction companies' practices to understand which synergies the construction companies achieved and which identified synergies could be considered new.

LITERATURE REVIEW

Al Hattab & Hamzeh (2015) defend that BIM and Lean are synergic practices. BIM functionalities support Lean Principles and vice-versa, having a synergic effect (Dave et al., 2011). However, BIM and Lean have been used separately to increase general productivity and the civil construction industry's efficiency (Heigermoser et al., 2019).

Despite being different, independent, and separate concepts, BIM and Lean can obtain their maximum benefits via simultaneous implementation, especially when their adoption is through Integrated Project Delivery (Sacks et al., 2010; Greenwood et al., 2017).

The number of researchers seeking to understand Lean and BIM synergy has been rising: Mellado & Lou, 2020; Schimanski et al., 2020; Bataglin et al., 2020; Tezel et al., 2020; McHugh et al., 2019; Dave et al., 2015; Dave et al., 2013; Oskouie et al., 2012.

BIM enables error detection, omissions, and clashes beforehand, which helps reduce waste and makes construction processes more linear (Eldeep et al., 2022). Bayhan et al. (2021) state that companies that wish to improve their production processes should invest as a priority in Lean and BIM to eliminate waste such as rework, time, and cost losses.

In their research, Dave et al. (2011) noticed that the interactions/synergies between Lean and BIM are found throughout the project life cycle, having powerful interactions in the construction phase. Thus, there is a potential to develop a system that integrates Lean with the rich information model provided by BIM. For Mollasalehi et al. (2018), BIM and Lean integration improve productivity and global performance. Therefore, there is an increased level of adoption of these two approaches in the construction industry.

RESEARCH METHOD

This paper proposed a qualitative research method through a case study to identify the existing synergies between Lean and BIM in Brazilian construction companies that already use such approaches. We chose a case study as a research strategy since researchers do not have control over behavioral events, and the research focuses on contemporary events. In addition, the case study provides a wide range of the studied object and allows a broad and detailed knowledge about it (Yin, 2015). We carried out semi-structured interviews with representatives responsible for implementing or using

Lean and/or BIM in the companies that participated in the study. With these interviews, we aimed to verify if these companies are using Lean principles and BIM functionalities combined and how this correlation is inserted in their processes.

We developed the interview script based on Sacks et al. (2010). We carried out a pre-test of the interview script with the technical director of a consulting firm that provides construction management solutions. The script dealt with BIM implementation, Lean implementation, obstacles, and gains obtained using these approaches. We also discussed the company's vision regarding BIM and Lean synergy, how it happens in practice, BIM functionalities, and how they help apply a Lean principle in a more specific fashion.

Three Brazilian companies that use both Lean and BIM participated in the study: two located in the State of Ceará and one that works nationwide, based in São Paulo.

We carried out six remote interviews in total, two in each company. We interviewed technical directors and professionals who worked in BIM and/or Lean sectors. From their answers, we identified the existing synergies throughout the life cycle of the companies' works. These synergies could be positive or negative when BIM helps or harms the use of Lean and vice versa, respectively.

The identified synergies were compared with those presented in the Sacks et al. (2010) matrix. In the matrix (Figure 1), we identified four classes of synergies:

a) Common synergies: refer to the synergies found in all interviewed companies and Sacks et al. (2010) matrix.
b) Partial synergies: refer to the synergies found in at least one of the interviewed companies and Sacks et al. (2010) matrix.
c) Empirical synergies: refer to synergies found in at least one of the interviewed companies and not in Sacks et al. (2010) matrix.
d) Matrix synergies: refer to synergies found only in Sacks et al. (2010) matrix but were not identified in the interviewed companies.

RESULTS AND DISCUSSION

Company Alpha has been implementing Lean since 2004 and has been developing practices and tools that nowadays are embedded in the company's management culture. BIM was first implemented in 2014, especially in architectural projects. Since 2016, it has started to be used more effectively by the project management team. Nowadays, it is applied to project development and compatibility, construction site implementation process, and construction work planning. Both 4D and 5D BIM are in the maturing stage.

Company Beta started its BIM implementation process in 2011, initially using it to transform 2D into 3D projects. Since then, they have finished 11 virtual construction projects, aiming to implement BIM in the maintenance stage as a next step and integrate the work into a single virtual platform. The Lean philosophy was implemented in their construction sites approximately simultaneously, seeking to stabilize production with the implementation of short-term, lookahead, and long-term planning, the identification of activities that add value, and prototyping, among other uses of Lean in their sites.

Company Gamma has over 70 years of experience with industrial projects, infrastructure works, urban mobility, energy, oil, and gas construction projects. Since 2018, the company has started BIM implementation in all its projects related to the Engineering Department; however, it has worked with BIM for about ten years in case projects. The company has been working with Lean for ten years and has a "Lean Excellence System." Nowadays, this system is applicable throughout the company, aiming to structure projects to integrate 100% BIM and Lean.

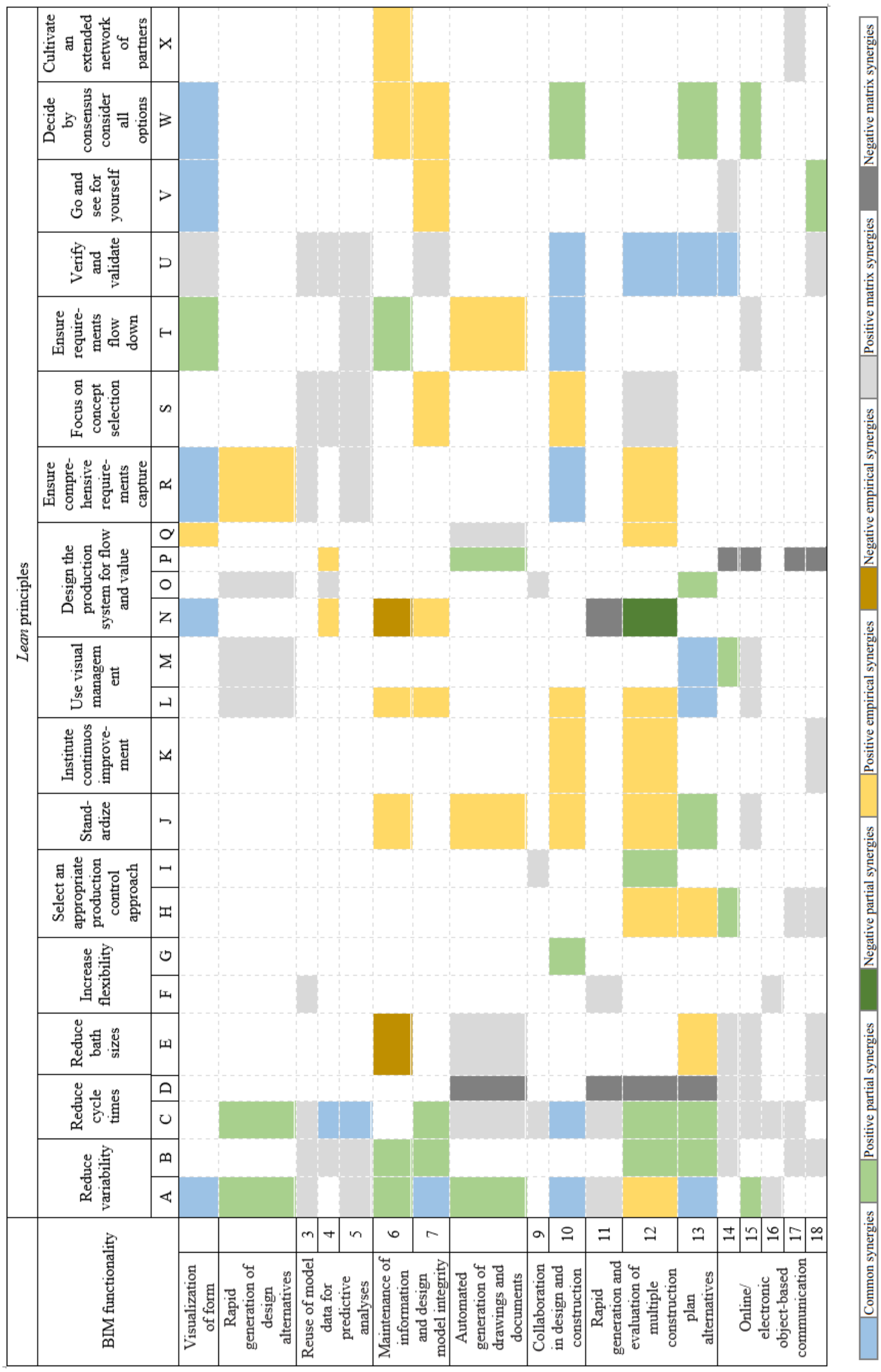

Figure 1: Companies' Practical Interaction Matrix for Lean Principles and BIM Functionalities

Sacks et al. (2010) presented an interaction matrix based on emerging evidence from research and practice. Figure 1 is a replica of the matrix presented by the authors, in which Lean principles are named "A to X" and BIM functionalities are numbered "01 to 18". In order to understand the terms better, the work by Sacks et al. (2010) should be consulted.

Next, each BIM functionality will be presented, and the synergies presented in Figure 1 will be explained. We will present the Lean principles associated with each BIM functionality and justify why we marked the synergy between them.

COMMON AND PARTIAL SYNERGIES

Visualization of form (1)

The 3D model makes possible a comprehensive and multidisciplinary visualization, helping to identify errors before they happen and ensuring a better quality **(A)**. The 3D model also simplifies **(N)** to present information in the product and construction process and help define execution order **(Q/R/T)**. As we can observe from the interview with Company Alpha: "In complex projects (...) we end up using (the model) as a way to better understand that project. The visualization allowed by the model also facilitates the Gemba walk **(V)** because now it is possible to visit the project and the construction site virtually".

BIM helps with decision-making process **(W)**, especially when many professionals are involved because it uses a single representation of information that everyone can access. According to the example given by Company Beta representative: "We involved designers of ambiance, landscaping, installations, and structures. When they start developing the preliminary study, BIM comes in, takes everyone's designs, and models them since the preliminary study. We can now visualize better how that product will be."

The processes simulation guarantees that planned will be executed **(U)**, as spoken by Company Gamma: "The "excellence" staff, for some doubts, used the model to see if the crane was going to hit some piece, if there was some interference. The *rigging* plans are much more assertive because they were actually made on the digital model."

Rapid generation of design alternatives (2)

Due to the rapid generation of several possible scenarios, the BIM model enables analysis and verification of which processes allow a shorter cycle time **(C)**, considering in each of these scenarios possible conflicts and complications to be defined, diminishing variability **(A)**. According to the example mentioned by Company Alpha representative: "It is a way of simulating construction site layout, rack positioning, work strategy, and crane positioning. We already use this approach for mapping primary and secondary trays."

The simulation allows greater process assertiveness due to visualization capabilities, ensuring that the customers' requirements are met; as Company Gamma representative said **(R)**: "We use it to see the coherence and consistency of our standards. If it is going to meet our needs, if it can quickly simulate if what we are going to standardize is going to meet customer's needs or not, should any changes arise along the way."

Reuse of model data for predictive analysis (4/5)

Using BIM models allows the exportation of information and documents automatically, with more assertiveness of model data and reducing the cycle time to obtain it **(C)**. By obtaining data from the model, construction planning becomes more accessible and more reliable **(N)**, as stated by the Company Beta representative: "We always had doubts regarding our construction execution layers, to get quantitative data. When we saw that the data extracted from the model was reliable **(P)** in comparison to manually extracted data, we saved time and evolved a lot when using BIM."

Maintenance of information and design model integrity (6/7)

Identifying incompatibilities and restrictions before execution **(T)** allows to remove them in advance **(A)**, resulting in reduced variability **(B)** and reduced cycle times **(C)**. As mentioned by Company Gamma: "Assuming that Lean has constancy and predictability, and this involves reducing variability, BIM comes in hand to assist in the ability to see, perceive what is a restriction, what is a problem, and what is an incompatibility."

By using parametric objects, model updates happen automatically **(N)**, allowing uniform detail representation **(J)** and construction methods **(L)**. As stated by Company Beta: "(...) We model facilities. We even know where the boxes are, the facilities, and their heights. In a kitchen, for instance, (…) we know that in the porcelain tiles, we will have the boxes at a given height, and we could improve a lot in the prototype so that after the prototype, we can replicate the standardization for the rest of the construction site."

A single database allows that the concept is well defined (**S**) since all stakeholders participate in the process and generates a virtual construction that can be visited off-site **(V)**, as mentioned by Company Gamma representative: "We realized that the collaboration of the tool **(W)** allows us to anticipate project problems that are dealt with immediately, with the collaboration of all involved **(X)**. That way, the lead time of the process is reduced **(C)**, besides avoiding revisions, unidentified errors as well as compatibility and interference issues **(A)**."

A negative impact identified during the interviews is that an over-detailed model can lead to more batches **(E)** due to the amount of information, which contradicts the ideal batch sizes for good management, hindering its use and diminishing simplification **(N)**.

Automated generation of drawing and documents (8)

Since it is a model formed by parametric objects, BIM allows the extraction of information and sets of coordinated drawings, diminishing variability **(A)** because any changes are automatically updated in the model, ensuring that the correct information is shared. As mentioned by the Company Gamma representative: "We have a standard spreadsheet that exchanges information with the library, that communicates with the budget. When the layout (the construction site) is defined, this spreadsheet is automatically completed and sent to the budget." **(P)**

It is possible to use BIM to generate automatic documentation of standardized parts, ensuring that the information is shared correctly **(T)**; as the Company Alpha representative said: "We takeout our documentation from BIM (framework and some accessories), door and countertop standardization."

Collaboration in design and construction (9/10)

Via the compatibility of design disciplines and collaboration amongst all designers, it is possible to identify what adds value to the customer and then execute the designs with quality **(A)**, reducing the variability of product and production. These characteristics allow fluid development without reworks and shorter cycle times **(C)**.

The opportunity to work with multipurpose teams **(G)** within the same data source might facilitate integrated decision-making, which allows better analysis, resulting in the best solutions **(R)**. According to Company Gamma: "BIM promotes optimization in engineering. We testes some market solutions, which nowadays involve the customer, our designers, our site project managers, our construction team, and our BIM team **(L)**, all in the same environment, working on the same model **(S)**. Everyone is working on the same database **(J)**, on the same information, defining the best solutions **(W)**. When we talk about the federated model, with all disciplines, everything is in the same place." **(T)**

BIM allows an analysis of the building before its construction due to the amount of information contained and how information is demonstrated. One possibility is the virtual Gemba **(U)**, which consists of verifying the whole building with professionals from different areas to collect data, identify possible problems, and resolve them during the design phase. As mentioned by the Company Alpha representative: "In Virtual Gemba, we involved the project manager, the project supervisors, the project designers, and the budget team. It is an event between the company and our suppliers." **(G/K/T)**

Robust models allow for more assertive constructions because they enable analyzing data visually before construction, generating better processes **(K)**, as exemplified by Company Alpha representative: "We made a comparison of how much we saved, how many incompatibilities there were, and the estimated savings in the construction budget. We found problems that would cost a loss of around 800 thousand Brazilian Reais, resulting in a three percent saving on the budget. Four significant incompatibilities that we found and the investment made on BIM represented 80 thousand Brazilian Reais, so there is nothing that compares to using BIM."

Rapid generation and evaluation of multiple construction plan alternatives (11/12/13)

By simulating construction from the BIM model linked to the schedule, it is possible to control the works, allowing a better understanding **(R)**, in addition to visualizing construction better in time, contributing to the identification of problems more quickly, correcting them as soon as possible **(Q)**. According to the example given by Company Beta representative: "So, we start with BIM, then we move to our line of balance, then to our 4D, and finally we take it to the construction site so that we can pull it (work) there **(H)**. And then, obviously, what goes into planning should reflect in the construction site."

BIM allows the visualization of construction processes **(L)** and, consequently, clash identification, either in space or time, enabling their anticipation, thus improving process efficiency **(K)**. As an example given by Company Gamma representative: "If you used to do it without BIM, you would have much re-planning to do, because you did not could see the whole picture. Now, with BIM, you can see everything, involve people visually, and have much less re-planning to do **(A/N)**."

Due to the better visualization of construction, BIM makes it possible that clashes are found in space and time **(U)**, allowing cycle time reduction **(C)**, improving project standardization **(J)**, and ensuring information flow between all professionals involved. As stated by Company Gamma: "Before BIM, we would take an operational procedure and the project and pin them to the wall so that our staff could see the procedure in their minds. And they started to have a perception of uncertainty regarding what the model was and continued to think that it was wasteful. If at this point in planning you can detail people's progress **(B)**, for instance, you can reduce cycle time **(C)**, because it is possible to see if there is overlapping work, which is part of the cycle time **(R)**."

The simulation process can indicate uneven work allocation, allowing a better assessment of work assignments and checking for peaks and valleys during the production process **(I)**. As mentioned by Company Gamma: "In our detailing stage, where we talk about pull planning, (…), you model and define which information level to be used when detailing and can use that information to level (production). If you do not use BIM and need to plan quickly, sometimes you will not have enough time, and might imagine that it is leveled. Using BIM, you have more flexibility and can generate these graphs faster to see if what you planned online is peaking or not."

It is possible to have a better perception regarding the size of work packages **(E)** due to the visualization offered by BIM. As mentioned by the Company Gamma representative: "We work with large projects, which means that we will not have repetitive structures. I cannot define a fixed batch for these projects. Usually, we go little by little, prioritizing flow to activities that are in parallel. We have already managed to identify restrictions on pre-defined batches through BIM."

It is possible to analyze processes that, in practice, would be challenging to test due to the various possibilities of simulating one-off events. As stated by Company Gamma: "In a dam project, for instance, BIM helps decide the construction methodology. You simulate the construction steps for the planned dam, and you realize there will come a time when the form will be so big that it is better to make it a sliding shape. These are solutions that we have applied numerous times, and at this point, we can be flexible **(L)**."

BIM facilitates complex detailing, allowing better process standardization **(J)**. The simulation of several disciplines within a single model, related to the experience obtained on-site, provides the possibility for lessons learned **(K)** that can be shared and used in future projects, thus generating continuous improvement. As pointed out by Company Gamma: "Usually, we waited until the end of the construction work to obtain the lessons learned and use them for future projects. Today, if we can simulate the model, we start to criticize our times, optimize things for the client, and provide them with a shorter schedule. So today, what we are using more in lessons learned are in the proposals."

A negative interaction was brought by Company Gamma: "BIM exposes a problem. You say: I'll do everything complete, detailed. (...) Sometimes, you spend more energy on the model to be able to make something that you won't even use **(N)**."

Online/electronic object-based communication (14/15/16/17/18)

Simulation of the process status enables visual management, facilitating the creation of a schedule with continuous activities, avoiding gaps during production, thus implementing a pulled flow **(H)**, allowing through online communication even off-site control **(M)**. With accessible information for all involved in the process, it is possible to identify problems and correct them before they happen **(A)**. According to Company Alpha: "BIM helps us guarantee the schedule, which already is pulled. It ensures this by allowing you to simulate, model, and visualize restrictions **(W)**." The same person stated: "With 4D you can visualize you should be, and where you are today (...). We can see what should be already finished, what we are executing right now, and what is about to start." **(V)**

EMPIRICAL SYNERGIES

Part of the empirical synergies is correlated with the Simulation of the Construction Process and 4D Visualization of Construction Schedules. The companies have been using such functionalities, and these interactions were not identified before by Sacks et al. (2010). These synergies show that interactions between Lean and BIM have increased over time, possibly due to BIM diffusion and the development of technologies and innovations in this field of knowledge. Another reason might be that Sacks et al. (2010) study used mostly theoretical references, while this study also used practical observations.

The Lean principles that had the most empirical synergies were visual management and standardization, related to the BIM functionality of conflict verification, visualization of multidisciplinary models, construction process simulation, single source of information, and automated generation of drawings and documents. Following this evidence, Bayhan et al. (2021) identified standardization, information accuracy, and continuous improvement as important production characteristics. The authors identified that clear communication and visualization, aided by Lean/BIM integration, enable more significant success in the construction processes.

MATRIX SYNERGIES

We can see a significant number of matrix synergies. Some synergies identified by Sacks et al. (2010) require aspects such as a high level of BIM and Lean maturity and their interaction, advanced technology, or supply chain integration. The interviewed companies did not achieve these aspects, which might explain this high number.

Also, some synergies are directly related to the product concept, which these companies rarely contemplate since they focus on the construction phase and not on the development of projects. In addition to synergies related to the reuse of data, it was identified, through the interviews, that none of them uses BIM models for performance analysis, such as acoustic, thermal, or energy analysis. Thus, no interaction of this profile was found. Another difference is the sample size for data collection. Other synergies could have been found from interviews with other construction companies.

DISCUSSION

Despite being companies of different sizes with different processes and implementation times for Lean Construction and BIM, the common synergies demonstrate that some of these interactions are supported in practice. It can demonstrate a common path traced by companies that decided to implement Lean Construction and BIM, which can be followed by companies that want to carry out this transformation.

The matrix shows that all synergies related to verification and validation were classified as common synergies. That can be explained by the multidisciplinary model, which helps with verifying interferences before execution, besides allowing a comparison of what was executed with what was planned from the 3D model visualization and construction simulation. In line with this finding, Fosse et al. (2016) state that visual management is the greatest benefit of BIM to Lean Construction, as it enables faster clarification and consensus thanks to a clearer flow of information.

Since 3D visualization is part of the BIM methodology, such advantages are perceived without further effort. The BIM model is used to anticipate problems and solve doubts that may arise in the construction site through visualization and multidisciplinarity (Bayhan et al., 2021), helping to reduce variability (Mollasalehi et al., 2017). From the matrix, we can see that BIM can contribute to applying this lean principle, being pointed out this way by the three companies.

Some reasons that explain the presence of partial synergies are the difference of BIM and Lean implementation maturity, construction type or construction system used by the companies, and each company's strategy. Most of the partial synergies were found in Company C, which can be explained because this company does not work with repetitive batches. So, it found more benefits in BIM in reducing cycle time and its production system since the company uses its features to have more assertiveness in batch size and better information management. Another characteristic is that Company C works sharing a single database, facilitating collaboration in various areas of BIM functionalities.

Given the found synergies, it is important to emphasize what differentiates BIM and Lean. One of the interviewees highlighted: "The more integration between Lean and BIM, the better. You can make BIM helps Lean a lot. However, I emphasize that the company's philosophy should be a management philosophy. Lean is a management philosophy. BIM is a work methodology that helps a lot when developing projects and construction sites. But you need to *breathe* Lean. BIM helps Lean." The interviewee also points out: "Lean does it all, and BIM helps you to visualize." and: "Lean has a greater importance degree in management terms than BIM, so as not to leave the two at the same level."

CONCLUSIONS

The research findings make it possible to verify how the synergies between Lean and BIM have been perceived in three Brazilian companies. From the interactions identified through the interviews with the companies, we could assemble a matrix similar to the original one to compare them. Through the comparative analysis, four classes were determined according to where the interactions were identified, and then each class was studied separately to understand them. Of the 146 results (positive and negative) indicated in Figure 1, 13.01% (19 interactions) were common synergies; 17.81% (26, one being negative) were partial synergies; 23.29% (34, two being negative) were empirical synergies, and 45.89% (67) were matrix synergies.

As we can observe from the results, most synergies presented by Sacks et al. (2010) were not identified in the interviews with the three companies, which some limitations might explain: a) Technology level and BIM and Lean implementation maturity of the companies; b) Some interactions may be occurring in the companies and were not observed during the interviews; c) A small number of construction companies were studies; d) Companies focused on construction/operation were interviewed, not considering companies that work with project development; e) the difference of more than ten years between the publication of Sacks et al. (2010) and this work.

The second most common classification was empirical synergies. Despite not being addressed in the original matrix by Sacks et al. (2010), companies have presented new Lean and BIM synergies, deserving a future theoretical discussion.

Through the matrix (Figure 1), we can confirm the result found by Dave et al. (2013). The lean principle that had the most interactions with BIM features was the reduction of variability followed by designing the production system for flow and value, enabling a better-designed product and thus reducing variability. Thus, it can be concluded that such aspects will contribute to a reduction in the overall construction time.

This work contributes to scientific knowledge by approaching the matrix developed in the seminal study by Sacks et al. (2010) with a practical view, a topic that had been previously addressed by other researchers, from a theoretical approach or with the realization of some comparative studies (theory x practice) of specific interactions. In addition to the scientific contributions, it collaborates with technical knowledge, indicating the most common Lean and BIM interactions to be implemented by companies, raising the possibility of creating a path to be followed in the future by companies.

Furthermore, empirical synergies can demonstrate that interactions between Lean and BIM have increased over time, possibly thanks to BIM diffusion and the development of technologies and innovations in this field of knowledge.

This exploratory study encourages new research, both qualitative and quantitative. We suggest, for future work, increasing the number and diversity of companies in order to ratify the original matrix constructed by Sacks et al. (2010) and facilitate the implementation of systemic interactions of Lean and BIM, thus contributing to the improvement of design and operations quality in civil construction.

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EMPLOYEE'S MENTAL WELLBEING WITH REFERENCE TO IEQ AND MANAGERIAL ENVIRONMENT IN OFFICE SPACES

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ABSTRACT

Pre-corona the economy flourished but number of employees suffering from mental-wellbeing issues was rising. This set the stage for understanding the relationship between workplace mental-wellbeing, Indoor environment quality and Managerial Environment. As employees are a significant expenditure for companies, human-centric design and workplace optimization is gaining ground. WHO reported that the costs incurred on the global economy because of depression and anxiety was estimated as 1-trillion US dollars per-annum in lost productivity in 2019. This lost in cost and productivity can be considered as waste which can be eliminated by using Lean construction to optimize the workplace environment. Therefore, the main research question here was to know that to what extent the IEQ parameters and Managerial Environment, relate to mental wellbeing while working at corporate office spaces. Employees of diverse scale firms of Ahmedabad were considered. A mixed-research methodology was being adopted and data was collected by means of a questionnaire survey and interviews. Data analysis was done with the help of descriptive and inferential statistics of the survey and coping strategies were noted with the help of interviews. This study would be a thirst area for a balanced work-environment considering the physical, social, and mental wellbeing of the employees.

KEYWORDS

Lean construction; safety, quality, health; waste; mental wellbeing; workplace optimization.

INTRODUCTION

The impact of the built environment on individual was obvious, yet not well-understood. To date the architecture, engineering and construction (AEC) industry has been strongly focused on minimizing any undesirable impact of design by improving efficiency. The regenerative approach recommended possible interactive components from a human perspective, and that were social interaction; IEQ in terms of visual and physical comfort; occupant productivity eventually increased health and well-being (Craft et al., 2017). As employees are significant expenditure for most companies, human-centric

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design and workplace optimization are gaining ground (Watson, 2018). However, the correlation between mental wellbeing and IEQ at office spaces were not well understood (Mujan et al., 2019). Managerial environment was also one of the major factors which affects the employee’s wellbeing. Quick et al., (2007) tells that the organization whose leaders are healthy, tends to maintain the organization’s vitality, productivity and completive edge over their competitors. According to research by Cobaleda Cordero et al., (2019) and Jensen & van der Voordt, (2019) an evidence-based approach research was required to clarify the correlation between employee’s mental wellbeing and the IEQ. The study by Oswald et al., (2019) emphasis that majority of the lean concepts discusses about the physical aspects rather than mental aspects of an individual. Thus strategies need to be developed using the lean construction concepts to improve the loss in productivity and minimize the cost incurred due to this ill-effect in construction industry. The need was further supported considering the change in mental health and IEQ on employees in post COVID-19 situation in AEC sector.

The main objective of this research was to find the correlation between IEQ conditions, managerial environment and employee’s well-being in office spaces which will provide evidence-based recommendations to scientific researchers, policymakers, and practitioners. In order to attain this primary objective, several sub-objectives were formulated:

1. To find out the parameters for mental wellbeing by reviewing extensive literature review.
2. To study the relationship between personal characteristics, IEQ and managerial environment parameters with mental being of the employee.
3. To study how personal character affect the perception of IEQ parameters, Managerial Environment factor and mental wellbeing of the employee.
4. To observe the variation of IEQ and managerial environment on mental wellbeing due to size of organization.

LITERATURE REVIEW

WHO, (2004) defines mental health as “…a state of well-being in which the individual realizes his or her own abilities, can cope with the normal stresses of life, can work productively and fruitfully, and is able to make a contribution to his or her community”. Based on extensive literature review variables associated with mental wellbeing has been identified. *Concentration, Fatigue/ Tiredness/ Insomnia/ Sleep Quality:* Fatigue is “the state of feeling very tired, weary or sleepy resulting from insufficient sleep, prolonged mental or physical work, or extended periods of stress or anxiety” by Canadian Centre for Occupational Health and Safety, (2017). Effects were reduced communication skills, productivity, ability to handle stress, increase in reaction time, Caldwell et al., (2019). Lighting conditions can also have impact on employee’s cognitive processes both in positive and negative way. *Depression/ Anxiety, Emotional Exhaustion, Mood:* Depression is “a serious event with which an individual cannot cope adequately”. *Motivation/ Engagement/ Burnout:* Employee’s engagement is “a distinct and unique construct that consist of cognitive, emotional, and behavioral components that are associated with individual role performance”, Saks, (2006). *Performance/ Productivity:* Bubonya & Cobb-clark, (2017) investigated the link between mental wellbeing and workplace productivity measures which were absenteeism and presentism which have direct effect on lean construction principles. IEQ parameters like thermal comfort, air quality and acoustics were also found related to employee’s workplace productivity, Horr et al., (2016). *Stress:* Stress means "a significant life event or change that demands response, adjustment, or adaptation" (Stangor & Walinga, 2014). Lighting conditions were also found relevant with the workplace stress.

Indoor Environmental Quality (IEQ) means "the condition of the inside of a building" by (Geng et al., 2017a). *Satisfaction with temperature:* Satisfaction with temperature is a subjective evaluation which means an expression of satisfaction with thermal environment (ANSI/ASHRAE, 2017). Productivity and thermal satisfaction has found to be positively correlated in the study by Geng et al., (2017b). *Satisfaction with Indoor Air Quality:* Indoor pollutants like volatile organic compounds (VOCs), fine particles (PM) and carbon dioxide affects the IAQ conditions therefore proper ventilation in office spaces is necessary. As an energy conservation measure in early 1980s, the commercial ventilation rate requirement has been lowered which led to more building related illness which is also known as sick building syndrome (SBS) (Allen et al., 2016). *Satisfaction with sound level:* Horr et al., (2016, p.6) in the study distinguished the acoustic problem of office environment. This causes distraction and it usually takes 15-20 minutes as a recovery time to get the concentration. Productivity is thus also affected by noise disturbance which thereby increases the mental workload of employees. *Satisfaction with lighting:* For a lighting system there were several requirements i.e., "providing enough light, create neither discomfort, glare nor reflections, be without flicker and well distributed, and provide acceptable colour rendering". The decline in productivity has been observed by Eklund & Boyce, (1996) on their office lighting survey when the expectation of the employees is not met. Work engagement has also been included in this model in further research by J. A. Veitch et al., (2013). The model shows the strong effect of work engagement and lighting conditions.

For managerial environment the factors found from the literature review were as follows. *Effective communication* enhances personal growth of an employee in an organization by King, (1992). There should be *career development planning and growth* programme offered by the organization to their employees so that they can maintain their skills and can remain useful to the organization. *Organizational Commitment* has positive and significant effect on job performance i.e., more committed employees performs better in their job (Walton, 1985). There should be an *emotional support from the supervisor* towards their employee to maintain their energy levels by discussing about their problems to reduce the mental stress of the employee which can help in boosting their work performance (Lapierre & Allen, 2006). *Flexible Work Arrangement* also helps their employee's by increasing their motivation and dedication towards organization. *Job Satisfaction* means that to what extend the employee is enthusiastic or satisfied about the job (Aryee et al., 1999). *Rewards and Benefits/ Compensation* for the employee's generally includes rewards, social support, fulfilment of reasonable demand and influence over decisions. This can enhance the mental wellbeing of the employees (Lowe et al., 2003).

Next parameters related to personal characteristics of the employees were selected. Frontczak & Wargocki, (2011) in the study talks about the relation of IEQ with the human comfort where it has been concluded that personal characteristics like *age*, type of job and country of origin has a significant effect. *Gender* of the employee is also considered as one of the important parameters in knowing occupant's office perception relating IEQ (Kim et al., 2013). In this study, significant relationship between the gender and sick leaves has also been observed. Murray et al., (2003) in the study shown that *household composition* was also an important parameter considering the mental wellbeing of the employee like sleep quality, depression and emotional exhaustion. The factor selected were *firm type, firm size, age, gender, personality, household composition, management level* of the employees. This research was needed because the newer generation employees will need a balance work environment considering their physical, social and mental wellbeing as this balance resulted into employee being able to work and flourish across the organization. Thus, improving the productivity of the employee and reducing the waste in terms of cost using lean construction principles since its major pillar is waste reduction.

RESEARCH METHODOLOGY

All the parameters related to each group were collected through extensive literature review. It was followed by Mix design research approach where data was collected by means of questionnaire and interviews. Questionnaire survey was prepared and scored according to existing scientific scales. Interview of field expert viz. psychologist (Qualification – Masters and Doctorate in Psychology) and Architects (Qualification – Bachelors and Master's in architecture) were used to know the coping strategies. Descriptive and Inferential statistical techniques were used to analyze the collected data using IBM SPSS Software and Microsoft Excel.

The questionnaire survey was validated by the field experts for mental wellbeing concepts, managerial environment concept and IEQ concepts of the study. Experts had to rate each question for its relevance and unambiguity and the feedbacks were incorporated while forming questionnaire. The data was collected by means of questionnaire survey using Google form and printed copies. Identifier codes (pseudonym) were also provided to each survey questions for better linking of data. Stratified sampling procedure was adopted for finding the sample size for number of responses.

Pilot study of the 30 responses was conducted and their reliability was checked using Cronbach alpha using IBM SPSS software. From pilot study it was observed that the response rate was low on Google form so printed copies were also distributed among the firms. For the reliability test for IEQ parameters, the value of alpha was observed as 0.903, for ME parameters, the value observed was 0.877 and for MW parameters, the value observed was 0.933. The value of alpha (> 0.5) showed that all the three scales were reliable. A total of 151 responses were collected after removing the outliers. Interviews of 4 psychologist and 6 architects were conducted. Descriptive analysis was carried out using mean, median, and standard deviation. Inferential Statistics viz. paired t-test, chi-square test and Pearson's r with significance level of 5% were used to test hypothesized relationship.

DATA COLLECTION

It was found that there were almost equal proportion of respondents from consultancy and contracting firms. Half of the data collected was from small scale firms which was followed by medium and large-scale firms. It was noticed that half of the respondents from the sample were from middle level management followed by equal proportion of respondents from low level management and top-level management. More than seventy percentage of the sample were male and around 30% of sample were female. Around 85% of the sample consist of young age group between age of 24-36 years and few were more than 37 years old. Five major personality traits viz. extraversion, agreeableness, conscientiousness, neuroticism, and openness were noticed among the respondents from the fifteen personality related items.

FINDINGS AND INTERPRETATION

Indoor environmental quality related items were asked to the respondents, and it has been observed that three-fourth of the population were not satisfied with the temperature of their office space. Around sixty percentage of the respondents were neither satisfied with air quality nor sound level or lighting condition in their office. The overall score of the IEQ satisfaction was categorized using the mean and two classes were prepared. It was observed that 55% of the population was not satisfied about their overall satisfaction with indoor environmental quality (Figure.1).

In consultancy firms it was noted that around 52% of the employees and in contracting firms around 42% of the employees were not satisfied with their indoor environmental quality of their office space. In small scale firms, major issue about the satisfaction with indoor environmental was observed with 50% of the population. Tt was observed that 70% of the male's shown dissatisfaction with IEQ. Respondents having the age group between 24 years to 36 years showed the higher dissatisfaction (75%) with IEQ in their office space compared with other age groups. Among the respondents who were not satisfied with the IEQ of the office spaces, 60% of them were from middle level management and around 30% were from low level management. Again, from the respondents who were not satisfied with the IEQ of the office space 60% belong from nuclear family and 25% belongs from joint family.

About *Managerial Environmental* related items, it was observed that around fifty-five percent of the respondents were dissatisfied towards the proper communication in their firms whereas 50% of them shown the dissatisfaction towards the proper career development and growth program in their firms. Three-fourth of the respondents stated that there was no commitment of work in the employees and no emotional supervisory support within the firms. Three-fourth of the population didn't have any flexible arrangement for work for their employees in the firms, also fifty-five percent of population were lacking in rewards and benefits for employee's wellbeing in the organization. All these factors led to job dissatisfaction among 75% of the respondents in the organization. Fairly equal proportion of the respondents shown satisfaction and dissatisfaction with their overall managerial environment of office space (Figure.1).

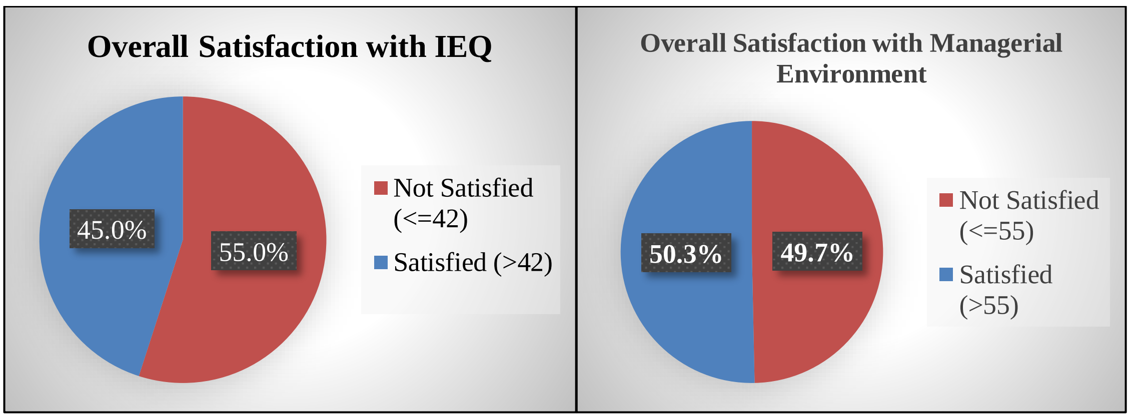

Figure 1: Overall satisfaction with IEQ and Managerial Environment

It has also been observed that fifty-five percent of the respondents were not satisfied with their managerial environment in office space in consultancy firms whereas 45% of respondents were not satisfied in contracting firms. Small scale firms were account for 55% of the respondents who were not satisfied with the current managerial environment followed by medium scale firms (36%). More than three-fifth of the total who were not satisfied with the current managerial environment was males. Again four-fifth of the respondents who were not satisfied with the current managerial environment lied between the age group of 24 years to 36 years. Among the respondents who were not satisfied about the managerial environment in their office space, three-fifth were from middle level management. Three-fifth of the respondents belonged to nuclear families who were not satisfied with their managerial environment in their office space. From those who were not satisfied with their managerial environment of their office space, 78% of them were also not satisfied with their IEQ of the office space

Then *Mental Wellbeing* related items were asked to the respondents. It was observed that around 60% of the population was experiencing the stressful environment in their office space. Fatigue and poor sleep quality has been observed in around three-fifth of the respondents. Three-fifth of the respondents reported that there was trouble in concentration and were emotionally exhausted while working in the organization. Decrease in productivity has been observed in 80% of the respondents. There was not much noticeable difference in the degree of engagement towards the work in the firms. Around 66% of the respondents were suffering from depression to some extend from the population and 52% of the population were having bad mood. Also, for overall mental wellbeing, more than half of the respondents were not so healthy as compared to healthy respondents.

It was observed that more than fifty per cent of the respondents who were not so healthy with their mental wellbeing belonged to consultancy firms while others from contracting firms. Firm size also matters, it has been observed that three-fifth of the mentally unhealthy respondents belonged to small scale firms, followed by medium and large-scale firms. Three-fifth of the mentally not so healthy respondents were male and other 40% were female. Again, the age group of 24 years to 36 years constitute the major part (78%) of mentally not so healthy employees (Table.1).

Table 1: Mental Wellbeing relation with personal characteristics

		Mental Wellbeing				
		Not so Healthy		Healthy		Total
		Frequency	Percentage	Frequency	Percentage	
Firm Type	**Consultancy firms**	41	52.6%	38	52.1%	**79**
	Contracting firms	37	47.4%	35	47.9%	**72**
	Total	**78**	**100.0%**	**73**	**100.0%**	**151**
Firm Size	**Small Scale firms**	45	57.7%	33	45.2%	**78**
	Medium Scale firms	23	29.5%	34	46.6%	**57**
	Large Scale firms	10	12.8%	6	8.2%	**16**
	Total	**78**	**100.0%**	**73**	**100.0%**	**151**
Gender	**Male**	49	62.8%	61	83.6%	**110**

	Female	29	37.2%	12	16.4%	**41**
	Other	0	0.0%	0	0.0%	**0**
	Total	**78**	**100.0%**	**73**	**100.0%**	**151**
Age	**<= 23 years**	8	10.3%	8	11.0%	**16**
	24 - 36 years	61	78.2%	49	67.1%	**110**
	>=37 years	9	11.5%	16	21.9%	**25**
	Total	**78**	**100.0%**	**73**	**100.0%**	**151**
Management level	**Low level management**	22	28.2%	15	20.5%	**37**
	Middle level management	43	55.1%	35	47.9%	**78**
	Top level management	13	16.7%	23	31.5%	**36**
		78	**100.0%**	**73**	**100.0%**	**151**
Household composition	**Single**	10	12.8%	6	8.2%	**16**
	Nuclear family	51	65.4%	30	41.1%	**81**
	Joint family	17	21.8%	37	50.7%	**54**
		78	**100.0%**	**73**	**100.0%**	**151**

Fifteen percent of the top-level management respondents were mentally not so healthy. Again, the respondents who were singles has reported only 13% mentally not so healthy. Majority of the mentally not so healthy employees were either from nuclear family or joint family. Out of the population who were not so healthy about their mental wellbeing, 68% of them were also not satisfied with their IEQ and 64% of them were also not satisfied with their managerial environment of the office space.

The interviews were also conducted to know the causes and coping lean strategies to continuously improve mental wellbeing and indoor environmental quality.

Causes of mental wellbeing problems in office spaces:

- Crowding of people inside the office space and lack of private spaces
- Management level of the employees and lack of support from the superiors
- Dark and shady desks/ space near washrooms; lack of fresh air and open spaces
- Slow system and poor internet speed; Improper planning of the work to be done
- No flexible arrangement to work, No incentives
- Peer pressure to work; Don't know when to say "No"
- Unsatisfied with their work; Missing drive to work

Coping Strategies to improve mental wellbeing:

- Companies must have the affiliated psychologist for the employees
- By having proper recreational space in the office like dedicated yoga area or cafes
- Power nap, small exercise like deep breath, pranayama or pressing the stress ball

- Proper incentives for extra work; Allowances for employees and his/her family
- Employees must have proper sleep quality and should maintain the daily routine
- Company must also consult the dietician for the employees
- Employees must feel comfortable in sharing their mental wellbeing issues
- Morning laughter or playing board games; By avoiding screens late night
- By finding out their motivating factors to work efficiently

Reasons of poor mental wellbeing and managerial environment due to IEQ:

- Quietness of the working place; Quality of air; Comfort level
- Satisfaction with temperature and lighting; Location of the office near road
- Employees may feel stressed, depressed, and may get arrogant because of poor IEQ conditions

Coping strategies to have better IEQ condition in office spaces:

- Vedic plaster/ Asian paint/ UPV cement to improve quality of air by reducing EM wave radiation; Need to have constant air circulation/ ventilation in office space
- Landscaping and vertical gardens with plants like sansevieria and crotons to maintain quality of air; Updated and speedy system
- Sound insulation material like double glass windows, gypsum ceiling and wooden flooring for better sound level; Reflective glass to have ambient temperature
- White/ Yellow light lighting with luminance> 4000K which follows LEED criteria to have ambient lighting; By increasing floor to floor height by 30 cm
- HVAC should be designed properly to have ambient temperature
- Playing soft music, wooden finish helps the employees in their work

Next for inferential statistical analysis several hypotheses were formulated and tested.

HYPOTHESES TESTING

$H_{01(a)}$: *There is no significant difference in the perception of IEQ due to gender:*

Paired t-test was used to test the hypothesis. The p value ($p = 0.043 < 0.05$) suggested that the null hypothesis was rejected. The mean IEQ score of male employees (IEQ male=42.41) being higher than that of female employees (IEQ female=38.82) suggested that males perceived IEQ parameters more comfortable than females. The authorities can find the point of discomforts from female employees in order to modify the office spaces and can then provide with better space to female employees.

$H_{01(b)}$: There is no significant difference in the perception of IEQ due to level of management of employees

The p value for the perception of IEQ ($p = 0.008 < 0.05$) suggested that the null hypothesis was rejected. The mean IEQ score of top-level management employees (45.67) was found higher than that of middle level management employees (41.08) which suggested that top level management employees perceived IEQ parameters more comfortable than middle level management employees.

The authorities can find the point of discomforts from middle level and low-level management employees to modify the office spaces and can then provide with better space to middle level and low-level management employees.

H_{02}: *There is no significant difference in the perception of managerial environment due to level of management of employees:*

Paired t-test was used to test the hypothesis. The p value ($p = 0.003 < 0.05$) suggested that the null hypothesis was rejected. The mean ME score of top-level management employees (59.58) was higher than that of middle level management employees (53.84) which suggested that top level management employees perceived ME parameters more comfortable than middle level management employees.

The authorities can find the point of discomforts from middle level and low-level management employees to modify their managerial environment and can then provide with better environment to middle level and low-level management employees.

$H_{03(a)}$: *There is no association between the perception of mental wellbeing and gender.:*

Chi-square test was applied to test the hypothesis of perception of mental wellbeing due to male and female employees. The result ($\chi 2 = 0.004 < 0.05$) suggested that the null hypothesis was rejected, and an association was found between the respondent's gender and their MW.

$H_{03(b)}$: There is no association between the perception of mental wellbeing and household composition:

Chi-square test was applied to test this hypothesis The result ($\chi 2 = 0.001 < 0.05$) suggested that the null hypothesis was rejected, and an association was found between the respondent's household composition and their MW.

$H_{03(c)}$: There is no difference in the perception of mental wellbeing due to level of mgt. of employees:

Paired t-test was used to test the hypothesis. The p value ($p = 0.017 < 0.05$) suggested that the null hypothesis was rejected. The mean MW score of top-level management employees (180.41) was higher than that of middle level management employees (168.53) which suggested that top level management employee's MW was better than middle level management employees. Further the difference in perception was also tested between top level and low level management. The p value ($p = 0.016 < 0.05$) suggested that the null hypotheses was rejected. The mean MW score of top-level management employees (180.41) was found higher than that of low-level management employees (165.94) which suggested that top level management employees had better MW than low level management employees. Moreover, correlations were performed between:

i) IEQ and ME ($r = 0.578 > 0.5$), ii) IEQ and MW($r = 0.377 < 0.5$) and iii) ME and MW($r = 0.559 > 0.5$). These correlations and respective "r" values inferred that IEQ was significantly related with ME but not related to MW. Hence, better IEQ could improve managerial effectiveness but not mental wellbeing. Also to note here that Managerial effectiveness was significantly related to MW thus when there would be an improvement in IEQ there would be improvement in managerial effectiveness and when managerial effectiveness improves, the mental wellbeing improves.

The framework was thus prepared based on the analysis of variables. Personal characteristics viz. age, gender, personality, household composition, management level of the respondents affected the perception of IEQ parameters, managerial environment, and respondent's mental wellbeing. Overall perception about the IEQ parameters affected the managerial environment of the respondents (I) which again affected the respondent’s mental wellbeing (II). It was also noted that gender (III) and management level (VI) of the employees significantly affected perception of IEQ in office spaces (Figure.2).

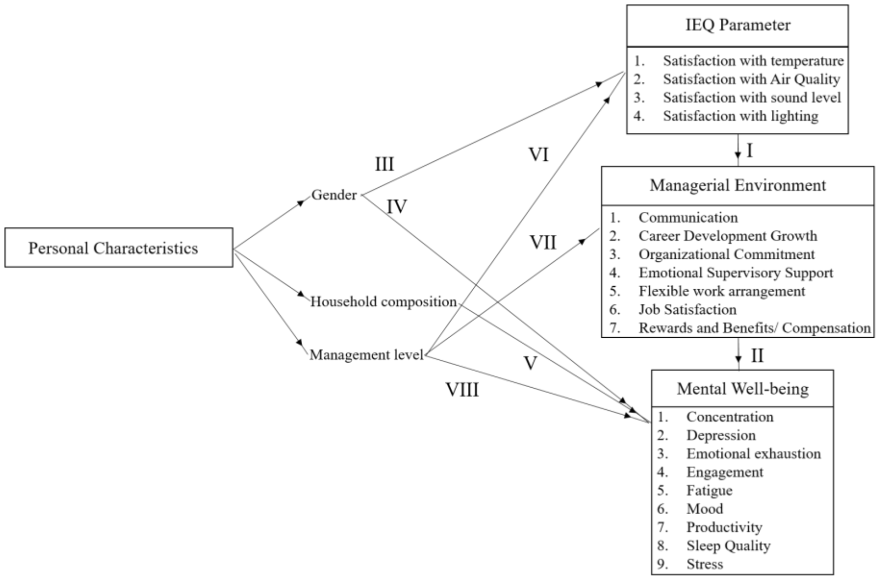

Figure 2: Framework showing relationship among the variables.

Also, managerial environment in the office space gets affected by the management level of the respondents (VII). Lastly, personal characteristics viz. gender (IV), household composition (V) and management level (VIII) of the employees affected the mental wellbeing. Through analysis it was observed that personality and age of the employees did not affect the perception of IEQ, managerial environment and mental wellbeing.

CONCLUSION AND FUTURE SCOPE

Every office has a different type of setting so the perception of the employees towards Indoor Environmental Quality, Managerial Environment and Mental Wellbeing can vary widely. Lean concepts and its principles have been used for providing strategies in terms of recommendation to continuously improve on the mental wellbeing of the employee in the office space by working of their indoor environmental quality and managerial environment. Moreover, more mental health concept can be introduced in the study to get accurate results like building related symptoms (e.g., headache), health status, visual comfort/satisfaction, disorders, phobias. The study can also be extended over a period of one year with more responses. The study was for the population of Ahmedabad, the results can vary for different cities/ states of India based on employee’s perception. One can use the results and recommendations of the thesis to optimize the office-based work experience of the employees by improving their indoor environmental quality and their managerial environmental which will improve employee’s mental wellbeing. The scope of future work can also be extended by comparing the effect of green buildings on mental wellbeing of employees and that of conventional buildings. Furthermore, future research can include questions related to the work activities done instead of solely categorized based on profession, like being on a call, report typing or processing emails. Having a variable on work activities can lead to more insights, since not each profession is the same but can have overlapping work activities. In-depth technical study can also be planned with the use of sensors to measure indoor environmental quality parameters. By fast improving technological possibilities and sophisticated data mining techniques, future research will be able to monitor and analyze objective data and subjective experiences with more detail. Thus, the research by its conclusion suggested that lean principles are also applicable in the mental wellbeing context within construction industry.

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MECHANICAL, ELECTRICAL AND PLUMBING COORDINATION PRACTICES: CASE FINNISH CONSTRUCTION MARKET

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ABSTRACT

MEP (Mechanical, Electrical, and Plumbing) coordination is a challenging task in construction projects. Failing to properly manage the MEP activities can lead to consuming up to 60% of the total budget, as noted in literature. Previous studies have documented several challenges of MEP coordination; however, they did not focus on understanding different stakeholders' perspectives. Thus, in this research, we have analyzed the challenges of MEP coordination from different stakeholders' perspectives taking the Finnish construction sector as a case. The study employed semi-structured interviews, web-based surveys, and experts' workshops as means of data collection. In addition, we have also analyzed current practices for MEP coordination and presented possible ways to improve the MEP coordination in Finnish construction industries. The results showed significant shortcomings including non-accurate initial design plans, lack of trust between parties, unforeseen MEP cost at early phases, and unavailability of real-time progress monitoring tools. As a contribution, this study presented several challenges, especially in the regional context. Furthermore, this study also analyzed currently used MEP coordination practices in the Finnish construction market and presented suggestions for improvements. The findings of this study will help in the reduction of construction wastes, delays, and cost overruns in construction projects.

KEYWORDS

MEP coordination, challenges, solutions, lean tools

INTRODUCTION

The design and execution of MEP (Mechanical, Electrical and Plumbing) systems, that provide all functionality services to a building, is a challenging endeavour in construction projects. At the definition level, the mechanical systems cover up the heating, the ventilation, and air conditioning (HVAC). The electrical systems mainly include power distributions, smoke and fire alarms, security system, and lighting, and the plumbing system that deals with water supply and wastewater collection (Korman and Tatum, 2001).

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The MEP system is responsible for the building's function that assures the comfort, safety and security of the occupants. During the construction period, they have to be installed in limited spaces and are required to meet constructability, operability and maintainability criteria which create more challenges to the coordination with various other systems in the buildings (Yung et al., 2014; Lavikka et al., 2021). For this reason, several previous studies have considered MEP coordination as one of the grey areas that affect the overall success/performance of building projects (Korman et al., 2003; Tatum and Korman,2000).

The MEP system installation cost may range from 15-60 per cent of the total building project cost depending on the complexity and size of the project (Hassanain et al., 2018). Time wise, installing the MEP systems may use up to 50% of the total duration of the project (Singh et al., 2018). Thus, the implementation of an appropriate MEP coordination system is necessary for the successful completion of the project. The poor coordination system may result in delays, demolition, rework and affects the operation and maintenance phase of the building project (Wan and Kumaraswamy, 2012; Khanazode, 2010).

A significant number of studies have been carried out on MEP coordination. Some studies propose different methods to improve coordination, e.g., virtual design and construction (VDC) (Khaanazode, 2010), building information modeling (Yung et al., 2014) and Mohamad et al., 2014 who suggested modularization and standardization of MEP systems to improve construction performance. Some other studies investigated factors affecting MEP coordination (Hassanain et al., 2018; Jha and Mishra 2007; Alaloul et al., 2016), while the study by Hassanain et al., (2018) presented 36 factors affecting the MEP coordination where the complexity of the project, the experience of the design team and the quality of where top in the list.

The fact that MEP works involves several stakeholders from different trades and contract sides (e.g. main contractor, sub-contractors, designers, project owner, and final customers) complicates the planning, coordination, execution and control of related activities. Even though previous studies have analyzed the MEP works' challenges, they did not fully address different stakeholders' perspectives. For this reason, this research aims to examine the MEP coordination challenges from multiple project parties in the Finnish construction industry. More specifically, this research aims at answering the following questions:

RQ1: What are the key challenges and contradictions in coordinating MEP systems from multiple project parties' perspectives?

RQ2: How stakeholders could make MEP coordination more efficient?

THEORETICAL BACKGROUND

This section reviews the previous studies conducted to investigate different factors that affect MEP coordination in construction projects, mainly focusing on buildings' projects.

MEP COORDINATION PRACTICES: PROBLEMS AND SOLUTIONS

Many parties are involved in MEP coordination process from contractors to owner representatives. All participants have their own interests. For example, general contractor is more concerned about meeting contractual quality and schedule, the owner might have more focus on best quality, budget and schedule. Thus, it is expected that several conflicts can arise among them as every party is focusing on their own objectives not the overall comprehensive project value.

Some studies have been conducted to investigate the factors affecting the MEP coordination processes in construction projects (e.g., Hassanain et al., 2018; Alaloul et al., 2016; Jha and Mishra, 2007). These studies mostly emphasized the complexity of building systems, limited budget, installation schedule and limited building space as the major challenging factors for the MEP coordination. Table 1 presents the major problems mostly cited in the literatures.

Table 1. MEP coordination problems mostly cited in literature

Problems	Explanations	References
Hurried schedules	Construction companies involved in several projects at the same time are usually characterized by hurried schedules and overload for professionals	Hassanain et al., 2018
Low budget for the project	While recruiting professionals for the construction project cost is a major determining factor. Experience and skills of the professional matters much while implementing the project.	Pennanen et al., 2011
Unclear architectural plans	Sometimes needs and requirements of the client are difficult to understand, and it may lead to challenges while creating a clear architectural plan	Hassanain et al., 2018
The design complexity of the MEP systems	While aligning MEP system into the structural system of the building several challenges need to be considered including MEP component route, component location and equipment requirements.	Lee et al., 2015
Increase in safety requirements	The recent trend of constructing complex buildings, such as high-rise buildings, has increased the safety requirements. Such as distribution of electrical energy, communication, water, waste disposal and safety of users	Korman et al., 2010
Inadequate space allocated	MEP installers are usually required to install MEP system	Korman et al., 2003
Owner's unclear requirements	Sometime owners are unclear about their needs. Their requirements can change in the later phase of the project.	Korman et al., 2003
Communication skills of the design team members	Effective communication skills is necessary while delivering and sharing of information during coordination.	Hassanain et al., 2018

The project delivery system adopted for the building project	Recent Integrated Project Delivery are more efficient as it allows involvement of all stakeholders during the life cycle of projects and thus improves the coordination process	Hassanain et al., 2018

To resolve the MEP coordination problems, previous studies have presented several practices. Majority of the approaches are focused on pre-installation phases–mostly, they suggest improvement using BIM (Building Information Modelling) tools. Major approaches discussed in the literature are presented in table 2.

Table 2. MEP coordination practices

Practices	**Explanation**	**Sources**
BIM with laser scaning	Automated geometric quality inspection using 3D laser scanning	Guo et al., 2020
Clash analysis framework	The framework provides a formal process for clash management and reuse of the knowledge.	Wang and Leite, 2016
Intra-inter teamwork concept	Partnering concept for interdependent work phases of trade and across interdependent MEP trades	Wan et al., 2012
Sequential coordination strategy	The coordination process in sequence resulted three times faster than the parallel coordination process.	Lee et al., 2014
Heuristic Reasoning	Helps to determine and resolve coordination conflicts by abstracting measurable data and relating it to a predefined potential problem.	Korman et al., 2003
BIM-based approach to automate the MEP coordination	MEP rule-based automated engine also called Autoroute is using Revit Application Programming Interface (API) tool.	Lu and Wong, 2019
Framework for BIM-based MEP layout design and constructability	This framework provides process for integrating the MEP layout from preliminary design to construction stage	Wang et al., 2016

METHOD

The overall approach to conducting this research is presented in figure 1. The literature review was conducted to create an overall picture of the topic. While reviewing the literature, we emphasized on lysing the factors that affect the MEP coordination, challenges, and solutions to improve the MEP coordination.

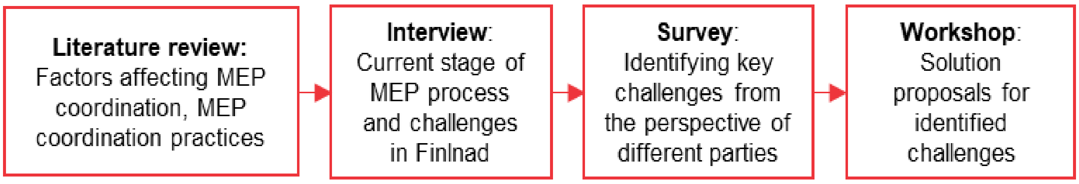

Figure 1. Research framework of the study

According to Dumas and Salzman (2006), the semi-structured interview is the best method of getting detailed or voluminous information. So, in this research, we interviewed: 3 MEP designers, 2 structural designers, 3 main contractors, 1 MEP specialist, 4 MEP contractors and 3 installers. The interviewee had experiences from different kinds of projects, e.g. hospitals, schools and housing projects. The semi-structure theme mainly focused on currently adopted MEP coordination practices in Finland, MEP coordination challenges and possible solutions.

Based on the interviewees' responses, a web-based survey was conducted to find out how significant the challenges discussed during the interviews are. For this, we have sent survey forms to various MEP stakeholders. In total, we have received 384 responses.

An expert workshop was conducted to discuss in detail about challenges with the current MEP coordination practices which were identified in interviews and surveys. A total of 41 experts participated in the workshop and they suggested several recommendations to improve the MEP coordination practices in Finland.

RESULTS AND ANALYSIS

A semi-structured interview with various MEP stakeholders was conducted. Themes of interview questionnaire were mostly focused to identify the current situation of MEP in the Finnish construction market. Table 3 presents the views of several stakeholders regarding the Finnish construction industry.

Table 3. Stakeholders' views of MEP coordination in Finland

MEP stakeholders	**Positive factors**	**Challenges/ Factors to be improved**
MEP consultant/design office	Adoption of alliance model: it makes actors think about common goals, implementation of prefabrication elements, utilization of software	Skilled designer is needed, too much additional work for MEP contractors, Involvement of MEP contractors in design phase, schedule management program could be developed, prefabrication should be decided in early phase, bonus could be provided if task is completed beforehand, BIM does not have a design standard that could be used for maintenance.

MEP contractors	Contractors are involved in the design, regular MEP contractors’ meetings	Biding shouldn't focus only on the price, more time is necessary for the planning, collecting agreement shouldn’t guide design choices, test period is too short,
Main contractor	Implementation of prefabrication is increasing, big rooms, last planner system, congrid software are being used	The contractor should be involved at an early stage. Alliance model should be developed- price shouldn’t be the only factor to be considered, People have not much experience with prefabrication, partners should be consulted in scheduling, additional and modification work is employment and should be reported early, the flow of information from real-time site should be developed,
Structural designer	Involvement of contractor in the design stage,	Younger designers cannot read the drawings but can only study the model, regular meeting with MEP designer is needed, better alignment of MEP design to structural design is needed.
MEP designer	Adoption of TVD process: the operating model is coordinated together, implementation of last planner system	Collective agreements should not control design options, preliminary plan should be improved, the method should be developed to get accurate initial data

All the interviewed MEP stakeholders were positive about the practice of the alliance model where all the project parties will share the risks and rewards of the project. Also, some reviewers mentioned that the involvement of the MEP contractors in the planning phase is a positive change. Other factors such as the implementation of lean approaches, such as prefabrication, last planner system and Target Value Design (TVD) process were the positive factors in the Finnish construction market. On the other hand, interviewees mentioned several factors that could be improved. For instance, improvement of schedule management program, collective agreement that restricts the innovation, skills of the worker and involvement of contractor in an early phase.

To get deeper insights into more factors during the semi-structured interviews, we conducted a web-based survey with the same theme as it was used in the interview. The survey collected views from respondents on multiple-choice questions, and in addition, each section included an open-ended question for comments and clarification. We received responses from 384 experts. Most of the respondents had worked in the construction industry for over 15 years. After analyzing the survey responses expert interview responses, the major challenges and the currently used practices in the Finnish construction market are presented in table 4.

Table 4. Challenges and current practices of MEP coordination in Finnish construction market

Challenges	Current practices
❑ Shorter project schedule	❑ LPS
❑ Innovation restrictive collective agreement	❑ Big rooms
❑ Over workload for designers	❑ Congrid: Construction solutions
❑ People to people communication during installation	❑ Implementation of prefabricated products
❑ Availability of real time progress simulation software	❑ BIM
❑ Determination of MEP cost at the beginning	❑ Kotopro: A documentation tool
❑ Less accurate initial plan/design	❑ Teams for meeting
❑ Lack of trust between parties	❑ Scrum thinking
❑ Lower budget for the design	
❑ MRL-maa rakennus laki (Land utilization act)	❑ A system dynamic model

Majority of the identified challenges in the Finnish construction sector were similar to previously identified challenges in other geographical locations. However, some challenges were new or unique. For instance, some provisions of the Land Utilization Act were unique in the Finnish context, as it dealt with the physical, chemical, and microbial condition of the building. Also, availability of real time progress simulation software, and unforeseen MEP cost at early phases were identified in the Finnish construction sector.

After analyzing the current practices and challenges, an expert workshop was organized to produce concrete development suggestions for MEP stakeholders. Overall, the workshop suggested nine recommendations. These could be classified into three categories: Project planning phase, MEP design phase, and production planning and control phase. There are presented in table 5.

Table 5. MEP coordination improvement suggestions for stakeholders

Project planning	MEP design	Production planning and control

1. More detailed analysis of MEP installation skills during project development stage	4. Planning and adapting the planning schedule to other project tasks	7. Involvement of the MEP Contractor in site scheduling
2. Emphasis on quality, competence and project objectives in the procurement of MEP contracting	5. Differentiation of design for procurement and implementation as needed	8. Better methods for assessing and communicating the wide-ranging effects of change
3. More balanced and transparent MEP contractor selection	6. Increase in implementation of prefabrication	9. Employee-driven digital applications for change management and scheduling

DISCUSSION

Some previous studies have also analysed the MEP coordination problems in construction projects in different geographical locations (e.g., Hannanain et al., 2018; Alaloul et al., 2016; Monsberger & Fruhwirth, 2018). Most of the challenges in the Finnish construction market identified in this research were the same as previous researcher has identified, such as long project schedules, work overload for designers and lack of sufficient skills of MEP installers. However, some challenging factors identified in this research, such as, land acquisition act, unavailability of real time progress monitoring tools and unavailability of accurate MEP cost estimation tools especially in the high buildings were not indicated in the previous studies.

To improve the MEP coordination system, several approaches are presented in previous studies (e.g., Mohamad et al., 2014; Wang et al., 2016; Guo et al., 2020). They mostly emphasised in the pre-installation phase, such as, BIM based approach to automate the MEP coordination, BIM with laser scanning and clash analysis tool in BIM modelling. Very little attention has been given for installation phase. In Finnish construction market BIM with all updated tools are implemented. In addition, to improve MEP coordination during the installation phase, several lean tools are applied such as, big room, LPS and prefabricated products.

However, currently adopted methods were not sufficient to resolve all the MEP coordination related problems. To analyse the causes of problems and make recommendations for improvements, we organised the expert workshop. Based on the workshop the major causes of MEP coordination could be categorised to: (a) Changes in plan during implementation (b) lack or late decision making on MEP services, and (c) Insufficient coordination between the implementation and procurement of MEP systems. Also, workshop made several recommendations for stakeholders to improve the MEP coordination which could be divided into three categories: 1) increasing stakeholders' cooperation, 2) changing processes and practices, and 3) utilizing technologies and product development.

CONCLUSION

The aim of this study was to identify the major challenges and contradiction of MEP coordination in Finnish construction market, analyse currently adopted solutions and present suggestions for further improvement.

The major challenges of MEP coordination in the Finnish construction sector were, among others, a certain level of confusion caused by the Land Utilization Act, unavailability of real time progress simulation software, and unforeseen MEP costs at early phases of construction projects. For instance, the Land Utilization Act was unique in the Finnish context, as it dealt with the physical, chemical, and microbial condition of the building, and its thorough implementation was considered a challenge, at least initially. The availability of real time progress simulation software and its accuracy were also issues of concern. Similarly, unexpected MEP costs also put financial burden on construction projects. Our study shows that to avoid these challenges, stakeholders needed to improve the inter-intra cooperation, needed to change the process and practices and implementation of new technologies and product development.

Several respondents in this research indicated the lack of real time work progress tracking tools, so further research could investigate the development of this reality capture technologies. Also, it is discussed that prefabrication is being implemented in a slow progress in the Finnish construction market, and previous studies have not given enough attention to identify the benefits of prefabrication connection with the MEP coordination. So, future research could analyse the impact of prefabrication for better MEP coordination system. As a limitation, this this study highlighted the challenges of the whole construction sector but did not analyse challenges considering from the building types or HVAC system. Future research could further investigate the MEP coordination challenges based on different building categories, e.g., hotel projects, hospitals and schools.

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EXPLORING THE USE OF DIGITAL VISUAL MANAGEMENT FOR LAST PLANNER SYSTEM IMPLEMENTATION

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ABSTRACT

The Last Planner system has been widely implemented seeking to offer greater transparency and predictability for construction projects through collaborative production planning. A major challenge in this context is increasing process transparency, which is one of the visual management (VM) purposes and a basic principle of the Lean production philosophy. Achieving this has required extrapolating the limits of the physical environment through the use of digital tools, which lead to the digitalization of VM and to virtual collaboration. This process was accelerated due to the COVID-19 context, the physical boundaries constraints, and the need for real-time information sharing and collaboration. This paper aims to explore and discuss the use of digital VM tools for LPS implementation. Action research was the methodological approach adopted in this research. The investigation was based on a consultancy in a construction company in Brazil. The digital VM tools and practices adopted in the different planning levels were assessed through requirements considered relevant to this context, including visual and non-visual aspects. Their impact in collaborative production planning is discussed. The ongoing results indicate that digital tools were better suited to the strategic and tactical levels, while traditional tools showed more suitable for the operational level.

KEYWORDS

Last Planner® System, Visual management, Collaboration, Digitalisation, Miro

INTRODUCTION

Last Planner® System (LPS) is one of the main tools and methodologies used for the implementation of Lean Construction. Developed by Ballard and Howell in 1992, LPS is a collaborative planning methodology for production control in construction projects. LPS makes detailed plans by those who execute the work, including all hierarchical levels of the project, seeking to reduce waste and increase planning and workflow reliability (Ballard and Tommelein, 2016). This methodology proposes workflow control with a planning system that tells what should-can-will be done in different planning levels, continuously learning over the production process (Ballard, 2000).

LPS employs Visual Management (VM) to provide a structure for collaboration and coordination of information in the planning levels in a transparent way (Erazo-Rondinel

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et al. 2020). VM is an important management strategy and a fundamental element of Lean Construction that creates highly visual information fields from which people can pull information for an improved self-management and control (Tezel et al. 2013). The purpose of a visual control for a production system is to provide clear visual indicators depicting the status of the system at an appropriate level for the audience to achieve shared understanding so that necessary actions can be taken (Ballard and Tommelein, 2016).

Traditionally, LPS is implemented through the concept of "Big Room", also known by the Japanese word “Obeya”, where collaborative planning meetings are held, milestones plan, pull sessions, weekly meetings, and daily stand-up meetings (Pons, 2019). For this, post-its, whiteboards and colorful pens are used to facilitate VM.

From 2020, the onset of the COVID-19 pandemic has forced production environments (the construction domain included) to become more sensitive regarding the safe working environment (Stiles et al., 2021; Wu & Wang, 2020), leveraging and valuing the use of digital technologies in construction. Recently, some traditional VM tools and Lean Construction techniques have been converted into IT-based prototypes (Sacks et al, 2010a; Dave et al, 2014) in order to fulfil this digitalization demand. Also, Lean construction and VM have been supported by the actively use of IT tools that collect construction field data (Barbosa et al. 2013, Kirchbach et al, 2014) and increase the quality of data (Dave et al. 2008), providing up to date information about the construction sites. However, this process of migrating from traditional to digital approaches can bring challenges in maintaining the operational requirements of the tools. In this sense, the VM role of continually communicating with all participants in a visible and comprehensible way (Koskela, 2000; Formoso et al. 2002) should be maintained in digital tools.

The main objective of this paper is to explore the use of digital VM tools through the implementation of the LPS. It describes the process of Lean Construction implementation in a housing construction company in Brazil in 2021 during the Covid-19 pandemic period, where traditional and manual tools were replaced by digital VM tools. These digital VM tools were assessed toward several existing requirements from the literature. The benefits and challenges of its implementation were identified, considering a scope of analysis that was limited to the construction phase of housing projects.

VISUAL MANAGEMENT

VM can be defined as a management system that attempts to improve organizational performance through connecting and aligning organizational vision, core values, goals, and culture with other management systems, work processes, workplace elements, and stakeholders, by means of stimuli, which directly address one or more of the five human senses - sight, hearing, feeling, smell and taste (Liff and Posey, 2004; Tezel et al. 2009). These stimuli communicate quality information such as necessary, relevant, correct, immediate, easy-to-understand, and stimulating, which helps people make sense of the organizational context at a glance by merely looking around (Greif, 1991).

Tezel et. al (2016) defined the main purpose of VM as increasing process transparency to promote improvements in the production systems and the overall management of organizations. Process transparency can enable decision-making by supporting increased employees’ participation and involvement in the process (Klotz et al. 2008). Visual approaches can support information accessibility, availability of real-time data collection and processing (Dallasega et al. 2018), and help to improve the understanding of schedules through the availability of information (Tezel and Aziz 2017).

The use of digital technologies in construction are bringing new opportunities regarding the capture, test, verification, and validation of information, as well as the support of management, construction, use, operation, and maintenance processes (Chen and Kamara 2008; Tezel et al. 2016; Koskela et al. 2018). The high level of information transfer in construction project management is a major challenge even with technological developments. Keeping information simple, straightforward, and accessible is at the heart of reliable planning (Tezel and Aziz 2017). Digital technology has contributed to extending the range of VM applications, improving (a) visibility by improvement of interface innovations; (b) temporal capacity by greater information gathering, storing, and analysis; (c) problem-solving capabilities due to the automation of information processing, and (d) geographical capacity through high connectivity (Murata 2018).

Constructs related to the adoption of Digital VM systems are presented in the literature in a dispersed way. However, Pedo et. al (2020) propose and discuss a set of digital VM constructs in a design management environment. The scope of the analysis was limited to highways and railways design projects. The constructs are: (i) simplicity of functioning; (ii) information standardization; (iii) autonomy to plan and control; (iv) right amount of information available; (v) easy information accessibility; (vi) flexibility; (vii) information traceability. Those constructs were adapted to the context of the present research in order to assess the digital VM tools used in a LPS implementation and will be better discussed throughout the paper.

RESEARCH METHOD

The investigation was based on a consultancy project undertaken under an eight months period in a construction company in Brazil, named Company A. Company A is a real estate and construction company based in South Brazil with 19 projects under development, which consist of 5.965 residential units. The company has been proposing a transformation of the organizational culture through the development of a Lean-based Production System and consistent, sustained efforts on innovative and digital projects. In this context, Company A started a Lean implementation with the Consultancy Company based on pilots implementation in 2021. The pilots were mapped to assist four construction sites built in conventional construction methods - concrete structure and mortar. The four low-income housing projects have similar characteristics, including location, number of buildings and apartments, and units' area. This research consisted of a critical analysis of the digital VM tools implemented in Company A to support LPS implementation in different planning levels.

Action research (AR) was the methodological approach adopted in this investigation. AR focus is on solving real problems (O'Brien 1998) and contributing to the organization's development, focusing on simultaneous action and research in a collaborative manner (Coghlan and Brannick 2001). According to O'Brien (1998), AR is adopted when circumstances require flexibility, involvement of the client, or change must take place quickly or holistically. The research was conducted through multiple iterative cycles of diagnosis, planning action, taking action, and evaluating action (Figure 1), with different levels of complexity (Coghlan and Brannick 2001), regarding different planning levels. This structure follows the cyclical, iterative, and repetitive nature of AR.

The study was divided into five cycles (Figure 1, Table 1). The first cycle, **Current State**, was held before starting with the LPS implementation in order to understand and analyze the deficiencies in the current production process context in the company. The findings were prioritized by the clients to define the next steps and actions. **Cycles 1, 2, 3, and 4** describe the LPS implementation in four construction sites, or pilots, and the digital VM tools used in the process. Those were held in four weekly AR cycles each of diagnosis (D), planning action (PA), taking action (TA), and evaluating action (EA), based on AR approach (Coghlan and Brannick 2001) and common to Plan-Do-Check-Act (PDCA) cycle (Shewhart and Deming 1939).

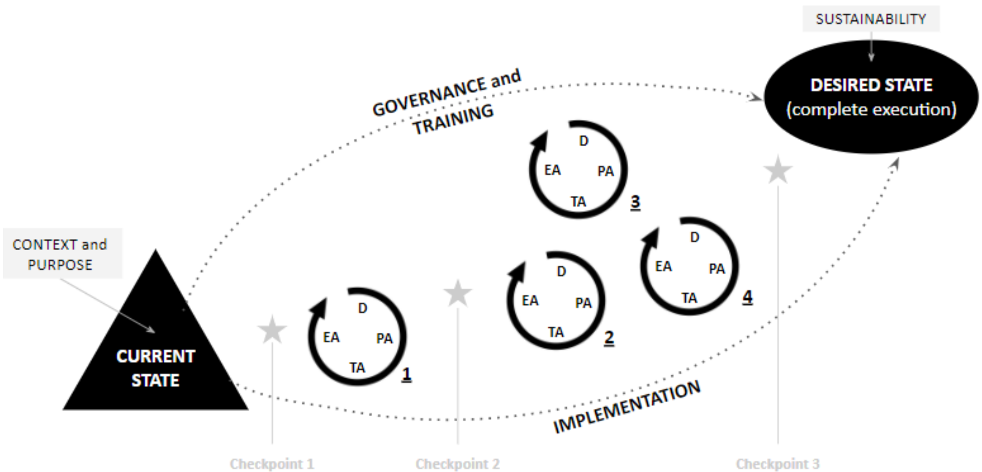

Figure 1: Multiple iterative cycles of AR, based on Coghlan and Brannick (2001).
Legend: Diagnosis (D), Planning Action (PA), Taking Action (TA), Evaluating Action (EA)

Each cycle of implementation was improved by applying the lessons learned and avoiding the mistakes made in the previous cycle. Throughout those cycles, an online training course and "knowledge drops" through classes in the construction site were held in order to change traditional patterns that were not aligned to the Lean Construction philosophy. This cyclic process in each pilot was repeated until achieving the understanding of the LPS and changing old patterns. The general goal was to create a simple, repeatable process of iterative learning, evaluation and improvement that would lead to increasingly better results for the practitioners, such as predictability, financial health, physical progress adhering to the plan, collaboration and motivated team.

Check-points were realized (Figure 1) in the company following Coghlan and Brannick (2001) recommendations of (a) systematically generating and collecting research data about the ongoing system; (b) engaging with others in reviewing the data generated and collected; (c) conducting a collaborative analysis of the data; (d) planning and taking collaborative action based on shared inquiry; and (e) jointly evaluating the results of that action, leading to further planning. Lastly, the adoption of digital VM tools and practices in the different planning levels to support the LPS implementation was evaluated through requirements developed by Pedó et al. (2020). Their impact in collaborative production planning were discussed.

Data was collected using multiple data collection techniques: (i) document reviews; (ii) 16 semi-structured and follow-up interviews with the main ten company departments; (ii) participatory and non-participatory observations attending all the implementation stages of LPS; (iv) individual and group discussions; and (v) plus and deltas. Using multiple sources of data and combining methods, as well as multiple projects, strengthened the AR study (Patton, 1990) and reached methodological triangulation. The results of these research phases were important for the consultants and researchers regarding the understanding of the company and their planning and control routines. The triangulation method supports the decisions and premises that were considered as ground for the current paper.

Table 1: Classification of tools in Traditional and Digital approaches

Phase	Tool	Diagnosis	LPS implementation			
		Current State	Cycle 1	Cycle 2	Cycle 3	Cycle 4
Duration (weeks)			6	4	4	4
Context	Swimlane	T -> D				
	Findings prioritization	D				
Should	Sequence activities	D	T	T	T	T
	Line of Balance	D	T	T	T	T
Can	Lookahead		D, T	T	T	T
Will	PPC		T	T	T	T
Will / Did	Check-in		T	T	T	T
Did	Check-out		T	T	T	T
Continuous improvement	A3		D	D	D	D
Governance	Plus and Deltas	D				
	Agenda	D				

Legend: Traditional (T), Digital (D)

PROJECT PHASES

DIGITAL VM TOOLS ADOPTION IN LPS IMPLEMENTATION

The work structuring of the Lean Construction implementation in the company included a diagnosis followed by the LPS levels of planning, based on should-can-will-did (Ballard and Tommelein 2016): (i) master planning, used to set milestones and phase durations; (ii) lookahead planning, when constraints are identified and removed; (iii) commitment planning, in which promises are make reliable; and (iv) learning, using five whys to identify countermeasures, and act to prevent repetitive errors. The diagnosis is related to the **Current State**. The implementation of LPS levels of planning refers to **Cycles 1, 2, 3,** and **4**. A set of tools were used and refined in each of those phases in different projects to support the meetings, seeking to provide an environment that supports collaboration, employee engagement, and information management between the different planning and hierarchical levels of the construction sites. Before Covid-19, those tools had a mostly traditional approach, such as worksheets and manual boards on the walls with post-its.

The diagnosis (**Current State**) in company A was planned in five steps (Figure 2), including the main sectors of the company. **Workshop 1**, mapping the company's process through a Swimlane, was carried out in large panels with post-its. Swimlane diagram is conceived for process modeling, connecting a series of steps and concerns in pools and lanes in order of occurrence by the participants. Due to the risk of Covid-19 contamination and the geographic distance of some key members, the coordination defined that the next workshop should be held remotely. The consultancy company transferred the information from Workshop 1 to a digital version in MIRO and adjusted **Workshops 2** and **3** for the same context. MIRO (www.miro.com) is an online collaborative whiteboard adopted to facilitate the virtual and digital collaborative dynamics. This was the abrupt moment of change from traditional to digital due to the emerging needs of the context. The company quickly adapted to MIRO, with great team engagement. A specific blank board was sent before the official boards in order to introduce Miro and allow the team to test its functionalities for five minutes. This simple action accelerated the team's learning and avoided mistakes on the official board.

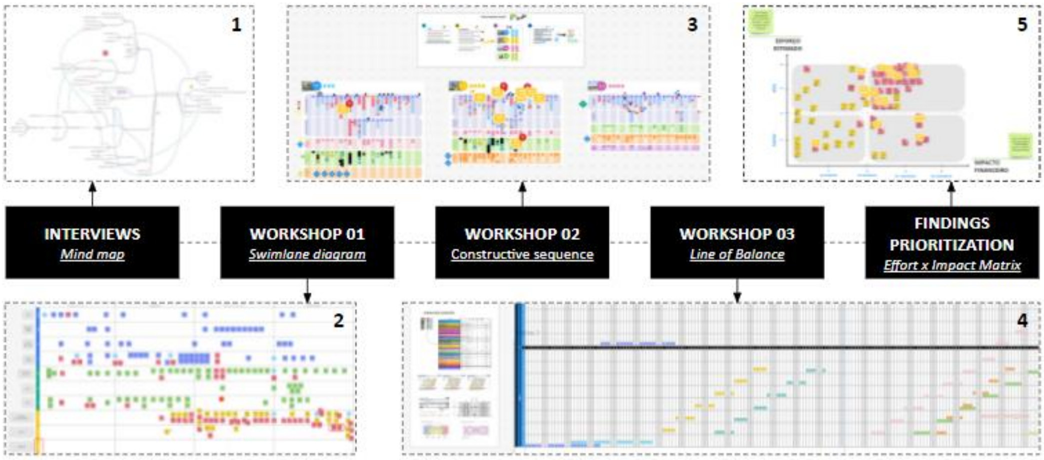

Figure 2: Digital VM tools from Diagnosis - Current State

A **findings prioritization** meeting was conducted with the different sectors in order to collaboratively design the results of the diagnosis, bringing a sense of ownership to employees and company's directors regarding the consultancy's interventions. The tagged post-its with opportunities for improvement should be positioned by the groups in real time in a matrix of financial impact versus estimated effort. The discussions resulting from this meeting served as the basis for defining the objectives and the next steps of the LPS implementation in the company.

Cycle 1 of the LPS implementation phase was carried out in the same construction project that served as the basis for the workshops (WS) 2 and 3 of the Diagnosis. Considering that the collaborative, digital and educational phase of the constructive sequence (WS2) and the line of balance (WS3) occurred in the diagnosis using MIRO, Cycle 1 ended up using traditional spreadsheets to test all possible scenarios for the line of balance and to define the pattern of the constructive sequence of that product. This process took two weeks to reach an adequate solution since it was the first pilot in the company and the product and construction standards were not well established yet.

Lookahead planning (Figure 3), with a twelve-week horizon, was built digitally for the first time using MIRO. All team members had access to the digital tool and could include constraints as they were identified, from anywhere. Implementing this weekly routine was challenging as the company did not have an established culture of anticipating problems and the young team had limitations in identifying possible restrictions. The constraints analysis and removal, breaking down tasks into operations and collaboratively designing those operations, was another weekly meeting realized in traditional spreadsheets in order to control performance metrics. Short-term planning tools were implemented in traditional spreadsheets and dashboards. **A3** tool, used for the improvement of some critical processes, was developed in MIRO, allowing all team members to access the digital tool all the time and track, record actions. **Cycles 2, 3,** and **4** had a similar structure, with the adaptation of the Lookahead planning from digital to traditional approach. In terms of governance, the recurring feedbacks with the team through the **Plus and Deltas** and the weekly **Agenda** were conducted in MIRO and were easily accessed and updated by lead members of the project. Although the tools maintained consistency and standardization throughout the cycles, each project went through its own stages respecting the uniqueness of each site development and team and promoting continuous improvement through transparency and collaboration.

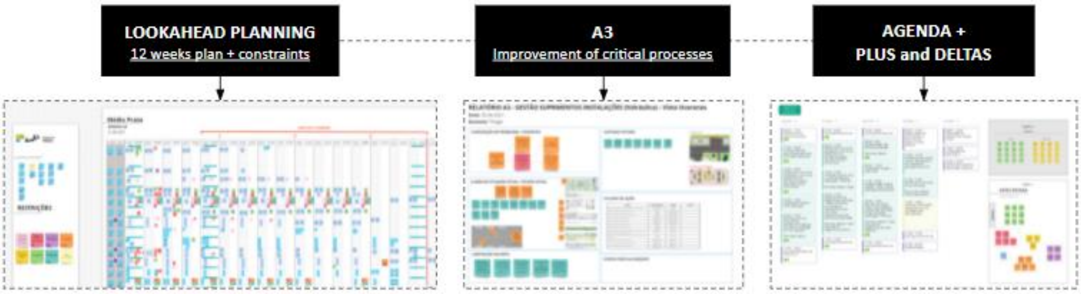

Figure 3: Digital VM tools from Cycles 1, 2, 3, and 4

RESULTS AND DISCUSSIONS

The use of MIRO and the digitalization of the workshops were the main Plus cited by the participants, highlighting the ability to make the meetings and discussions faster, keeping information and people organized, and its ease of use. Participants also mentioned the clear definition of the workshops' script and objectives, which were available for consultation throughout the meeting, in addition to the use of colors in the VM to help groups during the activities. The digital and virtual meetings carried out in MIRO with the support of parallel virtual rooms promoted the collaboration of a diverse group of employees from different locations. Furthermore, they facilitated the information to be quickly delivered and organized through friendly graphics, accessible and open to the participants who sparked their curiosity on the subject (Tufte, 2001). The tools started to be associated by the employees with learning initiatives and moments of reflection, helping to build communication rituals on the team. When it happens, the tools become important to people and relevant to the process (Valente, et al., 2019).

A Delta cited by the participants was the lack of automation of information between planning levels, with a manual pull of activities from the long to the medium and short terms. In this sense, the digital VM tools can be better explored in the company by the improvement of problem-solving capability considering the automation of information processing (Murata 2018).

The implementation of the digital VM tools was discussed and assessed by the authors based on constructs proposed by Pedó et al. (2020) for the design management phase, adapted to the operations phase context. Table 2 shows the classification of tools according to those constructs based on three levels of adoption (PEDÓ et al., 2020): adoption (A), partial adoption (PA), or non-adoption (NA). The four construction sites had a similar response regarding the VM tools implementation. The tools used in the Diagnosis, for Continuous Improvement, and for Governance can be classified as the most advanced as they adopt most part of the VM concepts (Table 2). In other respects, the tools from the four learning cycles of the LPS implementation planning phases lack the full attendance of almost all VM concepts, such as simplicity of functioning and easy information accessibility. Employees mentioned in the discussions and Plus and Deltas the simplicity of functioning, flexibility and communication as Miro main advantages, and automation as its main weakness.

The full adoption of the **Easy information accessibility** VM concept was not identified in any digital tool due to the lack of visual devices such as computers or television dedicated to an Obeya Room. This is harmful to achieve decentralizing decisions and to increase the degree of autonomy among production teams, indicated by Valente, et al. (2019) as a guideline for designing and implementing VM systems. In contrast, all tools had this concept partially adopted, showing its potential in this aspect with regards to geographically decentralized teams.

Table 2: Classification of applied digital VM tools according to VM concepts, based on Pedó et al. (2020)

Phase	Tool	Simplicity of functioning	Information standardization	Autonomy to plan and control	Right amount of information available	Easy information accessibility	Flexibility of tools	Traceability of information
Diagnosis	Swimlane	A	A	A	PA	PA	A	A
	Findings prioritization	A	A	A	A	PA	A	A
Diagnosis/ Should	Sequence activities	A	A	A	PA	PA	A	PA
	Line of Balance	NA	PA	PA	PA	PA	A	PA
Can	Lookahead	PA	PA	PA	PA	PA	A	A
Continuous Improvement	A3	A	A	A	A	PA	A	A
Governance	Plus and Deltas	A	A	A	A	PA	A	A
	Agenda	A	A	A	A	PA	A	A

In the case of the **Lookahead** digital tool, the traditional format had a more satisfactory result. The first learning cycle started by using a digital Lookahead in MIRO and changed to the traditional tool after six months of Lean Implementation in Company A. A positive aspect of the digital version was the possibility of sharing the link with other construction project teams to start getting familiar with the tool before the beginning of its learning cycle. Table 2 shows that Lookahead had five to seven VM concepts partially adopted. The same could be observed regarding the **Line of balance** digital tool. Six to seven VM concepts were classified as partially or non-adopted. During the diagnosis, this tool was carried out at the MIRO and helped also with the preliminary decisions regarding the constructive sequences and the activities packages definition. The traditional format was adopted for the implementation phase due to the challenges related to the simplicity of functioning. Company A has analyzed the implementation of this tool on a Web platform, seeking to fulfill more requirements. This analysis was not the scope of this work.

Throughout the learning cycles, the importance of having the information available on the walls close to the crossing path of different hierarchical levels became evident. By fixing on the wall the traditional tools of the learning cycles phase, such as line of balance, lookahead, and check-out, collaboration and autonomy regarding planning became more spontaneous, not being restricted to routine meetings. In addition, this format was key to supporting the understanding and engagement of the operational-level employees in implementing the LPS planning levels, contributing to the adherence and spontaneous construction of a lean culture in the company. The employees gathered around them to check and discuss their daily productions and compare them with other teams, and a routine of continuous improvement between the company and partners was built. Stopping in front of a board, even for a few minutes, is strong evidence that the visual device is useful (Valente et al., 2019).

The **right amount of information available** was another VM concept with limited adoption by the digital tools. This can be related to the MIRO challenges in fulfilling the VM concept of easy information accessibility and to its limitations in data processing, seeking to develop indicators. This VM concept is related to the waste of visualization in digital environments (Murata 2018), and to the lack of directed focus, when the structure of a visualization doesn't draw attention to the issue at hand (Eppler and Bresciani, 2013). According to Pedó et al. (2020), the excess of information available can result in difficulties to find and select, i.e. prioritize the information needed and, consequently, affecting the team engagement with the tool and creating barriers to access the information. Some practices were used to reduce the effect of the overload of information, such as visual signs, use of colors and arrows, step-by-step instructions, among others. These mitigations seem appropriate for the employees that use the digital tools to support the collaborative meetings on a weekly or daily basis. However, considering the other hierarchical levels, dashboards bringing the main results and their respective impact could be incorporated into the company's routine. Dashboards could also help to increase the adoption of easy information accessibility' VM concept.

Considering dashboards analysis, it was observed that variations in indicators may suggest distinct abilities to identify restrictions and a lack of **standardization** in the conduct of the LPS methodology and tools development. The digital tools used for continuous improvement and governance had this VM concept fully adopted due to its characteristics of having their information divided into independent and non-cumulative information or work packages, such as **Agenda** and **A3**. **Plus and Deltas** was always associated with another digital tool, allowing the traceability of information.

Although the **Swimlane** was held in a traditional format, its digital version was extensively used as a basis for discussions throughout the following workshops. The information, with particular reference to the problems or improvement opportunities, was revisited along the journey in order to remember the context and purpose of the project and to compare it with the desired state. Traceability and the easy access were of great value as they helped the team to achieve directed focus on the issue at hand.

The digital tools were better suited to the strategic and tactical levels; at the operational level the tools were mostly traditional. This can be explained by the greater detailing of activities and the importance of assessing performance and control indicators at each planning level. In this sense, the limitations of MIRO led to the adoption of traditional tools at the operational level, since most of the assessed constructs were not achieved in the digital one. Furthermore, the closer to the operational level, the further into the construction site the information is. Therefore, the implementation of digital VM at the construction site presented limitations (Murata 2018) in terms of cost, equipments' safety, availability of information, internet connection, among others. Advanced practices that support production are expected to be located close to their place of use, in order to facilitate their access by the user (Tezel et al., 2009).

The main benefits from the use of digital VM tools through MIRO identified over this exploratory research can be summarized as follows: (i) allowed the collaboration during COVID-19 and between geographically decentralized teams; (ii) increased process transparency on strategy and long-term planning levels; (iii) eased communication between different hierarchical levels and between construction sites, enabling autonomy of learning; (iv) facilitated the information to be quickly delivered, organized and connected with friendly graphics, enabling the team to become more engaged and autonomous; and (v) helped to tell the implementation story as information can be recorded and presented on a single endless board with high editing flexibility. Conversely, the barriers were: (i) a fragmented flow of information between planning levels; (ii) limitations in the development and analysis of performance indicators; (iii) limitations in standardizing information, such as the use of drop-down lists or error-proofing devices that assist in building a database to be used in decision making and continuous improvement; and (iv) unavailability of information regarding long, medium and short term planning tools into the operational level and at the construction site office, restricting the spontaneous continuous improvement of the planning to the routine meetings, as the tools were not available all the time for the team to stand in front of it and collaborate.

CONCLUSIONS

This exploratory study discusses a LPS implementation held in four pilot projects during COVID-19 that had its methodology abruptly adapted from traditional to digital tools using digital and collaborative tools. The full digitization of VM tools did not suit all the phases of the LPS implementation in Company A. Visual devices that do not reach their potential in the digital environment and lack most of the requirements discussed in this paper can coexist in a traditional format with digital VM tools or in hybrid formats. The results indicate that (a) digital VM tools seemed more suitable for the strategic level of planning and for the governance of the project, as it’s shown in Table 2, considering Swimlane for Process Mapping and the Sequence Activities for Master Planning, while (b) traditional VM tools showed a better response to the tactical and operational levels, as discussed on previous sections about the Lookahead Planning on Traditional tools. In this sense, there is a challenge regarding the integration of digital and traditional tools in order to achieve automation and a better flow of information between planning levels.

The discussed tools are not meant to solve individual problems but support the implementation of a methodology for managing construction sites and improving processes. In this regard, seeking ways to integrate them and to fully adopt VM concepts discussed along this paper seems essential to reach better results. Remote collaboration, communication between hierarchical levels, and the quality of the information’ register and organization were the highlighted benefits. The main gaps that must be addressed in the digital tools were the limitations on developing and analyzing performance indicators, the challenges on standardizing information, and its negative impact on generating databases that support decision-making.

Some limitations of this exploratory study are: (i) MIRO as the only tool used throughout the LPS implementation by the consultancy company; (ii) the use of VM concepts from a design management context. The discussion of the tools in the context of building execution showed that automation and communication are central themes for a broader analysis of their implementation, discussing digital versus human-centered approaches. Future research may (i) assess the global results for the four construction sites at the end of the execution phase; (ii) investigate their relation with the constructs proposed by Pedó et al. (2020); and (iii) explore MIRO plugins and other tools, e.g. MURAL and Google Jamboard, seeking to achieve higher automation, performance indicators, information availability and standardization. Consultancy and construction companies can benefit from these discussions regarding the adoption of traditional and digital tools in a LPS implementation.

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LEAN PUBLIC CONSTRUCTION IN THE PROJECT DEFINITION PHASE: THE CASE OF PERU

Guillermo Prado Lujan[1] and Danny Murguia[2]

ABSTRACT

Public construction in developing countries is characterized by a lack of quality design information, poor front-end engineering studies, fragmented procurement, and financial obstacles. As a result, projects exhibit major delays, cost overruns, and contract resolution during construction which end up in failed projects. These issues cause dramatic losses in value for end-users and society. Current literature suggests that the main issues in public construction are rooted in the strategic definition, briefing, and concept design. To tackle these problems, the current research will focus on understanding the value-generating principles of public construction at the project definition phase by using the Lean Project Delivery System (LPDS). The methodology in this research is inductive and based on qualitative data. The case of Peru was used as a case representing a developing country. The findings show that the value-generating principles for public construction are end-user consideration, asset functionality, transparency, efficiency, predictability, and efficacy. However, the institutional pressures both enable and constrain public managers' ability to deliver the expected outcomes and value. This represents a great opportunity to deploy lean methods at the beginning of the project to improve transparency, collaboration, and drive innovation. Future studies can develop a lean-enabled framework for public construction and scrutinize the constraints for value generation.

KEYWORDS

Lean construction, LPDS, project definition, public construction.

INTRODUCTION

Construction projects are influenced by country-specific institutional pressures that might drive the management of projects in different directions. Public construction in developing countries faces major challenges to deliver the infrastructure needed to improve citizens' quality of life and reach long-term sustainability targets. For instance, Ezzat (2013) found that the main challenges of construction projects in developing countries are related to engineering issues (e.g., lack of understanding of, and capability to deliver technical requirements), human capital issues (e.g., shortage of quality education and continuous professional development programs), financial issues (e.g..,

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lack of financial resources), and managerial and political issues (e.g., lack of political support, lack of vision from the project's owner).

Very commonly, public construction projects are managed with traditional management methods with a focus on time and cost but overlooking important aspects such as functionality and sustainability (Haddadi et al., 2016). As a result, projects can be delivered on time and within budget, but they do not reach the expected long-term expected outcomes or value (Cooke-Davies, 2002). Previous research has shown that the gap between value generation and project outcomes is commonly attributed to the lack of proper consideration of stakeholders' contributions, the lack of understanding of the influence of the stakeholder's decisions, and the lack of knowledge of the ways to generate value (Tillmann et al., 2013). Moreover, Tillmann et al. (2011) argued that urban regeneration projects in Brazil are influenced by a high dynamic environment due to myriad requirements from multiple stakeholders. Thus, a better approach to managing stakeholders is needed to deliver value. Nonetheless, different actors may have a different meaning for value. Therefore, the problem seems to be rooted in a lack of consensus in determining and/or identifying the value-generating principles that drive expected project performance and outcomes. From a lean perspective, Bølviken et al. (2014) argued that value is about the usefulness, functionality, utility, and benefit of the product. As such, *"Something wanted is wanted by somebody. Value is therefore always value for somebody"*. Bølviken et al. (2014) also argued that in lean construction, the value for the customer is the dominant value perspective. However, public construction is delivered in a complex network of tough regulations, societal expectations, and limited funding. Therefore, this definition suggests that identifying the actors beyond the customer, and their value-generating principles, might provide a better understanding of how to connect value and project outcomes in public projects.

In this context, the Lean Project Delivery System (LPDS) can be applied to facilitate this connection and focus on value generation. Thus, the main objective of this research is to identify the value-generating principles for public construction within the context of developing countries. To analyze the applicability of LPDS, this research will use the Peruvian public construction as a case study. As such, this paper is structured as follows. First, an overview of the Peruvian public construction delivery process, and the major issues facing the sector will be presented. Following, literature about the project definition phase of the LPDS as an enabler of value generation in public construction is discussed. Then, the research method is described. This is followed by the presentation of the results and discussion. Finally, concluding remarks will close this paper.

PERUVIAN PUBLIC CONSTRUCTION

THE DELIVERY PROCESS OF PUBLIC CONSTRUCTION

Peruvian public construction project delivery is determined by the National System of Multiannual Programming and Investment Management (INVIERTE.PE) which is the administrative system responsible for ensuring that public investment meets the criteria of efficiency, effectiveness, sustainability, and transparency for the use of public resources. In other words, it seeks that public investment closes the gaps in infrastructure and access to services in favor of citizens at all levels in all sectors such as water and sanitation, healthcare, and education. The public construction investment cycle has four stages as described below (MEF, 2018):

- Multiannual Investment Programming (PMI): this strategic stage determines the investment portfolio and cost allocation with a focus on closing infrastructure gaps on national, sectoral, and territorial levels.
- Formulation and Evaluation (F&E): this stage formulates the detailed investment proposal to achieve the goals established in the PMI. Here, public managers define service levels, quality standards, social profitability, and sustainability targets.
- Execution: this stage includes the delivery of the design outputs (i.e., drawings and specifications) and the construction of the project based on its design outputs. Likewise, progress and financial monitoring tasks are carried out.
- Operation: this stage includes the operation and maintenance of the built assets and the provision of the services. Here, public managers evaluate whether the expected value was delivered to the beneficiaries or not.

In addition to INVIERTE.PE, public managers must follow the public contracting system enforced by the State Contracting Law (SCL). INVIERTE.PE and SCL both enable and constrain the delivery of public projects in Peru. Previous literature has found many challenges regarding these legal frameworks such as the deliberate fragmentation of project stages, restrictions for using collaborative delivery methods, and lack of responsiveness to uncertain situations (Prado, 2021).

PROBLEMS IN PERUVIAN PUBLIC CONSTRUCTION

According to the latest report published by the Peruvian Audit Office (CGR), national and regional governments, as of July 31, 2018, had 867 projects at standstill for a contracted amount of S/ 16,870'855,767.00 (ca. $4 billion). The main reasons for failed projects were identified as technical deficiencies in both design documents and during construction, contractual non-compliance (39%), overbudgeting (28%) and unreasonable time extensions (15%) (CGR, 2019). Previously, CGR (2014) found that the F&E stage was characterized by poor front-end engineering studies such as soil mechanics or survey reports, as well as inaccurate architectural and structural concept designs. In the Execution stage, the major problem is the long latency of design changes due to poor design coordination.

In addition to the Peruvian government reports, other authors have tried to understand the challenges in the Peruvian public construction. Arnao (2011) stated that the drawbacks of public construction projects are caused by poor management during planning and execution (design and construction), lack of government control, inherent fragmentation of regulated contracting methods, financial obstacles, and incomplete basic engineering studies. Gomez-Sanchez (2015) found that overbudgeting is mainly associated with risks such as poor or incomplete design documents and the non-consideration of other risks such as bad weather conditions, unforeseeable site conditions, excessive bureaucracy in administrative processes, and other unpredictable situations after contract award.

Previous studies have analyzed Lean Construction (LC), Building Information Modelling (BIM) and Virtual Design and Construction (VDC) to improve Peruvian public construction performance. For instance, Prado (2021) described three interrelated challenges during the VDC implementation, namely, legal and contracting issues, culture of the organization and people-related. Similarly, Salinas and Prado (2018) proposed a framework for applying BIM in public construction to integrate design and construction with a focus on the transformation of the delivery process. Moreover, Murguia et al. (2020)

proposed a database structure for capturing lessons learned from facility managers to provide timely input to design and construction teams. Furthermore, Murguia et al. (2021) found cultural-cognitive elements that impact the adoption of BIM, which need to be considered by policymakers who are planning to mandate and control BIM adoption in the public sector. On the other hand, Chuquin et al. (2021) presented case studies for the use of lean design in infrastructure hydraulic projects. However, public organization structure and a lack of trained professionals were the major barriers to successful lean delivery. Huaman-Orosco et al. (2021) reported that one of the most important barriers to LC implementation is the lack of government policies to encourage the use of Lean. As a major player in the industry, the government possesses the power to engage and empower public organizations to deliver value throughout the project lifecycle. Together, these studies suggest that the application of Lean Construction tools and method, together with innovative technologies and processes can support performance improvement in public construction. In this context, the LPDS can be beneficial for providing a framework to determine the value-generating principles at the outset of Peruvian public projects.

LPDS AS AN ENABLER OF VALUE GENERATION

LEAN PROJECT DELIVERY SYSTEM

The LPDS is a delivery system in which the project team helps customers (beneficiaries) to decide what they want. Ballard (2000) described LPDS as a "project-based production system" because it is a temporary production system. LPDS contains five project phases, and each phase contains three project steps, as shown in Figure 1. Each phase is interconnected to the next one through a common step. Thus, each project phase has an impact on the following phase and is influenced by the previous phase.

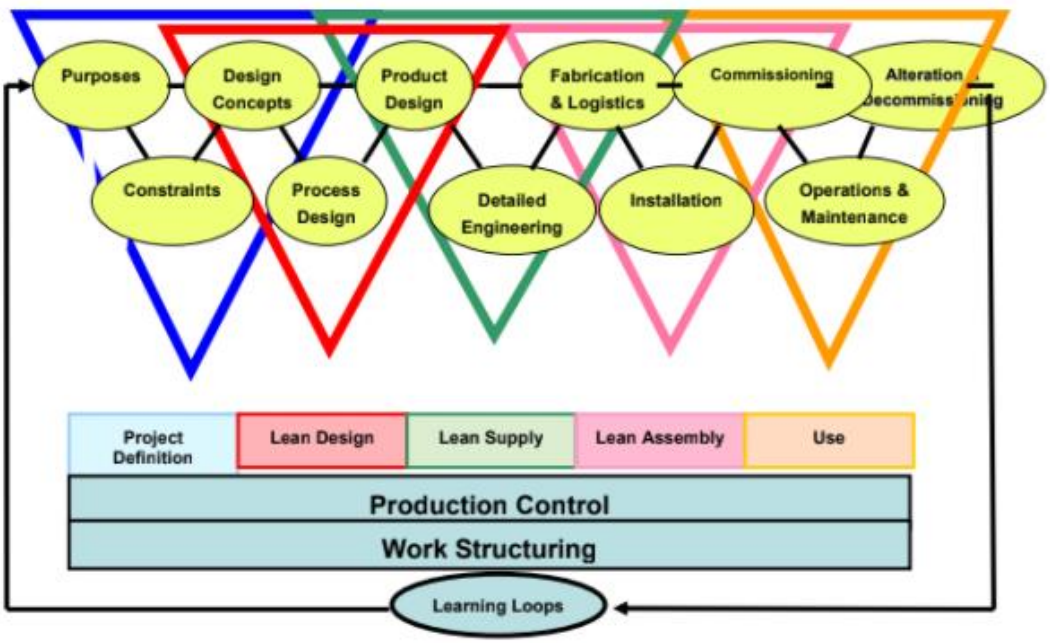

Figure 1: Lean Project Delivery System (Figure 3 in Ballard 2008)

In contrast to traditional project delivery systems, LPDS questions what needs to be done and who is responsible for the task at the very beginning of the project. The following points are key characteristics of LPDS:

- The project is structured and managed as a value-generating process
- Early involvement of downstream stakeholders to plan and design the project steps through cross-functional teams (Ballard, 2000).

As such, decisions, which are made in one phase, affect the other phases. Compared to traditional project delivery (design-bid-build or DBB), LPDS explicitly shows the relations and dependencies between the different phases, which are often ignored, compared to DBB. This research focuses on the LPDS Project Definition phase because many of the problems in public construction projects originate during the F&E stage which contains similar processes to the Project Definition phase.

LPDS PROJECT DEFINITION PHASE

Ballard (2008) presented the Project Definition phase as a process of aligning between Ends, Means and Constraints. Alignment is achieved through a conversation that starts with the customer stating what they want to accomplish (the end), the means (the how) for achieving their ends, and the constraints (location, time, cost) of those means. Defining these three aspects of Project Definition is critical for initiating a project:

- Ends: By understanding what is the final product that the beneficiary wants, we can understand what the purpose of that wanted output is, which then can be described by what are the valuable features of that final product. It is critical to translate from the voice of the customer into the voice of the project members, which then will provide specifications for the wanted product. Both linkages are difficult and critical, linking purposes and values, and linking values and engineering specifications for the project.
- Means: Since in the LPDS projects are described as production systems, it is sometimes necessary to first design how the built asset will be used before designing the facility itself. This idea reflects the need for incorporating criteria for the operation and maintenance stage of the expected product and using it as a trigger for describing the other features of the facility to deliver.
- Constraints: As Ends are more clearly defined and translated into specifications, and as the design-for-use of the facility emerges, constraints are also better defined. What are the customers able and willing to spend to get the means for realizing their purposes? That is the question to ask to find the constraints in projects such as time, geological conditions, or socio-cultural environments.

However, the common practice is that many projects first establish the means, without knowing the purposes of the ends. Tillmann et al. (2013) found that the LPDS can support the pursuit of value in construction projects by establishing favorable conditions for the different participants to collectively generate value. Ballard and Tommelein (2021) provided a variety of uses of LPDS and the Last Planner System with a wide range of lean methods and tools that can improve project performance. Similarly, researchers have found LPDS integration with other technologies. Khanzode et al. (2005) described a strong relationship between VDC as a virtual tool that can improve the implementation of LPDS, specifically using 3D-4D CAD technologies. Nguyen et al. (2008) found that process-based construction cost modeling may be used to assist the stakeholders in resolving a variety of decisions such as evaluating the cost of different design alternatives, establishing the cost impact of design changes and budgeting construction costs.

Previous studies have shown the use of LPDS in public and private construction projects to improve performance, and how technologies can support this delivery system.

However, no study addresses the lack of relationship between value generation and project outcomes in the context of public construction in developing countries. Therefore, the main objective of this research is to fill this research gap by developing a proposal that operationalizes the LPDS with the value-generating principles in the Peruvian public construction to potentially provide a better understanding of what is the value that should be generated.

RESEARCH DESIGN

A qualitative research approach to data collection was deployed to understand the principles that generate value for projects, from the perspective of public managers. Qualitative methods are appropriate when the intention is to understand a phenomenon from the point of view of participants in a particular social and institutional context (Creswell, 2014). Therefore, the research procedure consists of these three steps:

The first step was to collect data about the value-generating principles in Peruvian public construction. The authors selected semi-structured interviews using the critical incident technique (CIT) as the data collection method. By incident is meant any observable human activity that allows inferences to be made. To be critical, the incident must have significance and depict the phenomenon being investigated (Flanagan 1954). CIT enables the possibility to gather critical incidents from interviewees' narratives. Interviews were designed to obtain participants' individual opinions rather than an organizational perspective. Participants were identified through researchers' industry networks and a 'snowball' interview technique was utilized (Lingard et al. 2019). Interview questions were open-ended and project specific. Thus, participants were asked to narrate experiences and discouraged from answering questions in a general way. Questions explored participants' views about (1) their perception of value in the context of expected outcomes in public projects; (2) their perception of the drivers that generate value in projects; and (3) their perception of the constraints to reduce value generation.

The second step was a detailed analysis of the interviews' transcripts to identify the value-generating principles based on the experiences shared by the respondents. Since the interviews were semi-structured, the authors made sure that the experiences related to "value" were related to the benefits provided by the project as opposed to value as the project cost. The third step was to align the value-generating principles found in step 2 with the ends, means, and constraints proposed by the LPDS project definition phase and to propose an alignment matrix for value generation in the early stages of public construction projects.

RESULTS

DEMOGRAPHICS OF THE DATA COLLECTED

The criterion for inclusion was that the participant has had experience as a public manager in construction projects. Eighteen semi-structured interviews (25' on average) were held with public managers with varied backgrounds, as shown in Table 1. Data were recorded and transcribed, and then analysed using NVivo 12. A mixture of deductive and inductive analysis was used as the data analysis method. Nodes were inductively created by the authors to define the value-generating principles. The second round of inductive analysis helped merge nodes into higher-level themes and therefore identify who captures the value.

Table 1: Demographics of interview participants

Variable	Value	Frequency	Percentage
Degree	Architecture	4	22%
	Civil Engineering	14	78%
Years of Experience	5– 10 years	7	39%
	11 – 20 years	7	39%
	More than 20 years	4	22%

VALUE-GENERATING PRINCIPLES IN PERUVIAN PUBLIC CONSTRUCTION

The analysis revealed that public managers perceive that value is generated through the fulfilment of specific principles in three categories: the end-user, the government, and the public manager, as presented in Table 2. Therefore, the value-generating principle generates value for "*someone*". As such, it can be observed a relationship between the recipient of the value and its associated principles.

Table 2: Value-generating principles

Value for who?	Value-generating principles
For the end-user	End-user consideration
	Functionality
For the government	Transparency
	Efficiency
For public managers	Predictability
	Efficacy

Value for the end-user

This is related to the principles that can generate value for the ultimate customers: the end-users or asset beneficiaries. It is also associated with the Operation and Maintenance stage of the project. The value-generating principles for end-users are:

- End-user consideration: enabling a collaborative environment to allow the active participation of the end-users throughout the development of public projects.
- Functionality: considering early in the project the lessons learned and knowledge from the operation and use of facilities.

Value for the government

This is related to the principles that can generate value to be compliant with the laws that govern public projects to ensure competitiveness and accountability. Lack of compliance would have major negative impacts. The government's value-generating principles are:

- Transparency: ensure a transparent exchange of technical and administrative information. Technical information includes achievable schedules, fair quantities and payments, and specifications that meet project needs. Administrative information includes human resources allocation, legal documents, and insurance. Stakeholders are accountable for each process.
- Efficiency: public managers must ensure that the cost-benefit analysis encompasses social and economic benefits for society.

Value for public managers

This is related to the principles that can generate value for the management of the execution stage (design and construction). Public managers value good management practices that comply with the laws and regulations (technical and administrative). However, when public managers face uncertainties, they prefer to avoid decision-making to prevent future sanctions. The value-generating principles for public managers are:

- Predictability: having tools to make accurate time and cost predictions as well as being able to timely identify risks.
- Efficacy: achieving the expected project objectives defined at the beginning of the project and avoiding administrative sanctions.

ALIGNMENT OF PERUVIAN PRINCIPLES AND LPDS PROJECT DEFINITION

Based on the principles that deliver value to each category, Table 3 presents an alignment matrix between the value-generating principles and the ends, means, and constraints of the LPDS project definition phase.

Table 3: Alignment between the principles that generate value in Peruvian public construction and the sections of the LPDS project definition

Principles	Ends	Means	Constraints
End-user consideration	Early involvement of the beneficiaries to capture their needs and values	Understanding the key features of the asset and their functionality from the end-user perspective	Due to specific project conditions, project teams may not be able to involve end-users
Functionality	How the project ought to be operated and its purpose must be known	Lessons learned to meet the expected use of the facility and to allow them to influence project delivery	Lack of involvement of O&M actors due to the traditionally fragmented procurement system (DBB-operate)
Transparency	Maintain transparency of the information throughout the lifecycle to avoid corruption claims	The project delivery should be compliant with the laws for public projects (technical and administrative)	The legal framework and human behavior will frame the environment in which project managers should act
Efficiency	Cost-benefit analysis and an efficiency-driven approach to the use of project resources	The project should meet the need at the lowest “cost” to deliver the expected value	Lack of clearly defined tools to define realistic project costs in early stages
Predictability	Use mechanisms to manage uncertainties or poor information as they impact the project performance	Use of buffers throughout project delivery to predict and manage unforeseen situations	Poor front-end engineering studies, insufficient information, erroneous drawings, and specifications
Efficacy	Establish project objectives (outcomes and performance) by a consensus with relevant stakeholders	Maintaining and meeting objectives throughout project delivery by assigning a skillful project team	Time restrictions lead to poorly defined project objectives and selecting an incompetent project team

The examination of the six value-generating principles in Peruvian public construction and the three steps of the LPDS project definition phase helps to understand the ways public managers can generate value for public construction projects. The ends, means, and constraints were defined for each value-generating principle. For the end-user consideration principle, the ends are related to the involvement of beneficiaries to define the value to be delivered by the built asset, the means are related to key features of the built asset that will lead to delivering the value already defined, and the constraints are related to the situations when is difficult or impossible to collect the beneficiaries' perspective, such as a wide-range of myriad requirements or changing beneficiaries over time. For the functionality principle, the ends are related to defining how the built asset will be used and operated, the means are related to the inclusion of facility managers' inputs in the project delivery stage, and the constraints are related to the current DBB practice that limits the inclusion of more stakeholders at the beginning of the project.

For the transparency principle, the ends are related to the accountability to be maintained throughout the project, the means are related to the compliance with technical and administrative laws, and the constraints are related to the legal framework in which the project managers must act because of the current regulation. For the efficiency principle, the ends are related to controlling the public expenditure on public projects, the means are related to completing the project at the lowest cost possible while delivering the expected value, and the constraints are related to the lack of tools and methods to define project costs accurately at early stages of the project. For the predictability principle, the ends are related to the be prepared to manage uncertainty, the means are related to the use of buffers to manage uncertainty, and the constraints are related to the poor information in the project that does not allow to prepare for these situations. For the efficacy principle, the ends are related to establishing project objectives collaboratively, the means are related to maintaining these objectives throughout the project delivery, and the constraints are related to time pressures that lead to a poor objective definition.

DISCUSSION

The research findings represent the first attempt to align value-generating principles in public construction with the LPDS. This would provide an opportunity for the use of different lean tools and methods at the beginning of project delivery. In terms of the value for the end-user, an interviewee said that *"the end-user should approve my proposal so they know that later they can maintain it"*. This confirms that end-user consideration is relevant to the project. However, some interviewees pointed out that interrogating end-users might provide unwanted outcomes when the end-user has political influence, such as controlling design decisions that are not aligned with basic design criteria. They might also have the power to add unnecessary risk by reducing the established project timeline. Refurbishment projects are very high risk due to the inexistence of reliable asset information. For example, public managers need to survey existing assets to initiate a project. However, the existing asset management systems are paper-based and lack an agreed process that ensures reliability and consistency across projects. In that sense, the application of BIM for information management would provide the digital platform needed to integrate design information among stakeholders and share lessons learned from facility management systems. However, it is required to implement a robust system to collate lessons learned such as the approach shown in Murguia et al. (2020).

In terms of the value for the government, transparency and cost-efficient decision-making are paramount for public managers. An interviewee pointed out that *"not only the project is important, but also the procedures conducted by audit institutions that are looking for mistakes throughout the project"*. Public managers operate under tough pressure and scrutiny of the Audit Office which is often expressed as "fear" to make wrong decisions, thus, no decisions are made due to the civil and penal consequences. From the lean methods and tools documented by Ballard and Tommelein (2021), the authors of this study argue that Target Value Design, Set-based design, and Choosing by

Advantages can provide a better approach to addressing the project's conceptual design by considering cost implications and improving transparency. The current BIM mandate for public projects in Peru aims to increase transparency in the information and reduce errors across the supply chain, including cost estimators, designers, and contractors. However, there is a capability gap among practitioners, especially designers, that might threaten the expected outcomes of implementing BIM in public construction (Murguia et al., 2021).

In terms of the value for the public managers, predictability and efficacy are project-level value-generating principles during the management of projects. An interviewee said that *"We need predictable engineering documents that provide the right information to develop the project, and if possible, with no defects"*. To achieve improved predictability and efficacy, project managers need to simultaneously manage information and stakeholders. Therefore, lean methods that promote collaboration and knowledge exchange can provide environments to set achievable objectives and better predictions, such as the tools and methods proposed by Ballard and Tommelein (2021) that are used together with LDPS and Last Planner System. Also, the VDC framework can provide a way to focus on project and client objectives in a public organization (Prado, 2021).

By applying the proposed alignment matrix, we can align efforts to reduce the gap between the value generated from the three customers identified (end-users, government, and public managers) perspective and the asset delivered to society. Moreover, the lean tools and methods suggested to use with the alignment matrix can serve as a starting point to produce a lean-enabled framework for operationalizing lean tools and methods in the project definition phase of public projects. This is the baseline for future research.

CONCLUSIONS

This research aimed to identify the value-generating principles for public construction within the context of the project definition phase of the LPDS to provide a potential solution for the research problem: lack of consensus in determining and/or identifying the value-generating principles that drive expected project performance and outcomes. To achieve this aim, an inductive approach was taken, and qualitative data were collected via interviews with a range of managers working in public organizations. Interviewees were asked to narrate experiences about value generation (and loss) during the management of public construction projects and the means to achieve better project outcomes. The findings show that the value-generating principles for public construction extend beyond the end-user perspective. Public projects are deployed within a complex institutional environment that requires the generation of value for the government and the public manager to reduce controversies, cost overruns, corruption, and ultimately resolution of contracts and failed projects that cause profound losses to society. The findings show that the value-generating principles for public construction are end-user consideration, asset functionality, transparency, efficiency, predictability, and efficacy. Furthermore, the LPDS can be extended to consider the specific case of public construction and include the value-generating principles encapsulated in the complex legalistic and managerial context, which led us to propose the alignment matrix that potentially closes the gap of the lack of consensus between project outcomes and value delivered. Further research can develop a framework for Lean Public Construction and scrutinize case studies with the use of Lean tools and methods at the earliest stage of public projects in developing countries to assess performance.

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A COGNITIVE REVIEW FOR IMPROVING THE COLLABORATION BETWEEN BIM AND LEAN EXPERTS

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ABSTRACT

Collaboration between Lean Construction and BIM teams is a key factor in exploiting the synergies between Lean and BIM. Although various studies have underlined the importance of team cognition and Team Mental Models (TMM) in the success or failure of collaboration amongst teams, those concepts have not been sufficiently explored from a Lean/BIM perspective. Therefore, this study attempts to introduce the concept of TMM to the Lean-BIM domain by conducting a cognitive review of the Lean-BIM joint implementation at an engineering design firm in the UK with the principal aim of developing a set of suggestions to improve the collaboration between BIM and Lean experts. To collect data, this study used a mixed research approach including secondary research, a case study and semi-structured interviews. Data analysis was conducted through Thematic Analysis to find the main barriers hindering an effective Lean-BIM joint implementation. Findings also suggest that improving the components of TMM can result in an improved Lean-BIM joint implementation. A set of recommendations for Lean and BIM teams' collaboration is also given in the paper.

KEYWORDS

Design, team mental models, team cognition, BIM and Lean collaboration, BIM and Lean synergy.

INTRODUCTION

The importance of effective interaction, teamwork, and collaboration between teams to achieve project objectives is evident as project delivery involves different trades and stakeholders (Dave et al., 2013; Zhang et al., 2018). Furthermore, due to the complexity of teamwork, identifying the cognitive structures (mental models) of team members through which they organise information about team functioning is crucial (Langan-Fox et al., 2004). Effective team functioning is tied to the existence of a Team Mental Model (TMM) among colleagues in a project (Langan-Fox et al., 2000).

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According to Eynon (2016, p. 31), “Building information modelling (BIM) is the digital representation of physical and functional characteristics of a facility creating a shared knowledge resource for information about it and forming a reliable basis for decisions during its life cycle, from earliest conception to demolition”; whereas Lean construction (LC) is an effort to apply lean principals originated from Toyota Production System (TPS) to construction. LC aims at managing the construction processes with minimum cost, maximum value and in compliance with the customers’ requirements (Enshassi & Elsiah, 2019). Although BIM traits and LC principles are compatible (Zhang et al., 2018) and have been implemented jointly recently resulting in important positive synergies, due to various barriers, the construction industry has not used this opportunity to achieve the ultimate synergy between them, yet.

Mental model is described as “mechanisms whereby humans generate descriptions of system purpose and form, explanations of system functioning and observed system states, and predictions of future system states.” (Keasey Edinger, 2012, p. 21). Team Mental Model (TMM), however, transcends the individual mental models and analyses the shared realisation of a common subject among team members. Badke-Schaub et al. (2007, p.8) argued that “TMM does not only refer to multiple levels or sets of shared knowledge or just to an aggregate of the individual mental models but also to a synergistic functional aggregation of the teams mental functioning representing similarity, overlap, and complementarity”. Thus, it plays an effective role in communication and coordination amongst teams’ members and their performances.

Considering the benefits of the Lean-BIM joint implementation for the construction industry, improving it is required. Furthermore, Lean and BIM approaches are people- and process-oriented (Dave et al., 2013) and as can be realized from the literature, TMM can be considered instrumental for discovering the mental models associated with Lean and BIM teams. Therefore, identifying the Lean team’s and BIM team’s TMMs is expected to contribute to dissolving the barriers at team level, which are the key obstacles to enhancing the Lean-BIM joint implementation, and leading them to improve their collaboration, accordingly. This research has been conducted to address the gap in the literature on the role of team cognition in optimising the collaboration between BIM and Lean teams. This is done through studying the Lean and BIM team’s mental models at a case company in the UK from a TMMs perspective. Although the Lean and BIM synergy has been extensively discussed in the literature, beyond project management level, their integration at company and team level has rarely been discussed (Zhang et al., 2018; Tezel et al., 2020).

The primary aim of this study is to develop a set of suggestions to help enhance the collaboration between Lean teams and BIM teams, and support the Lean-BIM joint implementation in an engineering company. This investigation focuses on answering three main research questions:

- **Q1.** What are the main barriers affiliated with TMM (Task, Team, Team process and Goal knowledge), hindering the Lean-BIM joint implementation in an engineering company?
- **Q2.** How do the components of TMM influence the Lean-BIM joint implementation in an engineering company?
- **Q3.** What mechanisms can be suggested to address those TMMs which cause barriers for an effective collaboration between Lean team’s and BIM team’s members to improve the Lean-BIM joint implementation?

This paper is structured as follows. After a literature review on Lean-BIM collaboration and TMM, the research method of the study is presented. The data analysis is followed by the main findings. The paper concludes with a discussion and key recommendations.

LEAN-BIM COLLABORATION

BIM and Lean, as two main concepts for the modern construction project management are integral approaches, even though they are different (Sacks et al., 2010). Multiple studies have been conducted to date, examining the interrelations between BIM and LC (Evans & Farrell, 2021). For example, Sacks et al. (2009) investigated the ways of adopting BIM to fulfil the needs of effective information flow and transparency for implementing Lean. By juxtaposing BIM features with LC principles, Sacks et al. (2010) identified 52 positive interactions (synergies) out of 56 interactions between Lean and BIM, such as increased flexibility, improved collaboration in design and construction, decreased variability and cycle times.

Studies conducted by Dave et al. (2013) and Zhang et al. (2018) further emphasized the benefits of the Lean-BIM synergy in terms of completing construction projects on time and budget, reducing wastes and rework, and improving quality. Therefore, to acquire the most advantage of Lean-BIM synergy, BIM and LC are necessary to be implemented fully integrally (Evans & Farrell, 2021).

Nevertheless, various barriers to the Lean-BIM joint implementation were identified by researchers. For example, lack of collaboration and coordination, and lack of transparency (Evans & Farrell, 2021; Zhang et al., 2018) as well as various levels of readiness for accepting the changes in conventional methods (Evans & Farrell, 2021; Olawumi & Chan, 2018) were suggested to date.

To achieve most benefits from Lean-BIM synergy, the dynamics of this collaboration should be focused on and explored more (Azhar et al., 2012). However, the literature review shows that most of the research to date on Lean and BIM interaction is concerned with either exploring the mutual synergies between Lean and BIM or demonstrating how BIM facilitates Lean or vice versa at a project level. Yet, to the best of the researchers' knowledge no study has been conducted to date which underpins the role of TMM in the Lean-BIM joint implementation. Therefore, this study adopts the TMM concept to explore the collaboration dynamics between Lean and BIM teams and contribute to enhancing the collaboration between them.

TEAM MENTAL MODEL

According to Langan-Fox et al. (2000) and Badke-Schaub et al. (2007), most early research on mental models merely discussed individuals' mental models. This concept can help in describing the behaviour, knowledge, and performance of individuals and teams (Casakin & Badke-Schaub, 2017). The idea of Team Mental Model (TMM), however, was introduced initially in 1990, by Cannon-Bowers, Salas, and Converse, as a way to improve both realisation and studying the communication and coordination among team members through observing the operation of effective teams in various uncertain and complex circumstances (McNeese et al., 2014). Klimoski and Mohammed (1994) described TMM as knowledge or belief structures that are shared by the members of a team, which enable them to form accurate explanations and expectations about the tasks. TMM also enables team members to coordinate their actions and adapt their behaviours to the demands of the tasks of the project and of their colleagues (Bianchi et al., 2015; Badke-Schaub et al., 2007). Langan-Fox et al. (2000) argued that in order to operate and interact successfully in a team, the team members are required to adopt a similar way to understand, encode, store and retrieve information.

There are various areas of knowledge specified in TMM, which are prerequisites for working in a team (Wise et al., 2021; Burtscher & Manser, 2012). Wise et al. (2021) described the four major components of TMM as follows:

- **Task Knowledge** refers to the knowledge and skills required for performing the team members' duties.
- **Team Knowledge** refers to the team members' understanding of each role's duties, in addition to the specific skills of individual team members.
- **Team Process Knowledge** refers to the realisation of the needed procedures and behaviours for interacting and coordinating with other colleagues in projects.
- **Goal Knowledge** refers to the team members' understanding of colleagues' shared goals and objectives.

Many have reported the benefits associated with TMM in improving team performance and creating an effective coordination among team members. Klimoski and Mohammed (1994) and Banks and Millward (2007) stated that those teams whose members have shared models in both task work and teamwork perform more effectively through enhanced coordination, because the team members understand and predict the other members' needs and actions better (Lingard et al., 2015). Moreover, Langan-Fox et al. (2004) summarized the potential benefits of the relationship between TMMs and performance, some of which include more effective communication by less communication actions through using shared models such as common language (Langan-Fox, 2001), more prompt mutual learning, and improving the allocation of responsibilities by considering the strengths and weaknesses of team members (Langan-Fox et al., 2004). Van den Bossche (2006) drew the attention to the close relationship between cognition and interaction and then, Ybarra, et al. (2008) described that these two concepts have direct influence on each other (McNeese et al., 2014). Nevertheless, Houghton et al. (2000) proposed that TMMs may cause "groupthink" biases, which is defined as a possible disadvantage that groups may experience when conformity pressure leads to faulty decision-making (Janis, 1982) and can be seen in a wide range of groups working together in various fields (Rose, 2011).

Literature review found only a few studies exploring TMMs in the construction area. Fry (2004) focused on coordinating and describing various design terms through creation of an appropriate mental model. Badke-Schaub et al. (2007) investigated the relation of the theoretical concepts of mental models and design teams and Goldschmidt (2007) studied design teams' Mental Models. Casakin and Badke-Schaub (2017) explored the sharedness of TMMs in design-related interaction between architects and clients. Bridging two domains of construction management and cognitive science with the focus on BIM and Lean, TMMs can lead to the improvement of the Lean-BIM joint implementation and integration.

RESEARCH METHOD

Case study is the research method of the study. The Lean and BIM teams at an engineering design company in the UK are units of analysis. Case studies are suitable for studying phenomena in their real-life contexts where researchers have no control (Yin, 2003). The company is a large, international engineering design and consultancy company delivering solutions for natural and built assets in over 70 countries, however, the study was focused on the UK branch. They are considered advanced by their supply chain in terms of their Lean and BIM implementations.

To explore the Lean-BIM interfaces at the company, secondary data including company records, meeting notes, and documents related to the KTP project were reviewed initially. As the result, it was realized that this company has been involved in the implementation of some Lean and BIM initiatives approximately six years and more than twenty years, respectively. However, the Lean and BIM integrated implementation within the company was fragmented, lacked co-ordination and was still immature. The company is also collaborating in a Lean and BIM integration focused Knowledge Transfer Partnership (KTP), a government sponsored knowledge exchange scheme between universities and companies in the UK.

Alongside reviewing the company documents, five practitioners from the company's Lean team and five practitioners from the BIM team were interviewed using semi-structured interviews (10 interviews in total) and the cognitive interviewing technique in order to investigate their viewpoints, mindsets and various components of TMMs. The semi-structured cognitive interviewing technique was selected as it helps researchers to achieve in-depth and rich information regarding a specific domain through eliciting interviewees' experiences and thoughts (Turner III, 2010). Analysis was done by identifying and grouping similar themes and approaches through thematic analysis, to be described below, and the findings were shared with and validated by the company.

Firstly, the questions of interviews were developed so that participants were allowed to reply to the questions in their own terms and convey their views and opinions regarding Lean and BIM experts' work mentalities, advantages and outcomes of the Lean-BIM joint implementation identified by them in their affiliated projects. Four main components of TMMs (Task, Team, Team process and Goal knowledge) were investigated, as well. Then, the interview meetings were conducted through Microsoft Teams and the transcripts were recorded. Subsequently, collected data was analysed using the thematic analysis technique. This method is used to identify and represent patterns (themes) within a qualitative data set, enabling researchers to flexibly organise and describe the data with rich detail (Braun & Clarke, 2006). Six consecutive phases of thematic analysis, as suggested by Braun and Clarke (2006), were followed:

- **Familiarising with the collected data.** The initial ideas were derived from the transcriptions of Lean and BIM participants' responses and sorted into two categories comprising BIM and Lean.
- **Generating initial codes.** The similar ideas extracted from the raw data were classified in the shared categories, and then interesting features of the data which could lead the research to the TMMs of the participants were systematically coded.
- **Searching for themes among the data.** Coded data was analysed to identify those codes which could be combined to create an overarching theme. Then, the created themes were compared, and main themes and sub-themes were formed.
- **Reviewing themes.** The created themes were reviewed to decide whether they should be considered as a proper theme, should be converted into separate themes, or should be merged into a single theme.
- **Defining and naming themes.** To find out the essence of each theme and to identify the specific aspect of data covered by an individual theme, they were defined and named.

- **Producing the report.** The report of analysis was written to deliver a succinct, clear, logical summary of the story of data.

FINDINGS AND DISCUSSION

Key findings corresponding to the research questions Q1 and Q2 were categorized into two main groups affiliated with the Lean-BIM joint implementation barriers and TMM's four components as follows.

BARRIERS

Barrier 1. Lack of Motivation and Intention towards Collaboration

This barrier stems from two main reasons: (i) lack of readiness for accepting changes in the conventional methods as well as (ii) lack of awareness about the Lean-BIM joint implementation advantages, so the teams do not believe it is worth prioritising and dedicating time to it. These main reasons cause a lack of intention on the part of the experts, particularly in the BIM experts, for an effective collaboration.

Barrier 2. Different Work Mentalities

The way through which the BIM and Lean experts understand, encode, store and retrieve information is different. BIM and Lean experts work in a common data environment, set up by BIM experts at the outset of the project. BIM experts implement considerable improvements. However, unlike the Lean experts, they do not recognise these improvements as Lean improvements, they do not record and store the information affiliated with the benefits of them, and also, they do not implement them in a structured way. Following differences between Lean and BIM experts cause their distinct work mentalities, which may ultimately hinder improving the Lean-BIM joint implementation:

- Using different terminologies by BIM and Lean experts is one of the factors causing them to understand the work issues differently.
- BIM and Lean teams' different attitudes, perspectives, and expected outcomes cause them to encode, store and retrieve information differently. BIM experts mostly have a long-term vision to the projects, leading them to produce a product which can solve the problems for both current and future projects, whereas Lean experts mostly focus on current tasks, collaborative planning and tracking the current progresses.
- BIM and Lean teams' various priorities influence on how they encode and store the data. BIM experts tend to focus merely on delivering their ongoing tasks, while Lean experts concentrate on all the objectives of the projects. Lean experts look for efficiency and streamlining, while BIM experts look for quality of design.
- They have different tasks and use different strategies, tools, and techniques to fulfil their tasks, impacting the methods they encode, store and retrieve the required information.

Barrier 3. Lack of a Common Approach

A confusion among the experts of either field could be observed in terms of the required strategy for accomplishing their tasks in a collaborative context, as participants stated that they are not aware of how they should function more collaboratively while fulfilling their tasks. This is due to the lack of a designated collaboration strategy, introducing a structural and organisational gap. Parallelly this creates an opportunity for the company's decision makers to establish an innovative collaborative approach which will support providing the teams with an appropriate guideline.

Barrier 4. Groupthink Biases

Biases of "groupthink" were observed in the participants, so that either team's experts tended to expect that most of the actions and measures which are required to be carried out for improving the Lean-BIM joint implementation should be taken by the other team.

MAIN TMM COMPONENTS

Task Knowledge

The structure of this component is composed of two main concepts namely "knowledge" and "skill". The former can be improved through training, while the latter cannot merely be developed in a similar way, but through repeated practical application of the knowledge obtained through training. Therefore, "skill" and accordingly "task knowledge" are not flexible concepts for change in short term, as it takes time to improve individuals' skills.

Team Knowledge

This is the main component of TMM to address the waste of "lack of clarity in the transfer of information between disciplines" as it can contribute to increasing the transparency within team procedures and lead to an improved BIM-Lean collaboration.

Team Process Knowledge

This is the main component of TMM to address the wastes of "delay, waiting and rework". Thus, enhancing this component will cause increased efficiency. Not only time-related issues, but also other key concepts such as communication, personal traits, terminology, and the method of conducting meetings influence constructing team processes and therefore, play significant roles either in generating the aforementioned wastes or removing them.

Goal Knowledge

This is the main component of TMM to improve the efficiency. Sharing goals and objectives or having different ones is one of the main factors in either improving or hindering the collaboration within teams. Teams sharing goals will feel more obliged to interact and work together, increasing the level of trust that can be developed through collaborative interactions (Badke-Schaub et al., 2007).

RECOMMENDATIONS

It is worth mentioning that altering people's mental models occurs in time. In other words, it will be a long-term transition period to move toward conceptual and structural changes (Langfield-Smith & Wirth, 1992). In this regard, the following recommendations are proposed.

MOTIVATION

Being aware of the benefits of BIM-Lean collaboration in the outcomes of a project is not motivating enough for each individual expert, as stated by the participants. Therefore, they should become more aware of the direct benefits of the Lean-BIM joint implementation on streamlining their own tasks, and the specific benefits and outcomes that can be achieved through this synergy for them. For instance, they can be trained on the topic of Lean-BIM synergy so that they will realise that it can eventually help them improve their work/life balance and mental health.

PERFORMANCE-BASED REWARD SYSTEM THEORY

This theory should be considered by the managers and champions of the innovative mechanisms of Lean-BIM at the company. It asserts that employees will be motivated to undertake a task if they think a particular reward will be forthcoming (Vroom & Gimeno, 2007; Kerr & Slocum, 2005). There is currently no certain performance-based reward system defined for the Lean and BIM collaboration at the company.

TAKING COGNITIVE CONSULTATION

Cognitive consultation can help in maximising the team members' efficiency through optimizing their mental health as well as resolving the mental barriers hindering them to communicate and collaborate with others effectively. Individual and group cognitive consultations should be planned to focus on improving the collaborative perspectives and functions within BIM team's and Lean team's members. This also can lead them to approach the Lean-BIM joint implementations further. This aim can be achieved through taking specific consultations to reduce the resistance that team members have against changing the traditional methods and strategies, to reduce workplace stress, to improve time management skills, and to enhance communication skills. Therefore, taking consultation and professional advice from cognition experts will be beneficial for planning, implementing, and sustaining the Lean-BIM joint implementation from the viewpoint of cognition.

INPUTTING LEAN INTO BIM

Assigning Lean experts to BIM teams to train them about the Lean principles and techniques, and to guide them to implement Lean into the BIM processes at the company will be useful. This will help BIM teams to better understand the benefits, opportunities and mechanisms of Lean into BIM, encouraging the joint implementation as a standard practice in the sector.

TRAINING ON LEAN-BIM JOINT IMPLEMENTATION

A set of meetings and workshops should be planned and delivered on a regular basis, aiming to improve the awareness of the experts of either field on the outcomes of Lean-BIM for individuals' work, collaboration-related skills such as communication skills and punctuality, as well as the way through which the collaborative tasks should be implemented. Experts should be also trained and convinced that this collaboration can help them with time management and removing the wastes related to time; otherwise, they may look at this idea as an extra time-consuming task, exerting more pressure and responsibilities onto them.

Colleagues working together closely play a significant role on each other's collaborative approach and TMM. This is the case particularly for the juniors who are in their initial steps of working in the company. The juniors should be trained on the importance of Lean-BIM joint implementations and the standards of implementing it early in their careers.

PRESENTING THE NEW ROLE OF LEAN-BIM EXPERT

Assigning or nurturing Lean-BIM experts, who are knowledgeable and experienced in both fields of Lean and BIM, in order to function as facilitators to drive the concept of a Lean-BIM joint implementation within the company. It is worth mentioning that although the company has already this third group amongst their practitioners, they are categorized in either BIM or Lean team and thus, they are assigned to either Lean or BIM tasks likewise the other practitioners who are experienced in merely one of the Lean or BIM fields. In other words, they are not categorized as the third group or role which can be named as "practitioner with both BIM and Lean knowledge and skills" to undertake certain tasks affiliated with the Lean-BIM joint implementation.

DEVELOPING APPROPRIATE GUIDELINES

Sufficient consideration by the company's decision makers is required to provide the BIM and Lean experts at the company with appropriate collaboration guidelines for them to work "on the same page".

IMPROVING COMMUNICATION AND VIRTUAL MEETINGS

Multiple improvement measures affiliated with communication amongst experts as well as virtual meetings were suggested, which can be planned and implemented.

Suggestions for improving communication are related to three key areas: training, terminology, and managing communication. Training recommendations can be described as: (i) holding workshops for familiarizing teams with Lean techniques and BIM processes and tools; (ii) training about communications skills, so that experts can be open and effective in listening and communicating; (iii) creating awareness modules on teams' terminology. The terminology aspect includes: (i) increasing the clarity of roles and responsibilities; (ii) setting up clear communication protocols and guidelines; (iii) setting up dictionaries for defining abbreviations and unique terminologies. Finally, managing communication issues are related to the skills required for the Lean practitioner (e.g., extroverted) to manage the communication among project members. Furthermore, the suggestions for improving communication through virtual meetings can be described as: (i) training; (ii) attendees should be advised to set their cameras on; (iii) applying lean principles to remove the waste related to the confusion caused by multiple platforms; (iv) setting a structured agenda for sensible short meetings with a break time; (v) identifying and using appropriate platforms and technologies, for which training is essential.

SUSTAINING THE NEW COLLABORATIVE APPROACH

To sustain the implementation of the proposed recommendations, it should be monitored and checked through using lean techniques such as "plan, do, check, act" and 5S.

CONCLUSION

Although multiple studies have highlighted the importance of teams' cognition as one of the of most significant factors affecting the success or failure of teams, cognitive studies and functions have not been sufficiently prioritised in construction research and practice to date. To achieve the Lean and BIM benefits at the project level, their effective integration at the company and team level is essential.

This research merged the areas of cognition and construction to investigate and tackle the mental barriers hindering an effective Lean-BIM joint implementation. Using a set of research techniques, the TMMs of BIM and Lean experts at an engineering design company in the UK were explored and analysed. Findings demonstrated that different work mentalities, lack of motivation and knowledge, and groupthink bias have been the main barriers to their collaboration.

The results and findings can contribute to generating knowledge in the domains of Lean and BIM teams' TMMs, and Lean-BIM integration and joint implementation. They also can contribute to addressing the identified wastes and barriers to the Lean-BIM joint implementation in the context of the company, and to increasing the efficiency in mid- and long-term through the reduction of errors, which occur due to the lack of communication and collaboration between the Lean and BIM experts. Eventually, they may contribute to getting the TMMs of the Lean and BIM experts closer and achieving encouraging outcomes for all stakeholders of the company, including BIM and Lean teams, clients, and contractors.

Based on the results and findings, prioritising the cognitive studies and functions such as applying proposed recommendations affiliated with mental models (i.e. improving the practitioners' motivation, taking cognitive consultation, etc.) should be an important concern of the management at the company. Moreover, alongside the prior research, the findings of the current research imply that the “groupthink bias” creates a serious obstacle for the collaboration between different teams; this should be further studied.

As explained above, the findings of this research can contribute to enhancing the efficiency in the company by introducing an innovative approach of Lean-BIM interface based on developing the third role of the “practitioner with both BIM and Lean knowledge and skills”. This research considers the aforementioned role as a facilitator to support the practical measures proposed to the company in order to enhance the Lean-BIM joint implementation important. This requires exploring the necessary characteristics of the merged role (Lean-BIM practitioner) in future studies.

Furthermore, as stated in this paper, BIM team’s and Lean teams’ members may function further collaboratively provided that they become more aware of the direct benefits and outcomes of the Lean-BIM joint implementation for them. This introduces a topic to be considered by researchers in future studies.

The analysis presented in this paper was limited to a single case company. Expanding this study to more companies will be useful for generalizability. Moreover, the lack of awareness of the participants about the notion of TMM and its terminology might have affected the accuracy of the responses and analyses.

The dynamics between Lean and BIM teams in organisations is also very much open to study and analysis from a behavioural management perspective (e.g. the cognitive dissonance theory, reinforcement strategies, antecedent/behavioural approaches, organizational forgetting), which could be exploited in future research.

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HOW DOES *FLOW* IMPACT DATA CENTER ROOFING DURATIONS? A CASE STUDY

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ABSTRACT

Throughout the last few decades, a slow shift from the Critical Path Method to other, flow-focused scheduling methods has occurred in the industry. However, they have not yet been widely implemented by construction companies. This case study was conducted on a private data center project on a large site in which the project team has applied Takt time, pull planning, and location-based scheduling (i.e., Takt planning). The case study takes into consideration the roofing schedules for five buildings constructed over a span of three years and compares their total roofing task duration before and after the implementation of these techniques. The analysis has shown that a focus on flow and implementation of Takt planning on a large data center project decreases the overall duration of roofing construction tasks. This case study serves as a support for the transition from the traditional Critical Path Method to Takt planning or a flow-based approach since it has effectively decreased total roofing duration in this project.

KEYWORDS

Takt planning, location-based management (LBM), flow, pull planning.

INTRODUCTION

Scheduling using flow-focused methods isn't widespread in the construction industry. More commonly used is the Critical Path Method (CPM) created by Morgan R. Walker and James E. Kelley (1959). CPM was developed as a cost and resource optimization model and helps contractors focus on a common goal (Kelley & Walker, 1959). CPM optimizes construction by listing critical tasks and the order in which they should be completed so as to decrease overall construction and to estimate total construction duration for the project. In practice this optimization model soon changed into a management and planning technique (Koskela et al., 2014). The schedules created by CPM must consist of optimal tasks for the method to be effective. Issues have arisen in its application since there was no verification that the tasks in the schedule were optimal, leading to CPM producing unpredictable results (Jaafari, 1984; Koskela et al., 2014).

Flow methods differ from CPM by focusing on the importance of the quality of the process as opposed to merely achieving deadlines (Sacks et al., 2017). Emphasizing the importance of the process results in improved reliability and decreases the likelihood that delays on one task will delay the entire project (Bertelsen et al., 2007). Flow methods also

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contrast activity-based methods for scheduling because they consider all activities and objects as interconnected (Kenley, 2004; Garcia-Lopez et al., 2019). From the idea of flow, first found in the manufacturing industry, comes pull planning, the Last Planner System®, location-based management systems, and Takt planning (Ballard, 2000; Frandson et al., 2013; Kenley, 2004; Kenley & Seppänen, 2020; Yassine et al., 2014). All prioritize recognition of the interconnectedness of activities with the goal of creating more reliable projects and improved scheduling in construction.

The purpose of this case study is to analyze the impact of flow scheduling on a large-scale repetitive project. This analysis provides support for the use of flow-based schedules using Takt time, pull planning, and location-based scheduling as a guide. Generally, in lean, these are called Takt planning schedules, but flow-based schedules or flow schedules will be used interchangeably with Takt planning in the paper since that was the title given to these schedules by the general contractor of the case study project. This research was approached with the hypothesis that using Takt planning would result in faster and more effective construction. Analysis of the roofing schedules of the data centers was completed through comparison of both start/completion dates and duration for the scheduled tasks before and after the implementation of Takt planning. The analysis supports the idea that an increased focus on flow resulted in an overall drop in duration for the completion of roofing tasks. The case study is unique in the sense that it is a large-scale repetitive project which spans several years and several buildings. The buildings that have been constructed for the project are almost identical. Therefore, a comparison between the schedules for the buildings is a valid method for analysis. Although the findings are unique to the case study project, this research and analysis has shown that the shift from CPM to Takt time, location-based scheduling, and use of pull planning can lead to shorter construction periods.

LITERATURE REVIEW

Traditional schedules focus on the ordering of critical tasks required to finish construction. Although these tasks are necessary, activity-based scheduling methods prevent maximum efficiency from being achieved. CPM is one such activity-based scheduling method. Yet, despite its failure to create maximum efficiency it has been called the "most important innovation in construction management in the 20th century" (Koskela et al., 2014). It received such high praise based on its apparent ability to bring order and focus to the construction industry. However, more recent studies suggest that CPM prevents maximum efficiency from being achieved and acts as a zero-sum game (Sacks & Harel, 2006). CPM often lends to each trade making decisions in their best interest instead of the best interest of the project meaning that some trades will get ahead while others are put at a great disadvantage. Activity-based scheduling methods such as CPM struggle to be applied to construction because each construction task is too big, resulting in unpredictability and unreliability (Kenley, 2004; Koskela et al., 2014). Unpredictability and unreliability are the problems that flow-focused methods seek to solve. As such, flow-focused methods have been researched and applied in attempt to find better ways to manage construction sites.

After manufacturing was revolutionized by the Toyota Production System, Koskela realized that several concepts could be applied to construction (1992). Shingo's study on the Toyota Production System introduced two flows that work together to result in greater overall flow: operation flow and process flow (Shingo & Dillon, 1989). Although both operation flows and process flows are applicable to the construction industry, construction often emphasizes process flows (Sacks et al., 2017). There are two significant differences between construction and manufacturing that make flow difficult to apply. In construction the workers move around the project as it grows as opposed to having the project move to the workers (Tommelein et al., 1998; Kalsaas & Bolviken, 2010). Additionally, each project in construction is unique, making flow much more difficult to achieve (Bertelsen et al., 2007). These difficulties have led to both a slow transition away from CPM, and a large sum of research on how flow-based methods can be beneficial in construction.

In the construction industry, flow references any method that reduces variability and thus increases reliability (Tommelein et al., 1998). This often occurs by reorganizing resources so as to result in synchronized progress among all of the trades (Yassine et al., 2014; Tommelein, 2020). Building on the more generic 'process flow' presented by Shingo, Koskela classified seven specific flows that can help achieve overall flow in construction: labor, equipment, workspace, materials, precedence, information, and external flows (Shingo & Dillon, 1989; Koskela,1999). Other literature in construction builds on these seven flows or adds their own types of process flows to the list. However, there are two that are most heavily discussed and will be considered in depth: workflow and spatial flow.

Workflow refers to the flow of work within each trade and between each trade. When it comes to workflow, changing from a push planning method to a pull planning method can greatly increase the workflow in construction. Where push planning seeks to meet deadlines without regarding the feasibility of the work assigned, pull planning starts with the trades and asks what they can commit to accomplishing in a specific time period (Ballard, 2000; Khan & Tzortzopoulos, 2015). One example of a pull planning application is found in the Weekly Work Plans in Ballard's Last Planner System® where the subcontractors meet each week and use pull planning to schedule what work will be done before they meet next (Ballard, 2000). Weekly Work Plans have shown an increase in Percent-Planned-Complete for each week, thus increasing workflow reliability (Khan & Tzortzopoulos, 2015). However, workflow in construction consists of more than just pull planning techniques.

Spatial flow is a second general 'flow' researched most likely due to the fact that space is one of the most valued resources in construction (Häringer et al., 2019). In fact, having multiple trades working in the same area reduces productivity for all, and having space where no work is being completed is a form of waste (Deschamps et al., 2015; Sacks et al., 2017; Binninger et al., 2019). Therefore, the space use on a construction site must be maximized. Location-based scheduling recognizes the importance of spatial flow in construction by treating space as a resource to be divided among the trades (Kenley, 2004). It differs from activity-based scheduling methods by assigning each trade a space in which to work as opposed to scheduling a task to be completed (Kenley, 2004). Maximizing spatial flow results in more trades working on the site at the same time and furthers the development of the project. As aforementioned, using these location-based techniques with Takt time allow for greater overall flow to be achieved (Kalsaas & Bolviken, 2010). Not only does spatial flow refer to the development of location-based scheduling, it also generally refers to the impact of the physical movement of workers and products on flow (Alves et al., 2000). Alves (2000) also states that spatial flows should be considered in order to minimize unnecessary movement and increase mobility between work sites. Thus, all trades, work assignments, and products should be considered and managed in a way that maximizes the utility of space and increases spatial flow.

Takt time planning is used to increase both workflow and spatial flow by maintaining continuous work in all areas of the construction site (Sacks et al., 2017). Takt time planning is a combination of pull planning, location-based scheduling, and Takt time. The first decision when implementing Takt time planning is to choose a Takt time, essentially a cycle time, chosen with consideration to the demand of the customer (Frandson et al., 2013). A Takt time determines what size of task each trade should complete in the specified time, and the amount of space they will occupy. Choosing an aggressive Takt time, such as one day as opposed to a Takt time of five days would result in smaller, more detailed tasks scheduled for each trade as well as the occupation of a much smaller area on the construction site (Chauhan et al., 2018). Therefore, Takt time planning works in conjunction with location-based scheduling in order to break up tasks to fit smaller workspaces. An optimized Takt time will result in the trades completing construction at a rate that matches the demand of the customer exactly (Hopp & Spearman, 2008). Breaking up the tasks to fit a Takt time creates a rhythm of work and ensures workflow reliability (Binninger et al., 2019). Takt planning also allows for early recognition of workflow issues (Frandson et al., 2013; Kujansuu et al., 2020). Furthermore, it leads to an increase in workflow due to use of capacity buffers instead of time or space buffers (Kujansuu et al., 2020; Tommelein, 2020). A capacity buffer means that a slower trade might make up work on days not scheduled or have another worker come in to help speed up the work (Yassine et al., 2014; Tommelein, 2020). On the other hand, trades that move quickly reduce their capacity to keep the Takt time. The research done on Takt time planning has proven its efficacy as a method for improving workflow and spatial flow.

Flow is challenged by both the prominence of CPM in the industry and the concept of resource efficiency. Flow maintains a customer-value focus whereas resource considerations value achieving the lowest production cost possible (Wernicke et al., 2017; Binninger et al., 2019). Also, maximizing resources through flow may lead to more waste in other areas, making it appear as a trade-off instead of an entirely beneficial system (Ebbs & Pasquire, 2018). Therefore, although flow may result in greater reliability and less variability, it can increase the cost of construction and may result in greater waste in other areas. The combination of these two downfalls to flow can lead to hesitance on the side of contractors to adopt it as a viable method for construction scheduling.

Starting with the Toyota Production System that revolutionized manufacturing, the concept of flow continues to be studied in depth. The construction industry has been able to apply this concept specifically through the development of pull planning, a greater awareness of spatial flow, and Takt planning. Although there are some challenges to flow, a shift to scheduling with an emphasis on flow continues to be supported by recent research findings. The case study detailed in this paper will serve as a specific example of the impact of changing from a traditional construction model to a model focused on flow.

METHODOLOGY

The research done used a case study methodology to discover the impact of the use of Pull planning, location-based scheduling, and Takt time on the duration of roofing task construction in a project. A case study methodology refers to the exploration of a concept in a removed manner. Instead of conducting experimental design research, the researcher collects data from a natural setting in order to arrive at a conclusion about their topic of interest (Crowe et al., 2011). Case studies are inherently valuable due to their ability to apply theoretical concepts to real-life situations and allow for a better understanding of complex topics (Crowe et al., 2011). A case study approach is a valid form of investigation for the topic of the paper since research was completed on the impact of newer scheduling methods in construction and was conducted on a topic of study over which the researcher could not control the outcome (Yin, 2013).

Despite its value as a methodology, case studies have distinct limitations. A notable limitation is that the results from case studies cannot be applied to all situations since they are case specific (Crowe et al., 2011). However, these limitations are overshadowed by the value they provide in growing an understanding of theoretical topics applied to real-life contexts.

The methodology within this case study combines empirical analysis with qualitative information from an on-site Lean Innovation Manager. Numerical data from various schedules were analyzed by tabulating information on start and end dates for each task as well as the duration of each task in the schedule. During analysis, two different types of schedules from the project were consulted: schedules developed using CPM in the early stages of the project (for all buildings 1-6) and schedules developed using flow-focused methods for buildings constructed in the later stages of the project (5-6). The quantitative results for the different schedules were compared and further analyzed to determine the impact of the flow-focused methods on roofing construction periods and durations. The second part of the methodology was an iterative process of discussion with the Lean Innovation Manager. Bi-weekly meetings were held to check the progress of the data analysis and verify the interpretation of the data. During discussions the current results were reviewed in conjunction with clarification on how the data was analyzed and what other data would be beneficial to investigate the impact of flow-focused scheduling.

Data collection and analysis occurred during the construction of the final part of the project and thus Weekly Work Plans were also consulted to verify the information and conclusions from the analysis.

FINDINGS AND DISCUSSION

FLOW METHODS IN THE CASE STUDY

In the case study, the general contractor changed their scheduling approach from CPM to flow methods. The implemented methods include Takt time, location-based scheduling, and pull planning. The project consisted of the construction of five large data centers. The first three buildings (1-3) were scheduled using CPM while flow scheduling was implemented during the construction of the final two buildings (5 & 6). All the buildings in the project are essentially identical and have the same floor plan. Data from schedules (both projected and as-built) include both CPM scheduling techniques and flow-focused scheduling techniques. The existence of two different types of schedules for the construction of essentially identical building in the same project allows for the impact of the flow schedules to be determined within the case study without any specific experimental design by the researcher.

The Lean Innovation team on the project decided to implement a Takt time of one day. This means that in the large buildings being constructed, the areas for construction would need to be broken into much smaller pieces and the tasks altered to fit the short Takt time. This change was reflected between the two schedules. The flow schedules include more area assignments for construction. For example, in the CPM schedules the roofing tasks are assigned to an Area (A-E) while the flow schedules are assigned to an Area (A-E) and a cardinal direction resulting in seven more construction zones for the low roof (the buildings have both a low roof and high roof). Some tasks were broken into smaller pieces resulting in more roofing tasks in the flow schedules. It is important to note that although there is a Takt of one day, it doesn't mean that every roofing task was completed in one day just that roofing was scheduled day-by-day in a highly detailed manner in order to maintain a rhythm. The flow schedules are included below but due to the confidential nature of the project, the CPM schedule is not.

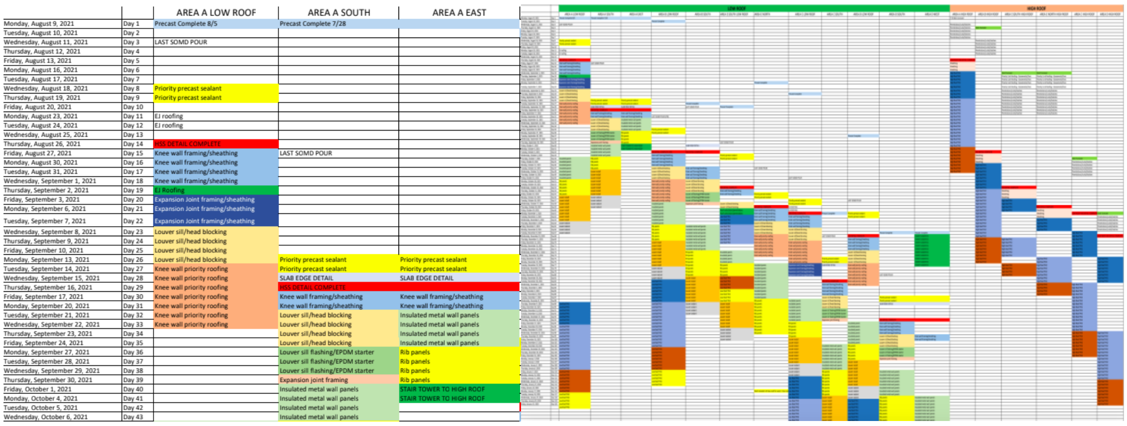

Figure 1: Flow Schedules (Takt Planning Chart)

In addition to splitting up the buildings into more construction zones, the Lean Innovation team addressed spatial flow by changing the order of the construction of the areas in the centers. Originally construction would start in Area E since it was the area that contained the most electrical work, then move outward to Area A and continue in alphabetical order from there. However, after the implementation of a flow-based system construction flowed through the areas in the order which the areas were located, going from Area A to Area B, Area E, then Area C and Area D. This simple change decreased the waste that occurs from unnecessary movement among and between the trades while moving from one Area to another. A map of the layout of the areas is shown in Figure 2.

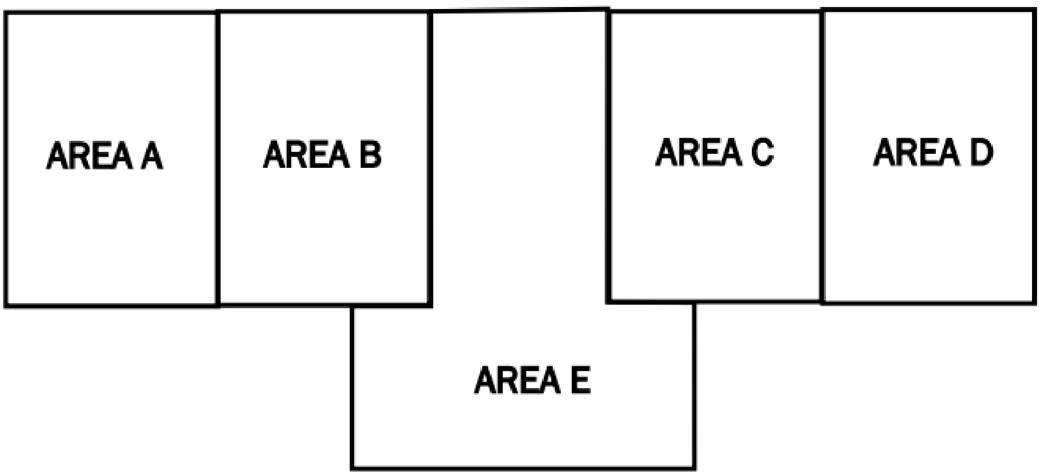

Figure 2: Building Layout with Areas

The schedules were also impacted by pull planning methods. Each week the contractors and subcontractors met and constructed a Weekly Work Plan (Ballard, 2000). The Weekly Work Plans (WWPs) reflected the Takt time of one day while also pull planning through the entire upcoming week. Although both the flow schedules and CPM schedules constructed for the project were created by superintendents with the job of creating and managing the schedules, the WWPs allowed for pull planning later in the project by updating the flow schedules to be as built and match current progress of the project. The flow schedules were updated to match current progress and aided by the WWPs for future work to be done. All schedules analyzed were up to date, reflecting the current progress and duration of roofing tasks despite the ongoing construction.

The combination of these changes to scheduling methods led to the current flow schedules used for the project.

FINDINGS FROM ROOFING SCHEDULE DATA

The roofing schedules were tabulated and analyzed in order to determine the difference in construction time between CPM schedules and more flow schedules. Roofing schedules were chosen for analysis since the research team was able to get in contact with the project coordinator of the roofing schedules and it was confirmed that Takt planning had been fully implemented in the roofing tasks. The data gathered include the duration and the start and end work dates for each roofing task and the total duration and start and end work dates for all roofing to be completed (for all buildings 1-6). All CPM schedules and flow schedules created for the project were sent directly from the Lean Innovation Manager, including a live document with WWPs and as-built flow schedules. The data was analyzed by summing the total work days required to complete all roofing tasks with overlap (adding the duration for all roofing tasks together regardless of date start and end overlap between tasks), without overlap (the amount of calendar days in a 6-day work week from start to end of construction), and the total number of tasks for each schedule. The tasks were labelled with their respective Area (A-E) and cardinal direction (if applicable). The tabulated analysis, as shown in Figures 3 and 4, does not reflect the Takt time, merely the total number of days to complete each task in order to determine the impact that flow has on overall efficiency and duration for roofing.

F Task	F Start	F Finish	F Duration
Area A Tasks and Dates			
Area A Priority Precast Sealant Low Roof	8/18/21	8/19/21	2
Area A HSS Detail Complete Low Roof	8/26/21	8/26/21	1
Area A Exterior Knee Wall Framing/Sheathing Low Roof	8/27/21	9/1/21	4
Area A EJ Roofing Low Roof	9/2/21	9/2/21	1
Area A Expansion Joint Framing/Sheathing Low Roof	9/3/21	9/7/21	3
Area A Louver Sill/Head Blocking Low Roof	9/8/21	9/13/21	4
Area A Knee Wall Priority Roofing Low Roof	9/14/21	9/22/21	7
Area A Insulated Panels Low Roof	10/7/21	10/15/21	7
Area A Rib Panels Low Roof	10/18/21	10/22/21	5
Area A Louver Install Low Roof	10/25/21	11/3/21	8
Area A Louver Sealant Low Roof	11/4/21	11/9/21	4

Area E Tasks and Dates			
Area E Exterior Knee Wall Framing/Foam/Sheathin (Low Roof to PH) - South	11-9-21	11-10-21	2
Area E Louver Sill/Head Dtl/Blocking Low Roof - South	11-11-21	11-12-21	2
Area E MEP Curbs and Penetrations (Low Roof)	11-15-21	11-16-21	2
Area E Roofing Low Roof Phases 1-2 (Conc Deck) North	11-17-21	12-1-21	9
Area E Insulated Metal Wall Panels (IWP/Tape) Low Roof South	12-2-21	12-7-21	4
Area E Rib Panels Low Roof South	12-8-21	12-13-21	4
Area E Low Roof Phases 3-4	12-14-21	12-27-21	8
Area E Louvers and Sealant Low Roof South	3-28-22	4-12-22	12
Area E Exterior Knee Wall Framing/Foam/Sheathing (Low Roof to PH) North	11-11-21	11-16-21	4
Area E Louver Sill/Head Dtl/Blocking Low Roof - North	11-17-21	11-22-21	4
Area E Knee Wall Priority Roofing - Low Roof	11/23/21	12/3/21	7

Figure 3: Example(s) of Organization of Quantitative Data from Roofing Schedules

Area D High Roof Phase 4	1/13/20	1/20/20	6	
Area D High Roof Phase 4 Part 2	2/27/20	3/12/20	6	
Start to End Date (actual construction):	**1/14/19-7/7/20**	**Total Duration (original then actual? with and without overlap):**	**1567**	
			without overlap: ~458 days (six day work with w/ 5 holidays)	
# of Tasks:	96			

Figure 4: Example of Quantitative Methodology

After all the data for the roofing schedules were summarized, they were compared to one another through numerical summary in the form of a graph. Graphs were constructed in order to allow for visual recognition of a pattern that may exist between the duration of construction, the number of tasks in construction, and the type of scheduling method utilized (Figure 5). Additionally, for the last building, complete CPM schedules and flow schedules were analyzed and compared to account for the fact that other results may be due to differences between each building, despite their similarities. A general trend in the graphs shows that flow scheduling results in a shorter roofing construction period both with and without overlap in work days, and a greater number of tasks. The duration of some individual tasks increased in the transition to a flow-focused model. For example, the task ‘Area D Low Roof Phase 2’ increased in duration by two days when the schedules changed from CPM to flow schedules. However, the overall durations for roofing construction have decreased. In the graphs comparing all the buildings, flow schedule data was used only for Building 6 since a complete roofing flow schedule for Building 5 was unable to be acquired.

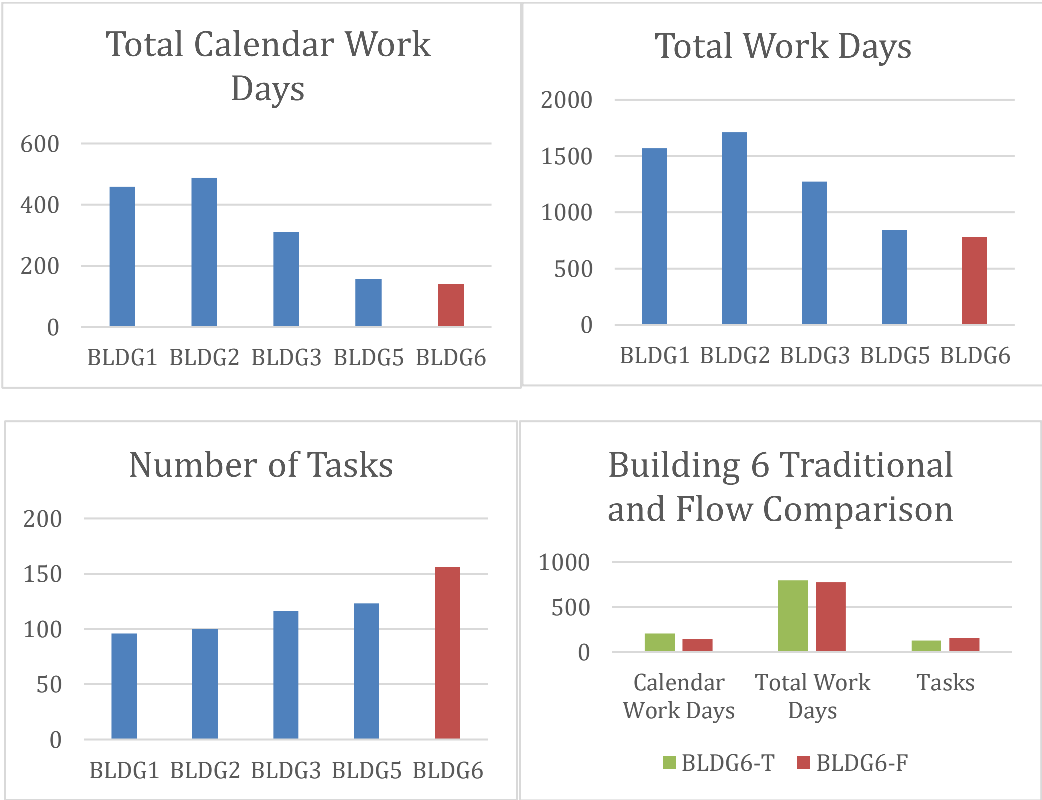

Figure 5: Graphs with Data Summary

The average for durations and number of tasks for CPM schedules were taken. This data was then compared to the scheduling data for the flow schedules of Building 6 in order to quantify the trends and overall impact that the flow schedules had on roofing construction duration. These calculations found that the total work days decreased by 72.9% in the flow schedules as compared to the average total work days for the other buildings. The total calendar work days decreased by over 200% on average. The number of tasks required for roofing increased on average by 43.4%. However, the data from Buildings 1 and 2 were skewed due to COVID-19 shutdowns in early 2020. Therefore, the same calculations were completed after removing the data from Buildings 1 and 2. These new calculations show that flow schedules resulted in an average decrease of 35.4% in total work days, a 64.8% decrease in calendar work days, and a 30.5% increase in total number of roofing tasks. Similar calculations between CPM schedules and flow schedules for Building 6 shows a 2.7% decrease in the total number of work days, a 42.9% decrease in the total calendar work days, and a 23.8% increase in the number of tasks for the roofing construction of the building.

Qualitative Data Findings

An iterative process of unstructured interviews with the on-site Lean Innovation Manager revealed that the findings from the data accurately reflected the impact of implementing Takt time, location-based scheduling, and pull planning on the efficiency and quality of construction. This process also revealed that the general contractor had received positive feedback from subcontractors that have transitioned to flow methods, despite their original doubts. Therefore, the empirical summary of the case study is supported by qualitative data from regular interviews with an on-site manager that has been involved in the shift from more traditional scheduling techniques to flow scheduling techniques.

LIMITATIONS TO THE FINDINGS

There are some clear limitations to the findings. The method only looks at one area of construction as opposed to the entire construction project, acting as a case study within a case study. Therefore, the results only reflect whether roofing efficiency has been improved. Additionally, there only exists one complete flow schedule for the five buildings. Since there is only one complete data point from which to understand the impact of flow schedules on construction time, the change in duration could be a result of the learning curve of the construction crews. Additionally, the construction of two of the buildings was directly impacted by the COVID-19 shutdown in early 2020. The case study was also conducted during the construction of the last building, meaning that the full impact of the flow methods on roofing in the project has not yet been realized.

However, despite these limitations, steps were taken to ensure a valid analysis of the efficiency of the different methods for scheduling. For data analysis, roofing was chosen for analysis (instead of all tasks in the building) to allow for a greater understanding of the impact flow methods had on the tasks. It was also chosen because it was revealed through interviews that the roofing subcontractors had effectively implemented the flow techniques meaning that the change in roofing duration before and after the implementation of flow schedules would accurately demonstrate their impact on duration and efficiency. Both schedules were considered for Building 6 in order to show that the impacts of flow were not merely due to a learning curve. When asked about COVID-19, those working on the project responded that the durations of the tasks were correct, but the total completion time was not. Therefore, the different data summaries help to balance out the results from the impact of COVID-19 on the total number of days for the completion of the roofing for each building. Furthermore, when computing the same calculations after removing the data from Buildings 1 and 2, the results continue to show a significant drop in both work days and calendar work days as a result of flow scheduling. Lastly, the data analyzed was as-built even if not fully constructed. Therefore, despite ongoing construction, the data still reflects the impact of flow-focused scheduling methods on construction duration.

The limitations must be considered in the interpretation of the results of the case study but do not undermine the findings of the case study.

CONCLUSIONS

A case study was conducted on a private construction site to determine the impact of the transition to flow methods such as Takt time, pull planning, and location-based scheduling has on the duration of roofing construction. Empirical analysis and qualitative data collection have supported theories proposed that a shift to flow methods decreases construction duration greatly. In the case study, on average they led to a 72.9% decrease in total work days and over a 200% decrease in calendar work days required for total roof construction. The case study also shows that a transition from traditional scheduling to flow scheduling results in an increase in the number of tasks required to complete construction. Although the results are specific to the case study, they support a transition to flow-focused scheduling methods. Further research should be conducted to determine the impact of flow methods on other types of projects such as those of a much smaller size and on projects of a less repetitive nature in order to discover whether the findings to this research are unique in nature. To conduct this research, similar methods may be used but will be specific to their respective project.

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PROJECTS ARE BECOMING 'LEAN', BUT NOT ORGANISATIONS

Paramjit Singh Lota[1], Vijayashree TM[2], and Bhargav Dave[3]

ABSTRACT

There is significant evidence of successful lean implementation at the project level. However, there is limited evidence of lean percolating through organisations in both literature, as well as industry. While the critical aspects of strategic adoption of lean to overcome organisational resistance have been clearly highlighted, the implementation is in most cases limited to select projects and not all projects across an organisation's portfolio.

Despite proven benefits on projects within their own portfolio and the knowledge and skills for successfully implementing lean, organisations still fail to change their approach towards continuous improvement and driving efficiency as a whole. The paper here focuses on the need for a revised approach towards the adoption and sustenance of lean within companies at a business level by highlighting the importance of culture across the company's portfolio.

The authors reflect on their experience of working with client and contractor organisations across multiple projects to review the difference in the maturity and implementation of lean. Following this, the authors corroborate their findings from discussion with a major public sector body and its supply chain on their lean journey over the last decade, to shed light on the approach needed today for successful lean implementation for organisation-wide sustenance.

KEYWORDS

Lean Construction, Lean Culture, Lean Implementation.

PAPER STRUCTURE

The paper first highlights the evidence in literature on the success of lean implementation, with a keen focus on the success factors for sustenance of the approach. Following that, limitations of organisation-wise penetration will be evidenced, reinstating the major challenges towards the adoption and implementation of lean.

Post the literature summary, the authors build on their combined experience to highlight the key factors that have made lean implementation a localised success, while being challenged across other projects within the same organisation across other businesses. The authors proceed to elaborate on the hypothesis with a semi-structured interview conducted with multiple lean practitioners for providing a discussion on the key factors addressing the research question.

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LITERATURE REVIEW

Research has provided immense evidence (a review of multiple "lean implementation/ lean culture" paper from IGLC itself) highlighting the limitations of isolated attempts at implementing lean to successfully percolate across organisation strategy (Kalyan et al. 2018; Neto and Alves 2007). Pekuri et al. (2012) highlight the problem of localised adoption of lean in organisations through the application of a few lean tools and process in some projects.

The Last Planner® System (LPS) (Ballard 2000) for collaborative planning has had immense success in driving this supply-chain inclusive approach towards lean outcomes, followed by other lean tools such as Kanban (Kim et al. 2007). A bottom-up approach to building a case for benefits obtained from lean implementation through LPS has been highlighted across numerous studies (Delhi et al. 2017). Tillmann et al. (2014) further emphasise this approach by highlighting the importance of participating with teams at the ground level to enable a cultural transformation towards lean outcomes.

Adoption of lean in organisations require changes in the overall business processes that needs a structured approach to sustain these improvements (Dave, 2017). Adoption of such a new business model must be governed by value offering, value creation, and revenue model, with a commitment from the management level (Pekuri et al., 2014).

Kalyan et al. (2018) highlights the critical factors of building organisation-wise lean culture in the context of Indian construction industry, by balancing the bottom-up approach at a project level with the top-down participation from the management across the organisation.

Driving lean initiatives at an organisation level with training and hands-on workshops has had proven success in building a lean culture of trust and participation amongst teams (Kalyan et al. 2018; Hacker et al. 2017; Alarcon and Diethelm, 2001; Delhi et al. 2017; Kim et al. 2007; Jang et al., 2007; Pekuri et al. 2012). This success has been evidently credited to lean leaders responsible for not just driving the initiative in the first place, but helping the implementation sustain through time (Tillmann et al. 2014; Alarcon and Diethelm, 2001). However, this approach is a double-edged sword since the dependence on a select few people can leave projects and teams crippled when such resources are not part of the organisation any longer (Neto and Alves, 2007).

Hackler et al. (2017) and Pekuri et al. (2012) both highlight the importance of building a lean culture within the organisation through a focus on people and lean principles, rather than tools and techniques, the rigidity and theory of which proves to be a critical factor for resistance from the teams. On the flip side, Neto and Alves (2007) emphasise the importance of strategic alignment of lean implementation with the company's goals as the first step, before considering lean tools or principles at an operational level. Failure to implement the lean business model at an organisational level can lead to friction and conflict amongst teams across the company's business verticals (Pekuri et al., 2014).

The balance of lean maturity between General Contractors (GC) and sub-contractors plays a significant role in the overall success of lean implementation on the project. Kim et al. (2007) evidences the positive impact of lean through increased plan reliability of a sub-contractor, the outcome of which was the adoption of lean by the GC itself. Jang et al. (2007) reinforces the need for active involvement by both parties towards improving collaboration and communication between the teams. Specifically crucial in this case was the role of the GC as the lean driver, supporting the sub-contractors through the implementation.

Technology plays a key role in enabling lean adoption (Kalyan et al. 2018), simplifying collaboration and information exchange across the projects to enable lean outcomes. Including a production management system with real-time updates has proven to be a driving factor for sub-contractor participation (Jang et al., 2007)

"One person cannot make a project lean. But one person can promote lean philosophies to a project team and foster a collaborative environment where these principles take root and are applied" (Hacker et al. 2017).

KEY FACTORS TO LEAN IMPLEMENTATION

In summary, the literature review highlights the following key factors towards driving the adoption and sustenance of lean implementation in the construction industry.

People in Leadership

Top-level management involvement plays a key role in enabling and driving the implementation of lean practices and culture within the organisation (Alarcon and Diethelm, 2001). Constant participation and observation by management is the key to sustaining the culture amongst the teams (Delhi et al. 2017).

Respect for People

Korb (2016) goes on to highlight the importance of "Respect for People" as a crucial driver towards sustaining lean practices within an organisation. Continuous improvement as a culture is heavily dependent on building an atmosphere of trust and mutual respect within the people, without which every CI initiative is ad-hoc and lacks the ability to sustain at an organisation-level.

A bottom-up Approach

Involving the teams at the ground-level for any lean initiative, either driven through a cultural approach or through lean tools, becomes extremely important to ensure the adoption and sustenance of lean (Kim et al. 2007; Tillmann et al., 2014; Delhi et al., 2017).

Business Opportunity

There is a need for the management to understand the strategies and business models before they decide to implement lean. The adoption of lean is heavily driven by business development, with a commitment by the team to deliver business improvement at various stages as the company grows (Kim et al. 2007). Having the 'lean' edge offers a competitive leverage in the construction market today.

HYPOTHESIS

The authors hypothesise that while lean tools and principles have evident potential in improving construction project delivery, the implementation in the industry today is limited to select projects, and not the organisation as a whole.

The authors acknowledge that success recipes for lean adoption, developed through pilot experimentation, need to be standardised and implemented using a balanced top-down and bottom-up approach across the portfolio of projects. A key role here is played by participating lean champions through working closely with teams at the ground-level.

The authors believe that a revised approach is needed to ensure the adoption of lean at the organisation level. While there are various contributing factors, as mentioned above, a key focus is needed on the overall business culture that can help sustain the implementation of the defined lean-processes and tools within the organisation.

THE TYPICAL LEAN JOURNEY

From their experience, the authors have noted a general trend in projects adopting lean. More and more clients are starting to demand efficient project delivery through proven competence. Driven by a motivation for bigger clients, profit, and business advantage, contractors in the industry are starting to deploy resources and tools to drive efficiency on such projects. This is generally where the localised implementation of lean stems from.

CONTEXT

As technical support to a lean tool on these projects, as well as lean champions driving the implementation within organisations itself, the authors' have been involved in the capacity of

- Working with clients who are top construction companies (in UK, Europe, USA)
- Working on 15+ Projects including hyper-scale Date Centres (over 500 M€)
- Working on various types of projects, ranging from Airports to Highways,
- Interacting with the clients on a weekly/bi-weekly basis through direct conversation, participation in various collaborative planning & review meetings, and strategy ideation & deployment meetings.

Pilot Projects

A lot of experimentation takes place in such projects; lean initiatives are introduced, lean champions driving the adoption start to emerge within the organisation, processes are revised, and lean tools/technology are deployed to further the implementation. While the first projects are experimental, this approach replicated across a few more prominent projects starts to shape some of these protocols towards performance improvement, tools that are playing a critical role, and lean champions who seem to be driving project benefits.

Lean Strategies

From a stand-point of execution specifically, some of the tools and practices commonly adopted on such projects are highlighted below.

- Production Planning and Control Protocols
- Sticky-note Planning
- Last Planner® System
- Lean induction for each Trade/Sub-contractor
- Work clarity through Daily Activity Briefing and Weekly Work plans.
- Digital lean tools
- BIM-tools to support efficient decision making (4D Visualisation, CDE, etc.)

Success Stories

These projects tend to become successful case studies – flagship projects that start to shape the future businesses of the organisation. Benefits and testimonials start to pull in similar large clients and the pilot project 'A-team' is deployed to continue this approach on such new projects. Supported by careful attention and amplified funding from management, and established protocols (the likes of which have been highlighted above), these projects become the foundations of a lean portfolio, which become the 'lean' impression of the organisation in the industry.

Ground-reality

While these pilot projects become exemplary demonstrations of lean benefits, the percolation within the organisation, at a deeper review, proves to be very shallow. This practice is evident across multiple projects, where on paper numerous processes and lean protocols would be established, however, the ground-reality would be evidently different.

PROBLEMS WITH THE TYPICAL APPROACH

As far as lean ´adoption´ is the target, the implementation tends to be quite challenging and limited to select projects. This is because the entire focus is taken away from the benefits of deploying lean to achieve efficiency in project delivery and performance improvement, and instead looked at as a check-box exercise of doing ‘lean’. Some of the key problems with this approach are highlighted below.

Resistance

The top-down approach of lean implementation faces significant resistance at the ground-level, as observed in most of these projects. New processes and tools are challenged by teams on-site and external participants as consultants or sub-contractors. Often, lean champions find it difficult to even get participation from the teams, which often reflects poorly on the initiative and hence, more resistance from the management as well.

Ad-hoc Approach

With conventional processes as the norm within the organisation, plugging in lean at every stage becomes an ad-hoc approach towards performance improvement. While this approach does provide localised benefits, it fails in changing the overall approach towards project delivery, hence, overlooking the business processes as a whole.

Push-based Approach

Instead of driving a pull-based approach, lean is pushed to the ground through tools and processes. This approach, being contextual to the project and team it is deployed on, faces challenges when replicated across other projects and business verticals.

This push in the industry is categorised by the deployment of lean tools at each stage. The implementation of lean tools is referred to as “lean implementation”, while the target of achieving lean outcomes is isolated out of the equation completely.

This becomes a major challenge towards delivering efficiency; while the deployment of lean tools will reassure clients and the industry that the organisation is lean capable, the achievement of any actual success in terms of value generation is still vague.

Lack of Faith

When project teams at the ground-level start to see through this fragile approach, there is no faith and reassurance in the approach, thereby limiting any potential of taking a similar approach on other projects. Therefore, the ground-reality is always different, and a simple *Gemba* can start to highlight the reality very clearly.

This is where the real challenge of lean implementation in the industry sits, and all the ad-hoc localised approaches to its adoption stem from.

INTERVIEW WITH LEAN PRACTITIONERS

The interview conducted by the authors has been used as a central point to orbit the literature reviewed and authors’ own experience around. The interview was profiled with the intent to include the entire supply chain for a major public sector body in the United

Kingdom. The supply chain involves various sub-contractors, who have been part of numerous projects, some even participating through joint ventures through various stages of the projects.

The semi-structured interview broadly covered the following categories:

- How lean initiated within these organisations
- Factors that helped them to expand the lean initiative further across various teams
- The sustenance of lean within the organisation, today
- Understanding role of client demand and business goals in lean adoption
- Tools and practices for deploying lean across various projects
- Critical success factors for lean sustenance from the experience of the lean practitioners

Please note: The interview was conducted over a two-hour period as a virtual meeting with the participants and authors present together through the entire duration.

The profiles of the participating lean practitioners have been described below.

Table 1: Profiles of Lean Practitioners participating in the interview

Organisation Type	Organisation Description	Profile of Lean Practitioner
Client	Public sector body	Lean Area Manager
Contractor	Civil Engineering Contractors	Lean Manager
Contractor	Engineering & Construction Company	Head of Quality – UK Construction and Group Civils
Contractor	Engineering Solution Providers	Quality, Performance and Lean Deployment Manager
Contractor	Multinational Infrastructure Group	Head of Project Services; Performance, Quality & Business Improvement

CONTEXT

The client started to look at driving lean initiatives back in 2008 towards improving the efficiency of their supply chain in delivering their projects. The initial investment played a very crucial role; the client invested heavily in the training and development of its supply chain, including some of the major contractors participating in these projects today (the participants of the interviews are from these organisations).

While it was certainly unique for a client back then to be adopting this approach, they were convinced that this is the best way to show where the pain-points are to encourage the teams to work towards resolving them. As the lean drive started to build momentum, the supply chain started to see benefits, from where the percolation within their own businesses started to seep through. The adoption strategies were deployed across some more projects, post which the client could start to mandate the use of lean tools and principles on its projects as a competitive offering in the market, rather than having to drive the adoption and training itself.

The primary factors contributing to lean adoption, implementation, and its sustenance within the organisations have been highlighted in the section below, as absorbed from the interview conducted.

INTERVIEW OUTCOMES

Lean Initiation

The initiation from the client was agreed to have been a stick and carrot approach – all contractors were clear of the fact that participation in the lean initiative was essential to sustaining business with the client. This led to the development of an extrinsic approach from the beginning of the lean initiative towards driving efficiency and performance improvement across the supply chain. This implied that a lot of training and mentoring was required to involve teams rapidly towards deploying numerous new protocols that were being pushed down to the site level, by which stage a lot of the knowledge had diluted.

Lean as a Business Driver

One of the contractors of the supply chain in this equation has undergone extensive re-organisation to reinstate business improvement teams that are now selling performance and efficiency driving services to not just other parts of the supply chain, but also to the client. What is interesting to note is the percolation across the supply chain, that had stemmed from the client-driven initiative - the contractor realised that the client itself lacked clarity on what they were expecting and how to efficiently drive the initiative towards a goal. This led to the contractor becoming experts themselves, following the principal approach of generating value within their business, successfully monetising on lean as a business driver.

Leadership Engagement

While the client is driving lean initiatives even today, they do acknowledge pockets of good practices within the business. However, what has remained as a critical factor is the leadership buying into the initiatives with reinforcing actions that really focus on driving improvement. This is further driven by added funding and opportunities, provided by management participation, the absence of which limits the scaling of such initiatives.

With participation from leadership or management, the focus shifts from an extrinsic approach to one which is intrinsic, growing within the organisation and evidencing benefits at the ground-level. You start to see a switch from strategic *jargon* to real-time benefits that can be documented, evidenced, and deployed at the jobsite; this approach is a critical factor for sustaining lean within an organisation. When other business verticals start to take notice, the intrinsic approach spreads across other parts of the organisation, thereby becoming seeds within their own sections to further the growth.

Managing People & Expectations

When lean cultures started to develop within automotive manufacturing, with setups offering relatively high levels of control and minimal variability, it still took organisations years to truly reach a level of sustainable lean. On the flipside, construction is very dynamic with teams constantly switching to different jobsites and locations with completely new teams to work with for a period of time. This makes the sustenance of lean culture within the construction industry incredibly challenging.

By the time you get the systems right, your human resources have generally moved onto another project, where they will encounter a different team at the ground-level and a different management to work with. This leads to hurdles at each stage, leaving teams with a feeling of *“starting-from-scratch"* again. Passion starts to vain within the lean champions themselves, when after all their effort and investment, the project ends.

Training & Support

To overcome this, the practitioners highlighted the importance of consolidated training. A tick-box exercise in the name of “lean induction” leads to no long-term benefits; you want to focus your efforts on where people are going to actually deploy process improvement and embed the learning such that it becomes self-sustained. Balancing the push-and-pull here becomes really important; the management can play a critical role by defining certain expectations from the teams at the ground, for which the teams on the ground can then deploy performance improvement for the management to take notice.

DISCUSSION

With a combined review of both the personal experience of the authors, as well as the interview of the industry experts, it is evident that organisations in the construction industry have started to realise the need for a revised approach to improve efficiency in project delivery. Stemming from this need has been the adoption and implementation of lean tools and practices by some of these organisations.

However, it is evident that lean is yet to become an organisation-wide practice across most cases; numerous of these organisations are still in the pilot project stage or struggling to multiply the learnings and protocols deployed across their portfolio of projects. Some of the key factors governing this for the organisations are:

- The strategic/business decisions
- The role of leadership and Lean Champions
- The culture & training of teams at the ground-level
- The adoption & deployment of standard processes and tools

While these factors have proven to be essential towards initiating and driving lean across these organisations, the factor that has stood out to sustain lean implementation is to develop an intrinsic approach and deploy it with persistence to keep driving the initiative constantly within the organisation, despite changes in management, teams, projects, or business strategies. This sustenance is heavily fuelled by the leadership participation, and lean champions, who can work with teams, offer training and guidance, and continue to encourage them.

Essentially, while the governing factors will always play a role, the inclusion of lean within the organisation’s culture and practices will require constant review of processes, tools, and culture, and most importantly, human resources who can continue to learn and apply the feedback.

THE APPROACH NEEDED

The target for construction organisations should be to deliver smart and sustainable models of project development. To revise your business strategy towards adopting an efficiency-based approach, and as evidenced by Hackler et al. (2017), processes need to be redesigned around the lean principles of value generation and continuous improvement as the defining core.

Learnings from the experimentation on the pilot projects need to be considered when defining the new implementation strategies. This is where the role of Lean Champions is essential in bringing together the benefits from success stories of the bottom-up approach aligned with the management´s business targets. Champions help by working closely with the teams at the ground-level and applying their knowledge and experience to break the notion of returns-on-investment dependency on project scale or type. The fact that lean outcomes are beneficial across any project and keeping the larger picture at the business level in mind, champions can help convince the management on driving this approach across their portfolio of projects. These can be evidenced by:

- Success stories in terms of data – Time & cost savings.
- Building a case for business growth for the organisation
- Protocols & tools that helped teams collaborate
- Feedback and learning through Continuous Improvement loops
- Developing a culture of communication and trust

A structured approach is required to implement the changes in the overall business processes. Teams need to understand the problems with their current state, the potential for improvement, and learn from the benefits achieved from industry case studies or their own pilot projects. Lean sustenance is an iterative process between the ground-level teams, lean champions, and the leadership, to be in constant dialogue and agreement on the implementation strategies. Without standardisation and clarity, managing human resources and expectations proves to be challenging.

This plan must be simple enough for teams across projects and business verticals to understand and implement at the ground level. Standard protocols, agreed by both the project and the senior management team, need to be simple enough for both new personnel and new projects to adopt quickly.

While developing these standard processes and protocols are important, the most critical factor is the culture that the senior management develops with the lean champions and the project teams. Communication and trust among the teams play a vital role here. Leadership can help bring the team to a common collaborative platform, where they can respectfully vocalise their expectations, provide feedback, and find solutions. This ensures there is continuous improvement within projects as well in the strategic plans. Aspects of collaboration, trust, respect and better communication are the main factors that shape the culture of the organisation.

CONCLUSION

From both the authors' experience and the interview with the lean practitioners, it is evident that a top-down approach to push lean initiatives in projects fails to sustain in the long run within the organisation. There are challenges faced at both the business-level, as well as the ground level, by the teams driving the initiative.

With lean implementation being primarily driven by client demand for increased efficiency and timely delivery of projects in the industry today, this approach isolates the implementation to a project or client-level scale, considering only the business value of that project or working with that client. This limits a business-wide implementation of lean while giving a false impression of a "lean" organisation

With the pilot project approach and ad hoc adoption of some lean tools and processes, the teams fail to see the overall picture of why these changes in project delivery are being brought. Without a structured change management process, with proper training and incubation period for teams at the ground, teams find it hard to share the vision and therefore, resist aligning towards the process changes.

Unless there is an overall standard adoption plan along with a continuous improvement framework, these initiatives remain weak and fade away with any change in the human resources within the organization. There is an evident need for an inclusive and collaborative approach, with each stakeholder enabling the other by acknowledging and appreciating the effort being invested into delivering value to one another.

To deploy lean is to constantly focus on one of its own pillars – continuous improvement; lean implementation will be an on-going process and must be championed through by passionate people within the organisation.

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DEVELOPING A MULTI PROJECT-COLLABORATION BASED IPD FRAMEWORK FOR SMALL & MEDIUM SCALE ENTERPRISES IN THE CONSTRUCTION INDUSTRY

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ABSTRACT

Small and medium enterprises (SME) in construction projects frequently struggle to manage labour, materials, finances, and equipment. The Integrated Project Delivery method (IPD) has the potential to solve these challenges. However, the existing IPD framework has a low feasibility rate in SMEs due to technological, financial, and managerial challenges. This is because IPD is a project delivery system that requires adequate capital, communication channels, software, training for workers, etc. which are usually available with large-scale construction projects but not with SME-based projects. Accordingly, this paper proposes a new IPD framework more specific to small and medium scale construction projects by improving the existing framework in terms of resource management and cross-validation of stakeholders. The proposed framework enables the SME projects to acquire and manage the resources for conducting IPD through the concept of "Multi-Project collaboration". In the collaboration, multiple contractors with individual projects cooperate with one another for achieving a positive impact on their performance through the IPD method. This study contributes to the body of knowledge by enabling the construction industry to understand the effective application of the IPD method to SME projects.

KEYWORDS

Integrated Project Delivery (IPD), Collaboration, Alliancing, SME, Challenges.

INTRODUCTION

We are all aware of the fact that not only the construction process is complex, but also the contracting systems used in the industry are complicated. Although much of the innovation and advancement in technology is heavily absorbed by the large-scale companies and SMEs lag behind in adopting such innovation, SMEs still play a key part

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in providing a broader choice for clients and thus are an important part of the construction supply chain ecosystem. For instance, IPD is heavily used in large-scale construction with limited usage in SMEs as there are many costs involved with implementing IPD that SMEs cannot afford. If SMEs are boosted with integrating new technology and innovation, they can drive better performance providing specialist capabilities, agile ways of working, and often independent views & approaches (UK construction media, 2018). In most countries, on average more than 95% of Construction contracting companies are SME however the revenues are barely around 50% of the total economy from the construction sector, this number can be increased if various challenges of SMEs are solved using an integrated project delivery system (Prasad S, 2020).

This paper addresses SMEs in general and not specific to any country. Furthermore, there is hardly a universally accepted definition of SMEs because the classification of businesses on a small and large scale is a subjective judgment (Ekpenyong & Nyong, 1992). The criteria to define SMEs include various combinations of the following: number of employees, financial strength, sales value, relative size, initial capital outlay, and types of industry (Carpenter, 2003). For example, in Ghana SMEs are classified in terms of a number of personnel; micro-enterprise - less than 5 employees; small enterprise - 6 to 29 employees; and medium enterprise - 30 to 99 employees (Oppong et al., 2014). In India, it is in terms of revenue; small-sized - investment up to US$1.3 million, turnover up to US$6.62 million; medium-sized - investment up to US$2.6 million and turnover up to US$13.24 million (Vasundhara R, 2020). In the European Union, it is a combination of a number of employees and revenue; small-sized enterprise - fewer than 50 employees; and medium-sized enterprise - less than 250 employees & annual revenue of fewer than 50 million euros (Liberto, D., 2019). The definitions of SMEs vary both between countries and between continents. However, the managerial and financial challenges almost remain the same except for a few local challenges. Hence, in this paper we are focusing on major challenges in the SMEs, how we can solve those problems using IPD and further changes to the IPD to make it feasible for the SMEs.

LITERATURE REVIEW:

CHALLENGES IDENTIFIED IN SME CONSTRUCTION PROJECTS

A literature review has been conducted on the failure of the SME construction companies in over 6 countries namely the USA, Ghana, Gaza strip, South Africa, UK, and India all of which have different demographics and economies. Although the definition of SME construction in these countries slightly varies, the challenges almost remain the same. The challenges faced by the SME construction companies can be categorized primarily into a) Acquiring the project and b) Handling the project. With thousands of small construction companies starting each year, acquiring the projects in the initial stages is a big challenge for the SME companies due to heavy competition and retaining loyal customers is another big challenge due to contractors' poor standard of delivery in the previous projects (Thwala & Phaladi, 2009). In addition, the lack of support from the government and change in the policies makes it even more difficult for them to survive. The second one is Handling the project which is dependent upon how efficiently the contractor can deliver the project to the owner and how effectively he can earn profits for his company to survive without compromising the quality of the project. This article focuses mainly on the challenge of handling the project as this is particularly where IPD could effectively solve the problems.

The challenge of handling a project is further categorized into Financial and Managerial aspects:

Financial Challenges:

Based upon the research by Bassam Tayeh and Wesam Alaloul, financial challenge is the biggest challenge for the small scale constructions (Tayeh et al., 2019). Delayed payments are very common in small-scale construction projects, where the owner delays the payment to the contractor and the owner is not conscious that most of the small and medium scale construction companies/contractors struggle to survive and fail during the initial years of their establishment (Eke et al., 2015). It was observed that a chronic delay in payment for the work done compounds the problems of small-scale contractors to a whole new level. It hurts their profitability which in turn affects their ability to meet deadlines (Offei et al., 2019; Thwala & Phaladi, 2009). Such cost of payment delays has been a major challenge with these small-medium enterprises. Unlike large construction companies, small-scale contractors operate on shoestring budgets (Offei et al., 2019). They do not have the financial pull to counteract challenges, expand their operations, hire skilled workers and full-time experts. Thus, the SMEs become subject to the limited working capital. This setback with the capital not just exists with the company, but with the owner as well. Owners do not have fixed capital at the beginning of the project which leads to the sudden halt of the construction, delay in the constructions, or delay in the payments which eventually becomes a challenge for the contractor to meet the financial needs of his company (Eke et al., 2015; Thwala & Phaladi, 2009).

These financial issues have been prominent in the SMEs. In the construction industry, where your work isn't likely to take place in a steady, predictable manner, cash flow problem is even more pronounced. Additionally, most contractors end up losing track of their daily transactions and do not account for their expenses & profits at the end of each month resulting in damage caused by poor accounting practices (Thwala & Phaladi, 2009). These SME contractors also bid desperately for a lower price to win the bid which usually has very high competition and are thus left with inadequate profits to run the company leading to low-profit margin. Coupled with this issue, The contractors often do not have funds to invest in the software licenses and infrastructure upgrades, which means they must manage with the older methods like spreadsheets and old-era client-server applications.

In addition to this, serious fluctuations in material costs were noted. For instance, ING research in European commission states that material inflation for cement, concrete and bricks on an average stands at 40% in 2021 (Maurice, 2021). These material cost differences with time affect the contractor financially to a great extent as increased material cost would be a burden for the contractor as it leads to reduced margins or project halts. Furthermore, the external stakeholders like bank and financial companies often do not give credit or charge heavy interests to the contractors due to less consistency in the success of the projects in SMEs (Thwala & Phaladi, 2009), thus lacking them access to credit.

Managerial Challenges:

It was analyzed that there has been an absence of comprehensive business plan during early stages of the small & medium construction businesses. The SMEs fall behind the large-scale companies in terms of supply chain management and investment in training of personnel (Kath et al., 2014). Due to lack of training and lack of experts in the team, small contractors experience difficulties in managing the workers, managing finances, and site monitoring (ILO, 2020). This happens due to the insufficient knowledge, experience, unreliable material supply base and lack of proper planning before the construction stage that leads to huge losses and causes failures (Offei et al., 2019; Thwala & Phaladi, 2009). This showcases the poor project management skills. It is also observed that contractors often claim unethical change orders just to make profits at the expense of the client which leads to loss of trust by the owner and eventually loses a loyal client (Thwala & Phaladi, 2009). Oftentimes, this results in owners trying to manage the construction process and are adamant to listen to the contractor's opinion which leads to trust issues among stakeholders (Raghavan, 2015; Thwala & Phaladi, 2009). The classification of different challenges can be clearly observed in the figure-1.

A big part of the managerial issues arises from the lack of technical expertise. On average, most of the contractors in the SMEs lack a degree and lack an in-depth understanding of the construction process which leads to errors and project halts. Furthermore, Small scale contractors either do not have adequate funds to afford skilled workers or train the unskilled workers and there is a lack of availability of skilled labor due to migration (T.G. Mofokeng, 2012). Communication problems were one of the notable issues with SMEs. Sharing of information is very critical in construction however it seldom happens in small-scale projects due to poor management of skills and lack of

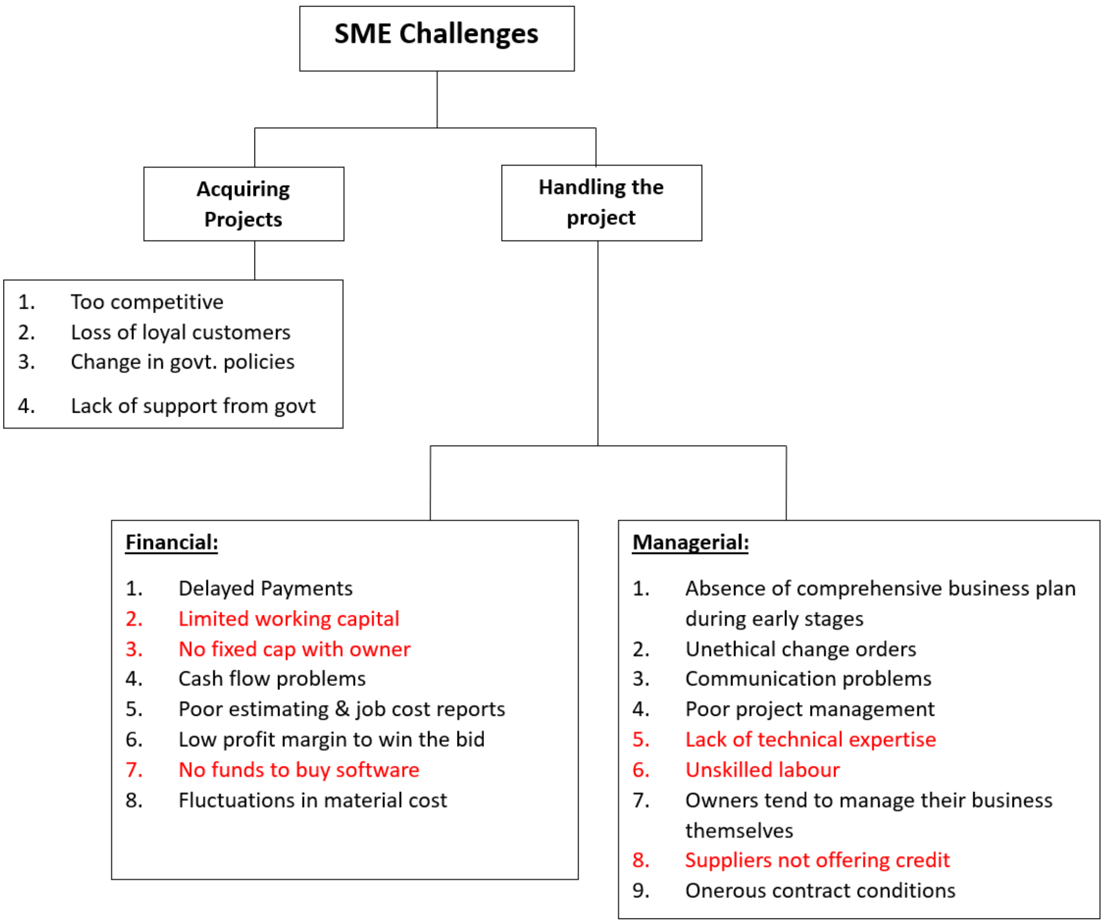

Figure 1: Classification of Challenges in SMEs

funds for IT tools (T.G. Mofokeng, 2012). Because of these factors, suppliers often do not trust the abilities of the small-scale contractors to give credit which leads the contractor to look for alternative methods of financing for supplies (T.G. Mofokeng, 2012).

Traditional contracts in which unavoidable costs required to fulfill the agreement is higher than the financial benefit to be obtained from it. This creates pressure on the contractor because of those onerous contract conditions (Offei et al., 2019). Figure-1 shows different types of challenges in the SMEs. Especially the challenges which are marked in the red are the one's which cannot be solved with the usual IPD framework which will be explained in later sections.

THE IPD FRAMEWORK

IPD is defined by all participants' early involvement, close collaboration, and the combination of each participant's unique contribution to the development and decision-making process, all to optimize the entire project rather than seek the self-interest of their respective organizations. The most typically seen benefits of IPD, include fewer change orders, improved cost savings, shorter schedules, and fewer requests for information (Roy et al., 2018). IPD framework defines the relationships among the project participants and guides their actions. The IPD framework functions on two interdependent levels, Macro-framework, and Micro-Framework (Khanzode et al., 2017). Macro-framework consists of the contract terms & business structure and a Micro-framework consists of the processes used to implement the project. They are together a road map to IPD (Khanzode et al., 2017). In this section, we shall first mention the different elements in the normal Macro & Micro IPD frameworks, and in the later sections, we shall propose possible changes to the frameworks to make them more specific to SME projects.

IPD Micro Framework:

The Micro-framework is a process and not a fixed formula that evolves during the project and is developed by the team based upon their capabilities and needs. The three major concepts which must be incorporated in all the projects are 1) Team design, 2)Work design, and 3)Information design (Khanzode et al., 2017). The team design tells that an efficient team should be formed to implement the IPD effectively and work should be divided to fit the size & competency of the IPD teams (Khanzode et al., 2017). The Work design focuses on how project tasks are divided, grouped, organized, and also about identifying different techniques to efficiently execute these tasks. Lastly, the Information design is about how the information will be created, exchanged, and managed (Khanzode et al., 2017).

IPD Macro Framework:

A full IPD project has five major structural elements which are 1)Early involvement of key participants, 2)Shared risk and reward based on project outcome, 3)Joint project control, 4)Risk allocation, and 5)Jointly developed & validated targets (Khanzode et al., 2017). All of these elements lead towards a successful implementation of the IPD at a macro level.

Now that we have described about the existing IPD frameworks, we shall now describe about our proposal of new IPD framework model specific to SME construction projects which could possibly solve challenges particular to SMEs.

PROPOSAL OF NEW IPD FRAMEWORK SPECIFIC TO SME SHOECONSTRUCTION PROJECTS

Some critical challenges identified in SME construction projects could be solved with the usual IPD framework. For instance, the problems such as delays in payments, cash flow problems, poor accounting practices, unethical change orders, and communication problems could be solved through collaborative working conditions offered by the normal IPD macro and microframeworks as explained in the previous sections. However, there are a few problems and constraints which challenge the implementation of the IPD framework itself in the first place. Unlike the large construction projects which have adequate capital and resources to implement the IPD, many of the small and medium scale constructions lack basic resources such as access to healthy credit, funds for the software license, funds for infrastructure upgrade, hiring qualified personnel, access to skilled labor, access to expert consultancy, high tech equipment and funds to train their personnel (Offei et al., 2019; Thwala & Phaladi, 2009). Considering these factors and including them in the IPD framework becomes necessary for the all-around success of SME construction projects.

Proposed new IPD Micro-Framework specific to SME:

As mentioned earlier, the usual IPD micro-framework contains majorly 3 elements namely Work design, Team design, and Information design. However, the newly proposed IPD framework specific to SMEs has an addition which is "resource management". The procurement of the resources, efficient resource planning to meet the project deadlines, and maximizing the resource utilization from project to project is of utmost importance for the successful implementation of the IPD. The resource management includes managing the financial resources, inventory, human skills, procurement systems, equipment, insurance, training, etc. The efficient management of resources is much more critical for SMEs compared to large-scale projects due to limited access to resources and shoestring budgets (Offei et al., 2019). Figure-2 shows how a new Micro framework has been developed from an existing one.

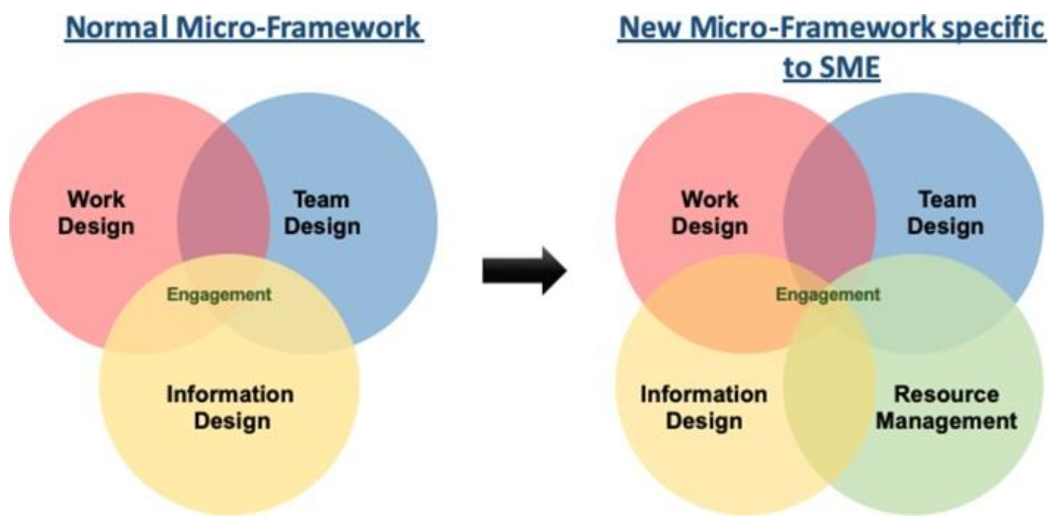

Figure 2: New Micro-Framework specific to SME

Proposed new IPD Macro-Framework specific to SME:

The normal Macro framework is shown to contain 5 elements namely early involvement of stakeholders, risk allocation, the joint share of risk/reward, joint project management, and joint validation of goals. The proposed new framework has a new addition which is "Acquiring Resources". This particular element is not included in the usual IPD framework which restricts the IPD framework to only large-scale projects. As arranging for adequate resources, as mentioned earlier, is crucial for implementing IPD in SME construction projects, adding "Acquiring resources" as a new element is significant. The acquiring resources include effective & affordable ways of acquiring bank credits, software licenses, skilled labor, experts, procurements, infrastructure, and expertise (Thwala & Phaladi, 2009). There could be multiple ways to solve the challenge of acquiring the resources in SMEs. One such possibility is multi project-collaboration which is presented in further sections of this paper.

In addition to that, cross-validation during the early involvement of stakeholders has been added to the new framework as transparency is key to the success of the IPD and eventually the project (Ashcraft, 2012). Hence, disclosure of available funds & assets by all the stakeholders is important for the smooth progress of the project. Especially in SMEs, owners start the projects without securing adequate finances for completion of the project which leads to sudden halts of the project causing losses to contractors. Hence cross-validation of the stakeholders before forming a team is very crucial for the project's success. Figure-3 shows the additions – Shared resources & cross-validation along with addition of new element "acquiring resources" to the existing 5 elements. In the next section, we shall discuss about a new proposed concept "Multi project collaboration" and how it could help SME contractors build access to adequate resources required to successfully implement the IPD.

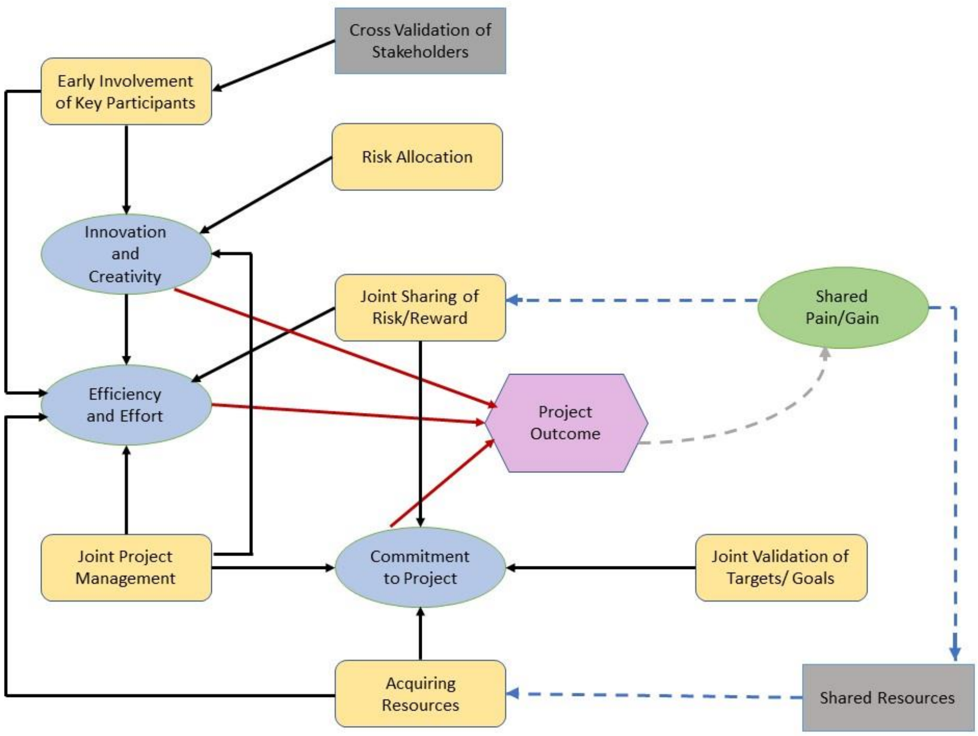

Figure 3: New Macro-Framework specific to SME. "Adapted from (Ashcraft, 2012)"

MULTI-PROJECT COLLABORATION: SOLUTION TO THE CHALLENGE OF "ACQUIRING RESOURCES" IN SME CONSTRUCTION

Multi-project collaboration is a system in which a few contractors, possible within certain area limits, with similar interests come together to form a "pool of contractors" in which they share the resources such as skilled labor, equipment, inventory, software, expert consultants, suppliers, finances, and expertise in their individual projects for the benefit of each contractor in the pool. This association increases the value of each contractor individually as they are able to access the resources which they were not able to access before. In addition, this collaboration could possibly share the profits and risks to some extent and utilize the shared savings to purchase software in bulk at affordable prices, train their unskilled labor, update their infrastructure. Furthermore, this added value helps the contractors and associated owners to get credit from the banks for their individual projects due to increased trust and stability of the contractors due to the pool.

Figure-4 shows different contractors of separate projects collaborating together. Contractors in the pool can take advantage of the resources offered which otherwise are only restricted to large contractors. For example, a contractor whose project is going on away from his own office can make use of some other contractor's office space (which is nearer to the project location), as colocation space where the contractor is part of the pool. One more example is that all the contractors can buy the software or advanced equipment in bulk together where they can get it for a lower price. They can even share the expensive equipment and communication tools.

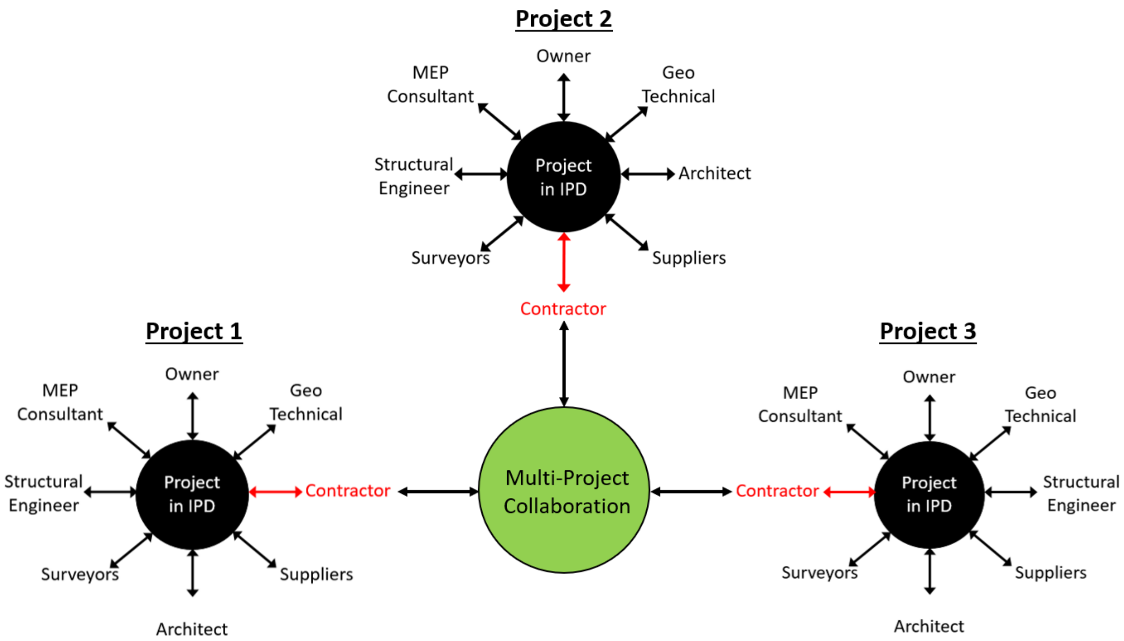

Figure 4: Multi-Project collaboration

Figure-5 explains how when the pool of contractors come together can share resources and create a value that is equal to a single large contractor. A single contractor in an SME project alone is in no way comparable to the kind of resources & financial stability that a large-scale contractor enjoys (Thwala & Phaladi, 2009). However, when some of the SME contractors come together to form a pool through Multi-project Collaboration, they are more stable financially, have access to shared resources, have access to credit to buy advanced equipment and overall generates a value which is equal to a single large contractor. For example, consider a city in which there is a pool of contractors many of whose individual small projects are going to start in few months. Here, when a single SME contractor purchases materials from a supplier, his buying power would be low as he procures in small quantities, whereas when a pool of contractors together orders materials, their buying power increases and could bring down the prices of the materials to some extent.

Figure-6 shows a comparison of existing AIA IPD contracts with the proposed IPD contract. The proposed contract system towards the right side of the figure has risk and profit share by the pool of contractors. The profit shared could be used to update the office infrastructure, buy software, equipment, communication tools, etc. At the same time whenever there is a loss occurred with a certain project, instead of the contractor shutting down his office, the pool could help him/her survive for a longer time by taking some part of the risk. In this concept of multi-project collaboration, it is necessary that all the projects are delivered in IPD to ensure transparency, mutual understanding, and collaboration among several stakeholders at the multi-project level.

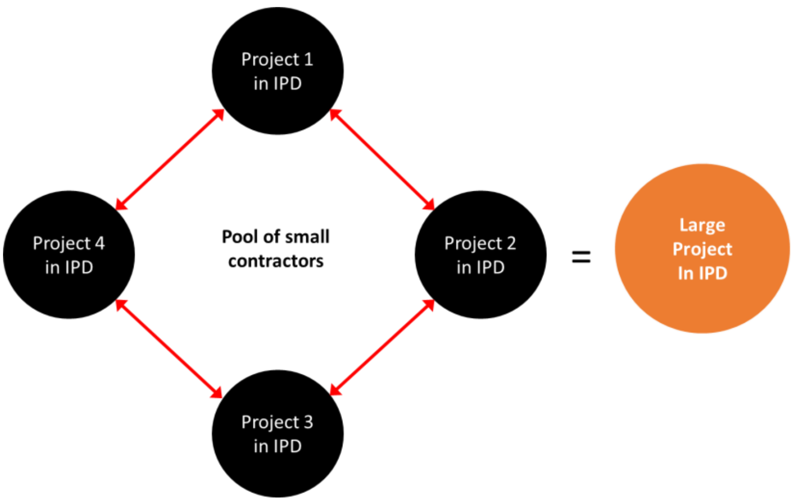

Figure 5: Formation of Pool of SME contractors and its equivalence to one large scale contractor

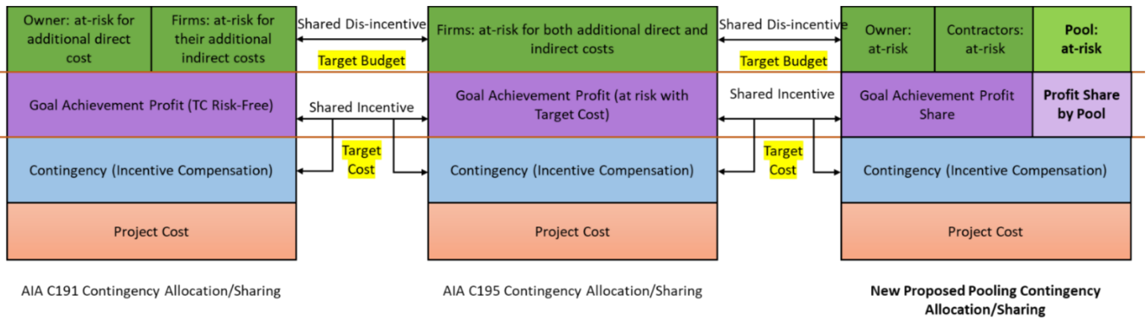

Figure 6: Comparison of proposed new pooling contracting system with the AIA contracting systems

CONCLUSIONS

The application of the IPD method by large construction companies leads to a profitable outcome, however, this isn't a solution for Small and Medium-size Enterprises, owing to the fact that SMEs are constrained by considerable financial and managerial limitations. Hence through this paper, we tried to find out the challenges which hamper the implementation of IPD in SMEs. Through this paper, we have also identified that Resource Management and Cross-Validation of the Stakeholders needs to be added to the framework to acknowledge the challenges specific to SME construction projects. Along with the identification of the challenges, we went one step ahead and have proposed possible solutions through multi-project collaboration. It demonstrates how the pooling collaboration can help SME contractors with resource sharing and allocation while at the same time sharing both risks and profits at the individual project level. This proposal thereby contains "Developed IPD framework for Small and Medium Size construction projects" and further "Multi-project collaboration for the projects delivered in IPD". The findings contribute to the body of knowledge by enabling the construction industry to understand a practical application of IPD method to SME construction projects. Consequently, this study facilitates and promotes the use of IPD for better productivity and collaboration in the construction industry.

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HOW A TAKT PLAN CAN FAIL: APPLYING FAILURE MODES AND EFFECTS ANALYSIS IN TAKT CONTROL

Joonas Lehtovaara[1], Iris D. Tommelein[2], and Olli Seppänen[3]

ABSTRACT

Construction projects need adequate planning to set a structure and direction for production, but simultaneously call for effective control to maintain the direction when something unexpected happens. Effective control is of utmost importance for takt production, which is especially vulnerable when disruptions occur. While previous takt production research has primarily focused on how to form a good takt plan, little attention has been given to how to control and continuously improve takt production systems effectively. Addressing the gap, this study inspects takt control through the lenses of failure modes and effects analysis (FMEA). First, we argue that takt control can be perceived through three different failure categories: failures within wagons, failures in handoffs, and failures in takt trains. We discuss the peculiarities of takt control through these categories and provide examples of failures with their respective failure mode(s) and possible control action(s). Second, we construct an FMEA-based framework for effective takt control that shows how to recover from failures and avoid them altogether. Future research may consider validating the failure categories and the framework through case studies or simulations, and examining their applicability in supporting digital takt production.

KEYWORDS

Lean construction, takt production, failure modes and effects analysis (FMEA), production planning, production control

INTRODUCTION

Takt production is a location-based method for planning, controlling, and continuously improving construction production systems (Lehtovaara et al. 2021). It has gained elevated attention in the last fifteen years or so among construction management professionals and scholars. Takt production focuses on planning production to advance with a consistent beat, or 'takt', vigorously controlling production to maintain the beat,

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and continuously improving the system as problems or learning opportunities arise (e.g., Frandson et al. 2013). The increased interest in takt production comes for a reason, as previous studies have reported several benefits from its application. These benefits include decreased production durations (Binninger et al. 2018), increased production transparency and stability due to clarity of handoffs (Frandson et al. 2014), and a more proactive touch to solving and controlling problems (Linnik et al. 2013).

Despite this increased interest, previous studies have focused mainly only on planning, but control and continuous improvement during execution have been addressed in a somewhat superficial manner (barring exceptions such as Binninger et al. 2017 who attempted to codify different takt control mechanisms). This is surprising as the success of takt production is determined in execution; takt production is especially prone to disruptions, requiring constant attention to controlling production and steering in order to adhere to the predetermined plan (e.g., Alhava et al. 2019). This study explores these peculiarities and constructs a framework for takt control to address them. We approach this exploration by combining failure modes and effects analysis (FMEA) thinking with takt production.

Widely used in several industries and especially in manufacturing operations since the 1950s, FMEA offers a structured approach to recognizing and evaluating different failures and failure modes, studying their consequences, and identifying means to address them (ASQ n.d). Failures are the consequence of the occurrence of errors or defects (e.g., a task finished late), while failure modes denote the possible ways of something "going wrong," i.e., what causes the failure (e.g., insufficient resources to finish a task on time). Aiming to minimize waste and value loss, FMEA is commonly used in the design and control stages of processes or products, ideally applied through their lifecycle to cultivate continuous improvement. In construction management, FMEA has been applied, e.g., in design process management (Andery et al. 2000), in innovation implementation (Murphy et al. 2011), and in production management (Bahrami et al. 2012). Construction failures include, e.g., tasks finishing late or too early, quality defects, or waste caused by excess movement or material transportation. Such failures may be caused, e.g., due to a crew's inability to complete planned tasks, poor planning, inherent uncertainty (Wehbe & Hamzeh 2013), inadequate commitment, or unsolved conflicts between parties during planning or execution (Iyer & Jha 2006).

For process design and control, FMEA follows these steps (e.g., Grout 2007), illustrated in Figure 1: (1) assemble a cross-functional team to perform analysis, (2) identify (potential or existing) failures and their related failure modes through brainstorming or process tracking, (3) identify (root)causes of the failures, identify (potential or existing) consequences of the failures, their occurrence rating and severity quantitatively or qualitatively, and (4) determine and implement countermeasures to manage adverse effects of failures and/or their occurrence in the future. The concept of mistakeproofing can further help categorize the possible countermeasures (Tommelein & Demirkesen 2018). Elimination or prevention of failures should happen in early process stages, before any failure might occur; in contrast, detection or mitigation could help identify countermeasures after a failure has occurred.

FMEA may provide an interesting complementary process for takt production, as takt production by its nature puts the production system in a stress test. On the one hand, takt production aggressively reveals failures and failure modes as they occur, urging for continuous problem-solving. On the other hand, FMEA provides a way to systematically spot problems that are surfaced during takt production and enables learning so that the recurrence of such problems may be reduced if not altogether eliminated. Thus, FMEA could increase the effectiveness of a production system that uses takt, nurturing both control and continuous improvement functions. To support our aim, namely to explore the peculiarities of takt control and construct a framework for takt control to address them, we pose two research questions: "*In which ways can takt plans fail?*" and "*How could these failures be recovered from, or avoided in the first place?*"

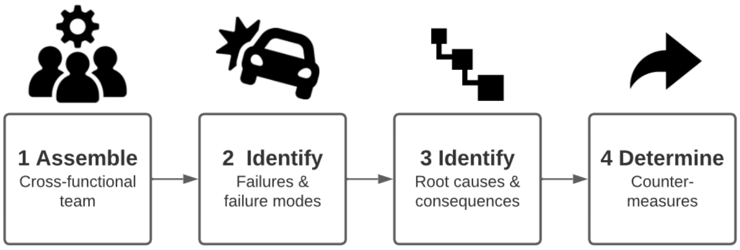

Figure 1: General FMEA process

This paper is structured as follows. First, we state the necessity of effective planning and control system in construction projects and introduce some of the most recent lean construction approaches used for planning and control. Second, we discuss the peculiarities of takt production, categorize possible takt production failures, and provide examples of possible failures, failure modes, root causes, and control actions in the context of takt production. Third, we present an FMEA framework for takt control that shows how to recover from failures and proactively avoid them. Last, we discuss the study contributions and possible future research avenues.

CONSTRUCTION PLANNING AND CONTROL

Construction projects are directed by plans generated at the early stages of their lifecycle. **Production planning** sets a structure for the project's execution, determining what needs to be done, when, and with which kind of resources (Vollman et al. 1997). However, making good plans does not guarantee success. While plans are necessary to envision the initial direction for production, they are merely forecasts, doomed to fail at some point during execution. Therefore, **production control** is needed. Control entails making changes to a predetermined plan when something unexpected or unforeseen happens, and new opportunities arise. Unpredictability is innate to complex systems (such as construction production) as the behavior of such systems can never be precisely anticipated beforehand (Snowden & Boone 2007). Arbulu et al. (2016) argue that to be effective, production control systems should constantly sense, analyze, and respond to any issues that surface. Moreover, control should be seen as a driving force for future direction to meet the customer's expectations (Drucker 1974), and the changes made should be informed by the project's overall goals.

Even though forward-looking production control is employed widely in other domains (such as in manufacturing), it is not so present in construction production practice; instead, the focus is on measuring what has been done to assess conformance to plan. Construction management practices tend to be based on the idea that the original plan should be an adequate pathway for production, with little need for adjustment during execution. This approach originates from the use of Critical Path Method (CPM; Kelley & Walker 1959) and Program Evaluation and Review Technique (PERT), which were created to focus on financial- and progress reports at the project level rather than to steer future direction on the production level effectively. Koskela and Howell (2001) and

Laufer and Tucker (1987) raise a concern that, when ignoring the production control aspect, a site manager's focus is put on producing reports and articulating justifications for past failures rather than proactively addressing them.

Next, we present some of the most studied and recent lean construction approaches to effective production management that entail control in addition to the planning function.

LEAN CONSTRUCTION APPROACHES TO PRODUCTION PLANNING AND CONTROL

The field of lean construction has produced various planning and control approaches for effective construction production, with the **Last Planner® System** (LPS; Ballard and Tommelein 2021) being arguably one of the most widely studied ones. LPS is based on conducting planning and control through converging horizons as the execution of work gets closer; tight collaboration with those who execute the work; revealing and removing constraints; making reliable promises by committing to what has been agreed; creating reliable handoffs; and pursuing continuous improvement by learning from problems (Ballard et al. 2009). The LPS process is divided into five steps. The first two (master level planning and phase planning; describing what "should" be done) consider production preparation and planning, while the latter three (lookahead planning, commitment planning, and learning; respectively describing what "can", "will", and was done ("did")) focus on executing, controlling, and improving the production system. During execution, control and continuous improvement actions are supported by "daily huddles" in which prerequisites and possible barriers for work, as well as learning opportunities, are collaboratively addressed (Ballard and Howell 2003).

Another widely studied lean construction planning and control approach is the **Location Based Management System** (LBMS; Kenley & Seppänen 2010). Seppänen et al. (2010) argue that LBMS and LPS complement each other when simultaneously implemented in production control. As LPS focuses on initiating discussions and reliable promising, LBMS produces a complementary counterpart by providing a systematic, data-based work structuring and production control method. Seppänen et al. (2010) reported that when combined, LBMS tracking data can support LPS control steps by providing forecasts and triggering early warnings in structured graphical and numerical format. This feedback can then be used as input for collaborative decision-making during the control process.

Previous LBMS studies (e.g., Seppänen 2009) have also considered possible failures and failure modes (however, these exact terms were not used), and their respective control actions in the (lean) construction planning and control context. Possible failures include deviations in production rates, start-up delays, and work being split into multiple areas; possible failure modes include a preceding task starting late, crew demobilization, interruption of work, or wrong order of locations or work sequence (Seppänen & Kankainen 2004, Kenley & Seppänen 2010). Possible control actions consist of adjusting the production rate (e.g., add or reduce resources, work overtime), steering the plan (e.g., change process logic, create a new task, split tasks, re-sequence work, review task data), or suspending the work (Kenley & Seppänen 2010).

TAKT PRODUCTION AND FMEA

Generally speaking takt production is more similar than different from other lean construction planning and control approaches. Frandson et al. (2014) mention that, similarly to LBMS, takt production can be used with LPS while providing synergies to each other. The 2020 LPS benchmark (Ballard and Tommelein 2021) also situates takt planning as a method in the system. Whereas takt production provides a way for work structuring that actively supports good production flow, LPS offers a sound production system structure with tangible horizons for planning, control, and continuous improvement. Even though using slightly different concepts and terminology, Dlouhy et al. (2016) also describe a similar combined process for takt production, called "Takt Planning and Takt Control" (TPTC). Their three-level process (with macro, norm, and micro levels) shares characteristics with LPS horizons. The first level is similar to master level planning, the second with lookahead planning, and the last with commitment planning and learning.

Despite similarities with other control methods, some unique characteristics of takt production (especially affecting the emergence of failures and failure modes and their control) should be considered before applying the aforementioned LPS and LBMS practices to takt production. Possible takt production failures can be categorized into three groupings that also reflect the peculiarities of takt production (Figure 2): (1) wagon content failures (corresponding to failures in a process step), (2) wagon handoff failures (failures between process steps), and (3) takt train failures (failures affecting the whole process, possibly causing cascading effects). The reason to group failures and failure modes into these categories originates from the idea of takt wagons being the fundamental units (Dlouhy et al. 2016) that set a base for work structuring in takt production. Inspecting these units, their interfaces (handoffs), and combinations of them (trains) provide a tangible and visual way of addressing FMEA in a takt production context.

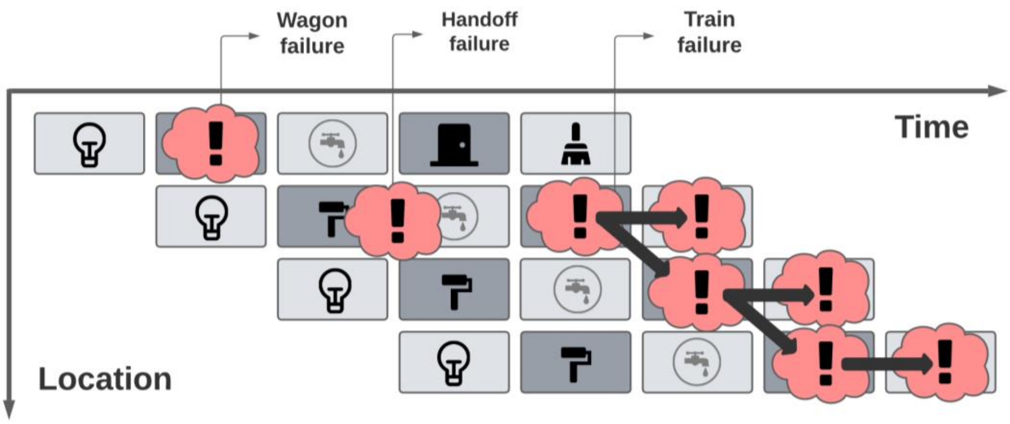

Figure 2: Wagon, handoff, and train failures

WAGON CONTENT FAILURES AND CONTROL

A takt wagon is the batch of tasks to be completed in a specified takt area within a given takt time. Controlling wagon content tightly in short intervals is necessary to avoid failures within wagons, such as unfinished tasks or tasks finishing late. Reducing batch sizes over time is often characteristic—though not required—for takt production systems. Small batch sizes can be employed to adjust the speed of the process in order to meet the (externally provided) milestones, and to provide an increased opportunity to identify opportunities for improvement. Small batch sizes further increase the need for tight wagon content management (Haghsheno et al. 2016), but also possesses particular advantages. Problems are constantly surfaced (while being visible to everyone), creating an opportunity to actively act on them within wagons before they significantly harm other parts of the production system. Here, rigorous and collaborative management practices (such as daily huddles) are necessary to enable timely failure (and failure mode) identification and control. Successful wagon content management can increase production reliability and reduce overall production risks (Haghsheno et al. 2016).

WAGON HANDOFF FAILURES AND CONTROL

Successfully managing the interfaces between wagons is critical for takt production's success (Frandson et al. 2015) and for production in any Parade of Trades (Tommelein et al. 1999). Therefore, in addition to intensive wagon content control, takt control calls for effective wagon handoff control because that reliably enables the work to begin in the next wagon. The inability to meet a timely handoff with the needed quality produces failures, such as missing preconditions for work, will affect the next crew's work immediately. This visible and immediate effect creates an urge for make-ready work, putting social pressure on crews to pay increased attention to wagon handoffs (Frandson et al. 2013).

A central element of takt planning in achieving reliable wagon handoffs is favoring capacity buffering (Frandson et al. 2015). In contrast to other lean control methods (such as LBMS), rather than fully loading crews resources and minimizing their downtime with excess time and space buffers (maximizing their utilization by avoiding "workers waiting for work"), in takt production crew resources are underloaded[4] by employing standby capacity (avoiding "work waiting for workers") (Linnik et al. 2013). Standby capacity provides additional means for achieving timely handoffs, as it makes it possible to absorb variability when needed, and when not needed the spare capacity can be used for quality assurance, problem-solving, or self-development (Tommelein 2020). Wagon handoff management is also a key enabler for effective wagon content control, enabling tasks to start (and finish) timely within the next wagon.

TAKT TRAIN FAILURES AND CONTROL

Takt control focuses on achieving a stable process flow that produces products in synchronization with the client's needs (Frandson et al. 2014). This flow should be maintained through the whole sequence of takt wagons progressing through takt areas; such sequences are called takt trains. Takt train failures are primarily caused by system-level failure modes such as an illogical production sequence or missing design information. These can cause wagon and handoff-related failures to accumulate (Seppänen (2009) refers to "cascading delays" and Dahlberg & Drevland (2021) to a "parade of delays") or cause the system to dysfunction as a whole, such as by generating a large amount of resource fluctuation.

Possible takt train control actions include, for example, pull-planning of supporting flows such as information and material flows (Lehtovaara et al. 2021) to support production reliability and prevent making-do (Koskela 2004); decoupling of logistics management from the crews' onsite work by using logistics operators and kitting of materials (Tetik et al. 2019); or stopping the train as a whole in the case of an accumulated failure until the causes are fixed altogether. Also, the aforementioned standby capacity as a buffering mechanism offers a powerful way of increasing the overall production performance and flow (Horman & Thomas 2005) while reducing the possibility of minor problems accumulating into a train failure.

[4] Court (2009) and Frandson et al. (2015) suggest that underloading to 75-80% of needed capacity can serve as a general rule of thumb.

FAILURE, FAILURE MODE, ROOT CAUSE, AND CONTROL ACTION EXAMPLES

Figure 3 lists some possible failures, failure modes, root causes, and control actions related to the aforementioned three categories. These examples are drawn from previous lean construction and takt production studies (e.g., Binninger et al. 2017, Seppänen 2014), and complemented by the authors' own takt implementation experiences. The provided list is not exhaustive but is to serve as a guiding example for readers as they encounter failures in their takt implementation initiatives. Next, we present a framework that illustrates the FMEA process in practice.

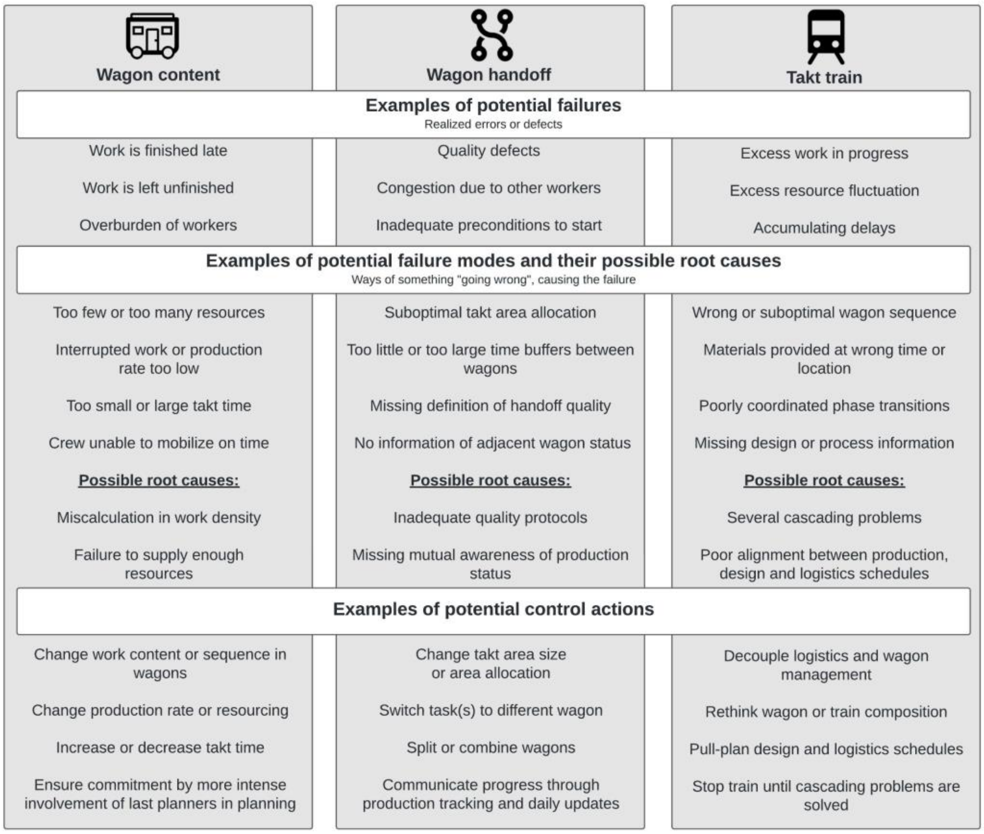

Figure 3: Examples of failures, failure modes, root causes, and control actions

FMEA FRAMEWORK FOR TAKT CONTROL

Based on the needs of construction production systems in general, insights from previous lean construction approaches to planning and control, and the peculiarities of takt production, the proposed FMEA framework for systematic takt control is presented in Figure 4. The framework combines the FMEA process with the planning and control horizons of the presented lean construction approaches, which can be applied to takt production context. The framework consists of four phases: (1) preparation, (2) FMEA problem-solving during planning and (3) during the control of production, and (4) post-analysis. It should be noted that the framework does not aim to replace the existing takt planning and control methods, but rather to serve as a support tool for them, whenever the combination of LPS and takt (Frandson et al. 2015) or a three-level method (Dlouhy et al. 2016) is employed.

In the **preparation stage** (that occurs during master planning or at the macro level), a cross-functional team (consisting of site/project managers, site crews, and other relevant stakeholders for production planning and control such as design or logistics managers) is formed to carry out the FMEA process. The master plan provides a basis to guide detailed production planning and control, and simultaneously, the FMEA process provides feedback for steering the master plan as needed. FMEA can also be used in the preparation stage for a project-level risk analysis to proactively address possible shortcomings of the master plan.

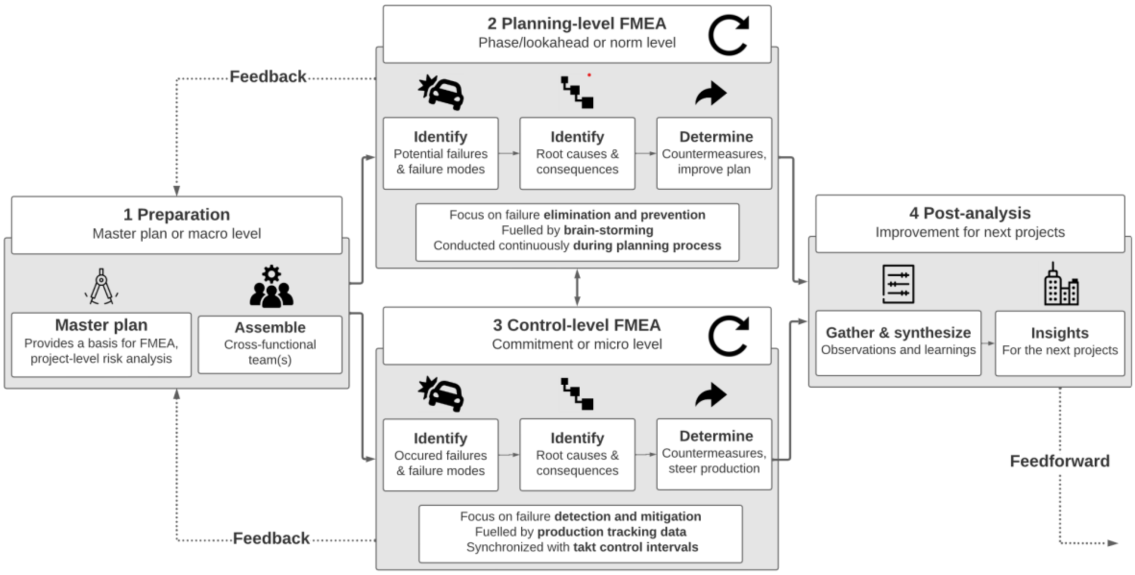

Figure 4: FMEA framework for systematic takt control

In the **planning stage** (that occurs during phase/lookahead planning or at the norm level), a detailed analysis is conducted in which failures and failure modes are identified and proactively eliminated or prevented before the production execution. The consequences of the identified (root)causes are analyzed by weighing their severity, assessing their likelihood of occurrence, the possibility for accumulating effects, and the timeliness and cost of possible control actions. FMEA is conducted through collaborative brainstorming and can done during ongoing production preparation meetings or workshops. Preferably, the FMEA process should be done on a whole production level but also individually for every wagon and takt area. Failure modes for two different wagons can be the same, but their effects and control efforts may vary. For example, the employment of buffers should be based on each wagon's unique characteristics, such as possible variability.

In the **control stage** (that occurs during commitment planning or at the micro level), the realized failures and related failure modes are identified from production tracking data. Tracking data serves as a catalyst for collaborative identification of (root) causes and determining adequate actions (to detect and mitigate the failure effects) during daily/weekly takt control meetings. For example, a failure to finish work on time within a wagon should trigger a discussion that aims to identify the failure mode (e.g., insufficient resources) and the root cause of the failure (e.g., inadequate involvement of workers in production planning), followed by deciding a corrective action to ensure production gets back on track (e.g., increase resources or increase takt time). Simultaneously, actions for eliminating or preventing the failures from happening again should be discussed and implemented (e.g., initiate additional takt training for workers).

In the **post-analysis stage** (that occurs continuously during or after production), learning from identified failures, failure modes, their root causes, and other relevant observations from production tracking data are collected and synthesized with the cross-functional team. The synthesis should be leveraged when preparing the upcoming projects or project stages, proactively aiming to eliminate and prevent similar failures in the future. For example, changing batch size could be an immediate control action but also a possible corrective action for the next project phase or the following project.

Even though the framework focuses on takt control, it inevitably extends to takt planning and continuous improvement, highlighting the interconnectedness of these functions; notably, the presented examples in Figure 3 could be identified and solved in every stage, either by preventing or eliminating them (preparation or planning phases) or detecting and mitigating them (control phase). Effective control feeds from the preparation and planning stages while offering feedforward for future takt planning. Use of the framework can provide a systematic path for effective organizational learning, development of organizational capabilities, and for reaching higher maturity levels of takt implementation (Lehtovaara et al. 2020).

STUDY CONTRIBUTION AND FUTURE RESEARCH

To answer the first question "*In which ways can takt plans fail?*" we categorized takt production failures as (1) failures within wagons, (2) failures in handoffs, and (3) failures in takt trains. We discussed the peculiarities of takt production related to these categories and provided examples of failures, their respective failure modes, root causes, and possible control actions. To answer the second question "*How could these failures be recovered from, or avoided in the first place?*" we constructed a framework for takt control that uses the FMEA process logic.

For practitioners, the study offers a systematic guideline for problem-solving in a takt control context that can be combined with their preferred takt production method. In addition, examples of failures, failure modes, root causes, and control actions can feed practitioners' imagination in applying the framework in action. For scholars, the study offers a novel view by approaching takt control through the lenses of FMEA, offering an interesting point of departure for future research.

More specifically, we identified two distinct future research avenues. First, as the failure categories and the framework are based on a conceptual study, they call for validation. The validation could be done through case studies, simulations, or expert surveys to gain insights for the framework's practical applicability. Case studies and simulations could also serve as a basis for objectively assessing the magnitude of different failures and failure modes and the effectiveness of their related control actions. Similar studies have already been conducted in the context of LBMS (e.g., Seppänen & Kankainen 2004). Constructing a comprehensive library of failure and failure mode examples through validation could also serve practitioners in identifying additional solutions for takt control in their specific context. However, one should bear in mind that even though similarities among takt production initiatives exist, each different organization and project will always require a unique examination of its failures, failure modes, and their effects grounded on their contextual needs. One should also note the magnitude of number of failures and failure modes that can exist. In practice, it may well be that the number of possible failures and failure modes is larger than those presented through the illustrative examples, possibly exceeding dozens or even hundreds of different variations. Thus, it would also be interesting to identify which elements are generalizable and which are unique for specific project contexts. This would help inform the learning process and determine which practices can be standardized vs. which need to be individually considered for every given situation.

Second, it should be examined if the framework can provide a platform for structured and automated data collection and analysis, supporting digital takt production (Peltokorpi et al. 2021). For effective digital takt control, detailed (in granularity of hours and minutes, instead of days and weeks) data collection and analysis are needed to feed the FMEA process effectively. Digital takt control could further serve as a building block for digital twin concepts (Sacks et al. 2020), data-driven learning, and systemic change.

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LEAN SOLUTIONS FOR PROGRAM DEVELOPMENT FOR CONSTRUCTION DAILY REPORT

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ABSTRACT

The construction industry follows societal trends in the Fourth Industrial Revolution and seeks to apply new Information and Communication Technologies (ICT). ICT can capture, store, process, and distribute information electronically and in large quantities. Thus, ICT can contribute to many construction documents, such as the Construction Daily Report (CDR), which has a considerable amount of data for processing and shared responsibility with several project team members. The research method used is the case study through a qualitative analysis of the information management software. The results demonstrated that its use enabled greater control of the production process, shared responsibility with the corporate sectors, and became a basis to minimize conflict between the stakeholders. The solutions incorporated in the program are presented to meet the principles of standardization, flow improvement, and increased transparency. Furthermore, the software collaborates with the solidity and quality of the enterprise's official document and their management information, bringing better storage reliability and greater agility in information retrieval.

KEYWORDS

Information management, Contract management, Production planning and control, Construction industry, Site construction.

INTRODUCTION

Information and Communication Technologies (ICT) are used in different sectors to improve data collection and processing processes. Computerization also helps automate contractual procedures, manage information, and monitor the work's stages and conditions. The construction industry follows this trend and has applied ICT to facilitate the acquisition and management of information on the progress of the building (El-Omari and Moselhi, 2011). To support contractual or legal obligations and simplify the

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collection of daily activities, the Construction Daily Report (CDR) is an important document for construction projects. The daily report centralizes the project's information from different work teams, whether activities performed in the field, meteorological data from the construction site, records of the supply chain and strategic communication, contractual milestones, requests for scope changes, among others (Navon 2007). As a result, the CDR is considered a strategic document and is consulted frequently to support agreements and resolve claims (Russel, 1993).

The CDR is an information management system that uses computational assets to improve and increase the competitiveness of construction companies (Russel, 1993; Shiau and Wang, 2003). Gurley and McManus (1998) propose an information management system based on the principles of lean construction, whose most important characteristics are transparency and the inclusion of the various agents participating in the construction project. The authors emphasize that information flows must accompany workflows so that all participants must have access and trust in this building information system. Furthermore, the management system tools can be customized according to the company's communication needs and ways of hiring.

The amount of data collected in complex projects is significant, needs criteria to be filled in, involves several stakeholders, and signature collection. Typically, the CDR is filled with a focus on execution information, with little focus on other processes such as acquisitions, hiring, or projects. Thus, there is a need for CDR to meet the management specifics of the companies involved and promote incremental improvements.

Although there are commercial CDR options on the market, the program will not always meet the user's or the company's needs, may not have the customization option available, or present limited customization opportunities. Furthermore, a commercial program cannot always cover all possible solutions, as each construction company has specific forms of management and organization. That way, customizing can seek the development of specific tools that meet a particular type of construction company.

The use of ICT can integrate management system processes adopted by the construction company, streamlining the collection, approval, and standardization of data, establishing formal channels of communication, and facilitating access to information and records of the work. Different agents can have shared access to information, reducing access time and facilitating decision-making. However, guidelines on the information to be incorporated in designing a CDR elaboration system were not verified. This article presents an exploratory contribution to fomenting the discussion about the subject.

This article will describe the importance of the daily report and the procedures adopted by a construction company using ICT to standardize their CDR and improve the management information. To this end, the company sought to incorporate lean construction concepts, such as transparency and improved information flow. As a limitation of this research, the results are restricted to this case study. Still, the article points out needs for future research, aiming to organize a procedure for designing information systems for CDR in the construction industry.

LITERATURE REVIEW

There is a diversity of information to be collected and processed in construction industry projects. A computerized system can facilitate the identification of the current situation of each activity, with different statuses (such as start, ongoing, completed, and postponed, for example), meteorological records, team productivity indicators, among others, enabling a flow of more efficient and faster communication (Russel, 1993). The author presents the management system called REPCON (Representing Construction) for a project, indicating its integration with the daily site and the planning and control system. Shiau and Wang (2003) propose a model integrating several functions into the CDR, such as project modification control and pricing, budgeting, and accounting systems. As will be shown in this paper, a computer information management system presents standardized procedures for data entry, visualization facilities for the analysis of results, and eventual corrections. The periodic or daily collection of relevant information and its organization will facilitate decision-making by the different stakeholders. In addition, the collected data can serve different internal processes of the company. This can provide agility, and reliability in the results, establish a form of communication and reduce conflicting results. With this, it was possible to improve the accuracy of the information, reduce human typing errors, control the actual cost, and integrate customers and designers.

The daily monitoring system of activities and services can be integrated with the Production Planning and Control (PCP). Lee and Cho (2020) verified the consistency between the daily work report and the schedule plan. They noticed that in 58% of the interviewed cases, the execution of the activities recorded in the daily work report was not according to the schedule. For this, Lee and Cho (2020) propose a CDR integration model with Last Planner System (LPS) and Line of Balance (LOB) planning techniques, allowing for effective communication about the plan and the execution of work between different teams. This paper will show that the developed system has an interface with the PCP, providing data on its physical progress.

Using a computer system associated with the development of the work can help formalize and optimize the company's communication channels with its suppliers and customers. To support the complex information system within a construction site, CDR models must consider established communication channels, eliminate barriers, and favor the flow of information (Tsai, 2009). Cho and Chang (2019) conceived a model using chatbot technologies aiming at an interactive and uniform communication interface. The communications database was designed to feed the CDR automatically. The system presented in this paper is developed for computer use, its data is stored in the cloud, following the data security standard, and accessible to all authorized stakeholders, facilitating information sharing.

The use of communication technologies can increase productivity in the management of the project. Chen et al. (2019) propose a web-based CDR management system with digital pen input. Data can be verified anywhere with an Internet connection available via PC or mobile device. Harstad et al. (2015) analyze that the application of tablets will improve information management in construction projects and may gradually improve the cost/benefit ratio after an initial introduction of computer systems. Although interesting, this system present does not have versions for mobile device applications or facilitating devices such as digital pens or tablets.

El-Omari and Moselhi (2011) present an automated system for collecting data from construction sites to measure execution progress. The user can power the system through a tablet to record data on the system, photos, and handwritten comments. The main entities of the database are Projects, Activities, Labors, Equipment, Materials, Photos, Sound, Videos, 3D Images, and Drawings. These options are present a computerized CDR program that integrates with other management processes, such as planning, supplies, and customer service. The computer program's development made it possible to standardize information, establish communication between stakeholders, monitor the construction process, insert photos and relevant information, and use the internet network.

Unlike other authors who presented a specific analysis of the CDR or a process, this article presents a study integrated with the management system of the construction company studied. It is expected to highlight that the CDR impacts the operational, tactical, and strategic management of the business and legal and contractual needs.

RESEARCH METHOD

The case study adopted the research method, which uses qualitative data collected from actual events to explain, explore, and describe phenomena in their context (Voss et al., 2002; Yin, 2009).

The first step of the research consisted of a literature review to identify the main functions expected for CDR use. Then, a protocol for the investigation of the studied program was followed, consisting of the following steps: knowing the program's essential functions, identifying the primary information and how it is completed, identifying the main stakeholders involved, and their routine procedures. Then, the collected information was analyzed, compared with previous results, and verified the improvements obtained from implementing the CDR informatized and the opportunities for advancing knowledge. Finally, discussions were held on the results found and the potential solutions to the problems. Figure 1 shows the scheme of the methodological procedure adopted.

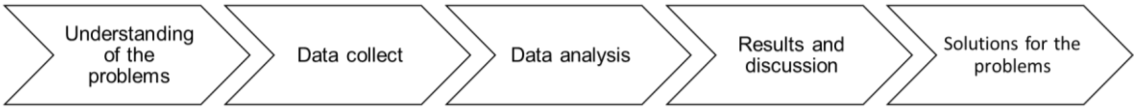


Figure 1: Methodological procedure adopted.

CASE DESCRIPTION

The construction company operates in the management segment and supports its clients in business development, leading pre-construction services. The company has been working for over 50 years in industrial constructions, buildings, and infrastructure. A finished project was selected to be explored in this paper to present the software interface and main results. This project is called Teatro Cultura Artística (TCA), held between 03/26/2018 and 07/31/2019.

The software studied is part of a set developed by a company specializing in computer programs that provide software dedicated to the construction industry. The program was created to improve CDR management information that is electronic, easy to access, and in version 4.0. The construction company designated a person responsible for internal monitoring of the development of the program who held the position of the architect in the Innovation area. In addition, the same was defined as a "key-user" of the system. He centralized all requests for improvement, monitoring, and testing of customizations with the service provider that developed the CDR program. Since 2017, the construction company has used the software in 29 projects, including infrastructure, industrial, and building projects. Access to the platform is done through an internet browser, and it works online. The data is collected by the different sectors and operators involved, who fulfill the document from computers. Data storage is performed in the cloud.

Prior to using this program, the CDR was filled in a standard form in MS Excel and later printed for signature by the parties. However, searches for any information were performed manually on the form, which generated delays and, possible loss of relevant information. In addition, the process was too slow and error-prone due to the concentration of data reception in the engineering sector.

CDR ACCESS LEVELS

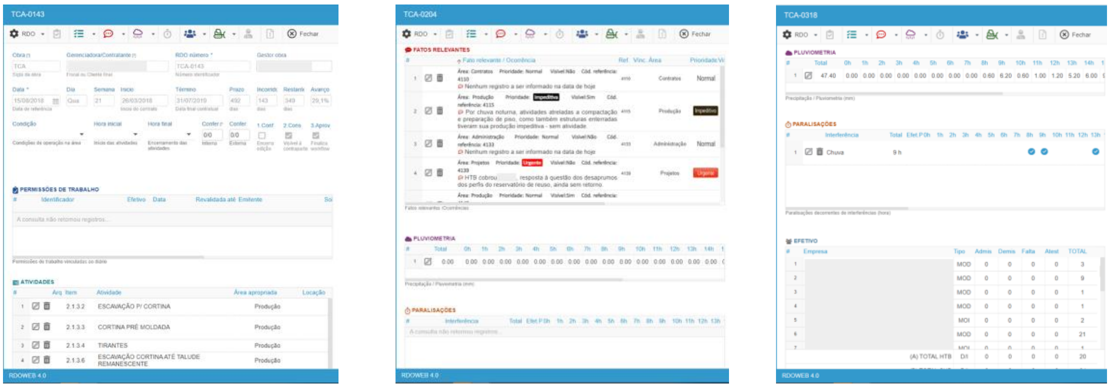
The fulfillment of the CDR is carried out collaboratively and simultaneously by teams of the construction company. Each team inserts the specific information. The sectors that manage the information are Engineering or Production, Human resources (HR), Contracts, Design, Planning, Supply chain, Health, Safety, and Environmental (HSE). The contracting customer (Owner) also can indicate different access profiles, such as managers and consultants. Finally, the builder can assign "Executive Office" profiles to the higher hierarchical levels with access to various projects. Table 1 shows a summary of the system's usage permissions.

Table 1: System permissions by the levels of hierarchy and stakeholders

Sector	System permissions for construction project
Executive office	EXECUTIVE OFFICE – Access to all projects in the consultation-only mode
Engineering	SITE MANAGERIAL – Allowed to insert information, assign, and remove "checked" and "consolidated" status that releases the CDR to external users
	SITE ADMINISTRATION – Allowed to insert information from all sectors and assign "checked" status, locking out the CDR to the internal public
Other sectors	AREA MANAGERIAL – Allowed to insert information in area-specific, allowed to access information from other areas
	OPERATION – Allowed to insert information exclusively in area-specific
	CONSULTATION – Only query. ADM defines what he can see
Owner (external)	CLIENT MANAGERIAL – Allowed to make defense/contestation and comments, to apply for the "approved" status, closing the approval flow
	CLIENT AREA MANAGERIAL– Allowed to make defense/contestation and comments in area-specific and assign the status "area conference"
	CLIENT – Allowed to make contestation and comments in area-specific
	CONSULTATION – Only query. ADM defines what he can see
ADM	DEVELOPER – System key user access

COMPLETION OF THE CDR

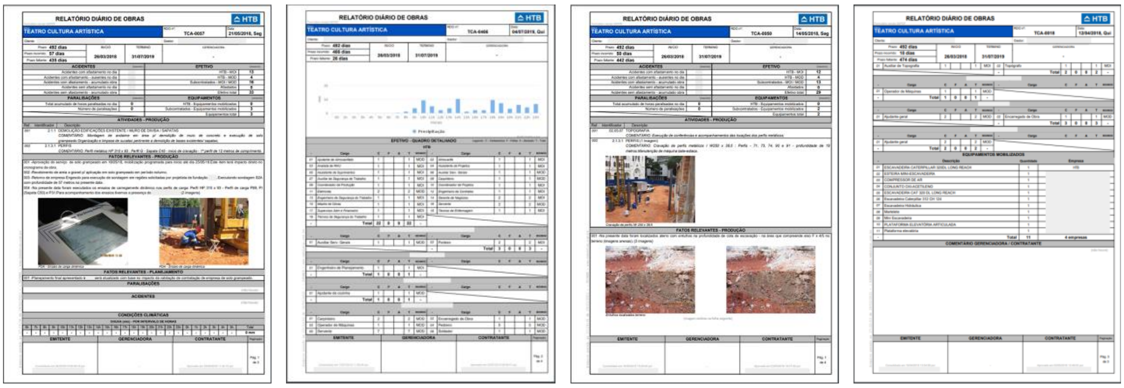
The fulfilling information or "Launches" in the CDR occurs by selecting pre-registered items in the system, thus generating a standardization in the data included. All team members of each sector are previously registered in a database standardized by the construction company. Figure 2-a shows the initial screen of CDR, with several automatically filled data, such as the project's duration and the CDR number. Moreover, this figure shows the project activities planned based on the project's Work Breakdown Structure (WBS). To fulfil the information about the Production Sector, it must select the activities carried out that day. Selecting WBS items instead of typing the activities ensures the records standardization and facilitates their traceability. Figure 2-b shows the "Relevant facts" indicated by each corporate sector related to the project. The black marking indicates a "blocking factor" for developing a particular activity; the red mark indicates a "critical priority" to solve a particular pending issue. Then the occurrences related to the pluviometry are shown in a bar graph. Figure 2-c shows the software's integration with existing weather station data in the construction site region. The software automatically converts rainfall information to the standard established by the builder. This figure also shows the number of workers present at the construction site and their companies (identification omitted). Furthermore, the system allows importing information from past CDR, highlighting the recurrence of similar records. Information about the equipment used that day is inserted below.



(a) **(b)** **(c)**

Figure 2: CDR daily launch views.

When filling out the CDR, it is possible to include daily photographic records and attached documents. The daily report's export is adaptable to a standard defined by the construction company and PDF format. Figure 3 shows the CDR of TCA-0057, corresponding to the project "Teatro Cultura Artística" on its 57th day of execution.



(a) (b) (c) (d)

Figure 3: Views of the final CDR standard.

After all the information is inserted, the CDR progress for approval by the project manager. Based on the contract, the internal approval flow may contain these steps: approval within a specific area (e.g., production), approval by the project ADM (usually from the agreement sector), and then finally, the approval of the project manager. However, in most construction company projects, just one level of approval (project manager) is used. After approvals, the document is blocked for edition by the system, which guarantees its reliability.

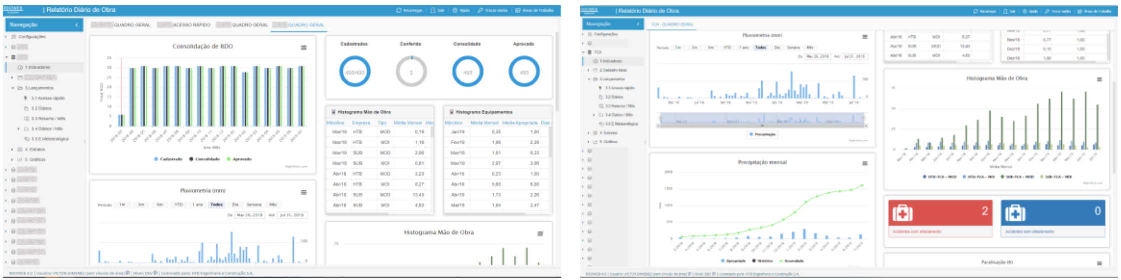
Data Analysis

The operations available in the system and the corresponding objectives can be seen in Table 2.

Table 2: Operations and indicators available in this information management system

Operation	Objectives
1. General Control	A dashboard of summary information containing graphs of CDR consolidation per month; comparative of issued x consolidated diaries, consolidated by project, released by the client; histograms of crew and equipment, graphs of weather information, a graph of shutdowns, and safety accident occurrences
2. Base Registration	Registration of standardized information in the database that will be selected: Management areas, Technical Record Annotations (TRA, *in Portuguese: Anotações de Registro Técnico - ART*), Activities (WBS), Service Authorizations, Positions, Classes, Disciplines, Staff, Companies, Equipment, Teams, Manufacturers, Supplies, Locations, Levels, Shutdowns, Historical Rainfall; Work period, Projects, blueprint/sites; Sector
3. Launches	Information consolidation by the construction company: Quick access to CDR for information fulfill; Diaries: check of pending information by organizational sector; filters with general information; access to Meteorological Station data
4. Extracts	For traceability records about information search segmented by: Safety accident, Activities, Contractor Comments, Consolidation Time, Worker, Nominal Histogram, Equipment, Relevant Facts, Shutdowns, and Rainfall
5. Diagrams	Various graphics for analysis and capturing management information: Consolidation of diaries, Shutdowns, Temperature, Rainfall, Histogram of the Workers, and Map of Contents. The graphs are dynamic, and the information can be crossed according to analysis. In addition, it is possible to export the diagrams in PDF, XLS, or image file format outside the system.

Figure 4 shows the software dashboard containing a summarized and graphical form of project management's leading indicators. Figure 4-a shows the following indicators: CDR consolidation by day, rainfall index (mm), workers, and equipment histograms in charts. Figure 4-b shows the following indicators: monthly rainfall, histogram of the worker (graph), number of safety accidents, and absenteeism. In addition, information about the occurrence of stoppages and the physical progress of the work can be presented. Thus, this information's systematic and simplified presentation brings a holistic view of the project's development.



(a) (b)

Figure 4: Information summary dashboard.

The software allows the view of the daily and monthly control of the CDR, pointing out activities in progress, the relevant facts, the workers in the project, the quantity of equipment, status of evaluation and consolidation of the CDR, registration of contributions, and access to the complete CDR. Furthermore, multiple graphs can be generated about service shutdowns in a detailed and daily form. The way information is disseminated through customized graphics fulfills several lean objectives: increasing transparency, improving communication between agents, using visual management tools, recording evaluation indicators, and monitoring performance.

Results and Discussion

The development of the program over five years also aimed at integration with other sectors of the company, such as planning. Through the CDR, it is possible to report the physical progress of the work. However, compliance with the plan is verified through another procedure - the follow-up of the action plan, which is discussed weekly at the team meetings. The planning report presents the control planning indicators, such as removing restrictions and compliance with the Percentage of Plan Completed (PPC).

The time spent to fill in the CDR at work is, on average, 5 to 20 minutes per day/employee. This time directly depends on the amount of information (for example, if there are many production fronts with personnel and equipment or many concomitant activities). At the construction site, the filling team is usually made up of five people responsible for each department: engineering, field, HSE, HR, and project manager. They work concurrently and independently due to the program's features. Figure 5 shows the current procedures for daily elaboration of the CDR.

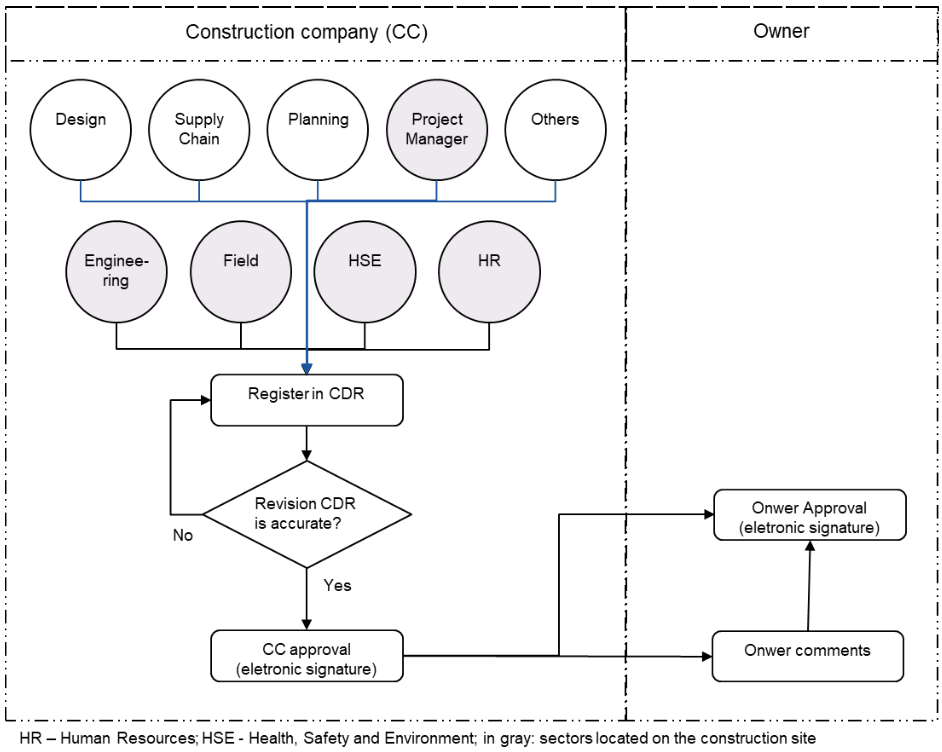


Figure 5: Procedures after the implementation of the computer program.

The customization of the program CDR with the developer allowed aspects of lean construction such as standardization of management activities, increased transparency, and improvement of the communication process, among others. For this study's constructor, the CDR has documentary value, considered more relevant than the minutes of meetings and other documents exchanged between the stakeholders. Both companies signed this document and have daily regularity and a wealth of managerial and technical information on the project day-by-day. Before the ICT implementation, problems were usually identified in filling and approving some records. The delay in consulting the records can lead to divergences of understanding regarding contractual issues. Table 3 shows the difficulties, causes, and proposals or guidelines to solve problems.

Table 3: Difficulties, causes, and solutions for the management process of the CDR

Category	Difficulty	Causes	Solution proposal
STANDARDIZATION	Lack of forms of standardization	The file was editable, and each responsible for filling it out adapted it according to the needs of the project	Non-editable form, with fields to meet all types of situations encountered in the projects
	Lack of information standardization	Information was recorded in different ways on each CDR, defaulting traceability	Cadaster of repetitive records, avoiding spelling divergences, and facilitating traceability
	Non-detailed information	Manual fulfillment causes data inaccuracy and difficulty of understanding by external agents	Select items listed on the project's WBS to fulfill the CDR
	Difficulty retrieving information	Forms were printed to collect signatures, generating analogical documentation, hard to be cataloged and retrieved	Digitalization of the entire process documentation. Information traceability facilitated through smart search functions
FLOW	Difficulty in filling in information from different sectors	It was a single file, and it allowed only one to edit it at a time. The nomination of one responsible for filling out the CDR in each project (usually from the production area) neglected relevant information from other areas.	Simultaneous access by agents to the same document, the different fields' editing is authorized according to the sector. Through pending control, all areas must discharge the information.
	Slow flow and extensive process	As was a single file, the process flow had pauses between steps para signatures different	Reduction steps number and duration
	Delays in the approval of documents by stakeholders	The signature of the counterparty only occurred after document approval, which generated revisions	Linking the CDR review with the signature, allowing comments on the subsequent CDR
	Process monitoring by different agents	Access to documents was physical, limited to the construction site on which it was developed	Permission to access the CDR and extract the process flow by management sectors, remotely
TRANSPARENCY	Difficulty accessing information outside the construction site	Access to documents was physical, limited to the construction site on which it was developed	The information can be easily accessed remotely by authorized people whenever necessary

These difficulties generated impacts on contractual administration, often giving rise to discussions regarding deadlines, unsolicited scope changes, limitations on on-site service at the project, limitations on project activities and acquisitions, supply, or modification of designs resulting from other impacts. Therefore, the CDR process was studied for optimization, and ICT was identified as the best strategy to face the founded problems. Among the results obtained, the flow of the current CDR process was reviewed. As a result, it is observed that different agents involved in the project can perform the insertion of data simultaneously.

Furthermore, the printing step has been suppressed, and the approval steps have merged due to the possibility of remote approval. It also appears that the interaction with the project's stakeholders occurs in a fluid, tangible, way and with no room for misinterpretation. With the review of the CDR documentation process aided by software, it was observed that the Flow and Standardization problems were solved. The Standardization problems were solved by using a digital document format and the facilities for using them remotely. The concurrent development process of the program proved to be an efficient procedure, as it incorporated user suggestions and best practices into the project management process.

CONCLUSIONS

Several benefits could be seen in adopting an ICT for the CDR management process in project construction. This study showed that its most significant benefits are processing information and preserving it from technical, judicial, financial, and deadline impacts. Conflicts are increasingly recurrent in enterprises due to the greater competitiveness of the market and customer specialization. They arise from specific situations and market dynamics that depend on numerous factors internal and external to the business. In this way, conflict resolution is not directly linked to the use of this tool. However, its use facilitates the search for information, records the exchange of information during the work, and speeds up decision-making by agents.

With the standardization and centralization of information, a technical database of the projects was created. However, despite the success in implementing the digital CDR, it has not yet been possible to analyze quantitatively the impact of its use in the resolution of contractual conflicts. This may be a new focus for the continuity of this research.

The system incorporated several lean construction principles, such as improving the flow of information and communication between the participating agents. In addition, it managed to standardize the collection and processing of information, making the entire management process quite transparent.

In addition to the benefits mentioned, a culture change was noticed after implementing the system related to the importance that the construction teams started to give to CDR. Employees understood that a well-formulated and information-rich CDR can be a great ally in several aspects. The project members started to become more responsible for their daily records, regardless of the project's activity area. They cultivated the daily habit of systematically detailing the records so that the CDR is always up-to-date. In addition, the use of electronic CDR has become a new paradigm in the company, which does not start any new work without it. The work teams recognize how this digital practice has greatly facilitated daily records in each sector.

Five years after the start, the program's update project is still ongoing and may seek integration with more lean principles and new technologies, BIM models, and mobile devices. Further research can realize more in-depth analyses of the data available, such as observation of recurring patterns in contracts and productivity calculations, which will serve as an essential basis for lessons learned, impact prediction, and process optimization.

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METHOD TO ALLOCATE COVID-19 PREVENTIVE MEANS OF CONSTRUCTION WORKS BASED ON EXPERT PRIORITIZATION

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ABSTRACT

COVID-19 has severely impacted construction projects, not only by contagions and imposed restrictions but also by dynamically changing supply, work, and labor conditions. Management teams have had to adapt to these dynamically constrained conditions, mostly reacting through trial and error. Since decisions regarding planning, resource, and preventive means allocation must consider multiple internal and external conditions such as restrictions, schedule impacts, risks, and costs; this study proposes a method to evaluate the compared criticality of multiple construction work items and select sets of recommended preventive and reactive means accordingly. A criticality assessment tool was developed in collaboration with 11 academic and industry experts using the Analytic Hierarchy Process, which allowed to weight the compared impact of nine criticality criteria. The empirical application in nine work items from three Chilean construction projects allowed to determine four ranges of critically, where expert' proposed sets of measures were recommended. The instrument allows assessing the items using a five-level evaluation scale in nine criteria to determine compared criticality, assign them to one of four criticality ranges and obtain a set of recommended actions.

KEYWORDS

COVID-19, safety, health, action research, construction work prioritization

INTRODUCTION

The construction industry represents approximately 6% of the world's Gross Domestic Product (GDP) (Kenny, 2007) and employs approximately 7.7% of its population (International Labour Organization, 2021). Its main activity consists of project development and infrastructure delivery for residential, industry, and service use. Project execution is highly complex since it involves the collaboration of multiple stakeholders to carry out resource and labor-intensive tasks, which constitute highly interrelated

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activity programs that extend over several months or years (Brissi & Debs, 2019). Also, researchers have long studied how uncertainty and variability negatively impact the dynamicity of construction and induce a tendency for scope, budget, and schedule deviations if not properly controlled (Gómez-Cabrera et al., 2020; Grau et al., 2019; Przywara & Rak, 2021). Under the rapidly changing conditions induced by the COVID-19 pandemic, uncertainty and variability increased considerably, significantly impacting project development and infrastructure delivery (Araya, 2021).

The COVID-19 pandemic has severely impacted the construction industry, and its recovery is key to economic activity and employment creation (de Henau & Himmelweit, 2021; Denny-smith et al., 2021). Many construction companies have experienced severe limitations in their production, planning and control capabilities (Ling et al., 2021) due to supply-chain outages, labor and resource limitations, protocols and restrictions imposed by authorities, among others (Kim et al., 2021). Moreover, the lack of existing protocols for uncontrollable events such as a pandemic and lack of previous experience since a similar event has not occurred globally since the early stages of the 20th-century forces management and execution teams to adapt their strategies through trial and error. Therefore, companies and particularly project teams are being forced to react to impacts after the fact or allocate preventive measures based on their best assessment of current and expected conditions (Jeon et al., 2022).

The sanitary measures established because of the pandemic have affected construction work planning, execution, and control (Parameswaran & Ranadewa, 2021). Traceability requirements make it necessary to know the interaction and contact between crews and the risk associated with the site where these activities occur (Assaad & El-adaway, 2021). In addition, capacity restrictions and personal protection measures vary according to the type of work to be performed, the conditions, and the context in which the work is carried out (Simpeh & Amoah, 2021). Moreover, the effectiveness of measures such as the modification of processes, incorporation of technologies, changes in construction methods or industrialization (Brissi & Debs, 2019; Leontie et al., 2022) depends on the type of work item in which these measures are implemented, the conditions of the worksite, and current risks according to the foreseeable tendency of the contagion rate (Gan & Koh, 2021; Yang et al., 2021).

The need to adopt new sanitary protocols combined with production method changes presents an opportunity to do it in a safer, more productive, and sustainable approach (Assaad & El-adaway, 2021; Verán-Leigh & Brioso, 2021). This can be achieved by integrating infection prevention protocols with production management protocols that incorporate available technologies and methods to implement industrialized, more efficient, and sustainable construction processes that allow safer and more productive construction (Al-Mhdawi et al., 2021; Brissi & Debs, 2019). Nevertheless, since implementing such protocols, managerial and production changes can be costly and resource-intensive, project managers and safety professionals need to prioritize preventive, proactive, and reactive actions (Hallowell et al., 2013).

It is a complex endeavor to prioritize how to secure productivity and schedule viability while lowering the expected risks of contagion or other impacts on the project and its team (Yang et al., 2021). Furthermore, since conditions vary rapidly and often, current protocols and implemented actions can rapidly cease to suit the project's best interest or cause unexpected side effects (Chih et al., 2022; Gan & Koh, 2021). Selecting a combination of these protocols and actions presents three alternatives: Implementing a minimum required set of preventive measures and accepting a certain level of risk;

oversizing planned preventive measures and accepting greater costs, resources, and effort involved; or allocating a specialized set of measures to different project areas based of risks' probabilities and expected impacts (Assaad & El-adaway, 2021). The latter alternative would require project teams to be able to react in advance to changes through a systematized method of evaluation and prioritization.

Decision-making under these circumstances requires systematically combining planning and control, workforce monitoring, and context data to ensure the most efficient allocation of measures (Amoah & Simpeh, 2021; Kim et al., 2021). Hence, the current situation forces the adoption of information technology (IT) to a greater extent, paving the way for improvements in the integration of IT with project planning and control, resulting in new workplace health and safety protocols adapted to the pandemic context (Ebekozien & Aigbavboa, 2021). Suppose available technology, protocols and information use are well integrated. In that case, they can allow to carry out prioritization of needs and available options periodically and in advance, based on risks and potential benefits.

Also, given that the exposure and risk of infection, as well as the loss of productivity and impact on the site, differ according to the type of work item affected, these decision-making systems must consider the type of work and conditions involved in different construction tasks and work items (Gan & Koh, 2021), establishing alternative batteries of measures that best suit each context, risk relevance, and work item assessed (Simpeh & Amoah, 2021). Therefore, this research aims to design a method for evaluating and prioritizing work items at the construction site. In addition, the method will allow a selection of IT-supported alternatives, which can be implemented to reduce the risk of contagion and prevent negative impacts on performance.

RESEARCH METHOD

The research methodology was conducted through action research to secure the study's goals through three main stages: (1) Design of a work item evaluation instrument based on a risk and criticality assessment; (2) applying evaluation instrument in a set of work items from 3 projects to identify criticality cohorts; and (3) proposal of a set of IT-supported actions for each type of work item.

STAGE 1: DESIGN OF THE EVALUATION INSTRUMENT

Three workshops (WS) of 2.5 hours each were carried out to design the evaluation instrument. The participants were 11 people: two were from the research team; two from a Lean project management consulting firm; and seven construction professionals from three large construction companies based in Chile. The consultants were civil engineers with more than 10 years of experience in the application of Lean in construction companies. The seven professionals were civil engineers or construction engineers with more than 10 years of experience, project managers and production managers. Table 1 describes the objective, activities, and deliverable for each workshop.

During the first WS, a set of 19 possible criteria was proposed by the participants and refined until obtaining nine assessment criteria. This refinement consists of grouping similar sets of criteria and creating a more specific description of that set to conform to a new criterion and, thus, reducing the number of areas from 19 to 12. Then, the participants were asked to agree on rating the easiness of evaluation, relevance to assessing criticality, and ability to differentiate items objectively. That assessment concluded with selecting nine relevant, easy to rate, differentiating criteria.

Each participant was asked to use an Analytic Hierarchy Process (AHP) rubric through an Excel template for multiple participants to assess the compared relevance of each criterion against the remaining eight (Klaus, 2013). The AHP is a decision-aiding that aims at quantifying relative priorities for a given set of alternatives on a ration scale, based on the judgement of the decisions-maker, and stresses the importance of the intuitive judgements of a decision-maker as well as the consistency of the comparison of alternatives in the decision-making progress (Can Ylldlrlm et al., 2021). The results were consolidated in WS 2° to create a judgment matrix, and the calculation of the consistency ratio allowed to iterate in the workshop until each individual and the conjoint judgment matrix obtained a consistency equal to or greater than 10%, who it is a typical value in the AHP method (Klaus, 2013). The resulting eigenvector of the judgment matrix represented the relative weight of each criterion within the instrument.

The definition of rating levels for each criterion was carried out in WS 3°. A standard five-level Likert Scale was selected, and each level was assigned a rate in a Fibonacci ladder to differentiate the responses significantly (Can Ylldlrlm et al., 2021). Hence, the resulting levels were very low – 1, low – 3, medium – 5, high – 8, and very high – 13. The participants were asked to propose objective attributes to define the level that better represented a given work item's criticality in each criterion. For example, the participants agreed on five ranges to establish the criticality level of the average crew size. Finally, After the three WS, the instrument was presented to the participants, and a detailed explanation was carried out, enabling them to apply the evaluation instrument in their construction projects.

Table 1. Activities and deliverables from stage 1 workshops

WS	Objective	Activities	Deliverable
1	Identify a set of factors required for the evaluation of work items.	Brainstorming factors for assessing the relevance of a work item Qualitative analysis of factors according to the value of the work item and the ease of evaluation	List of factors
2	Establish a prioritization of the evaluation factor using AHP	Presentation of factors considered in WS1 Preparation of individual judgment matrix and calculation of consistency coefficient. Elaboration of judgment matrix using the median Calculation of weights per factor.	Weights of factors
3	Create a rating rubric for each evaluation factor	Presentation of factor weights in WS2 Definition of rating levels Description of the levels for each factor	Rubric of factors

STAGE 2: EVALUATION OF WORK ITEMS IN CONSTRUCTION PROJECTS

Three construction companies evaluated the criticality of their work items using the instrument created in the previous stage. A total of nine work items from high-rise building projects were evaluated, all of which belonged to the framing construction phase of the projects. After gathering the evaluation results, two meetings were carried out to obtain the results for each work item and make final adjustments to the instrument. The first meeting focused on describing how each team evaluated their work items and aligned criteria, after which a set of recommendations was established to ensure a standardized assessment. The second meeting focused on resolving concerns and capturing proposed adjustments to the evaluation scale, such as refining objective quantitative ranges required for each scale-level in each criterion. The second meeting concluded with a final update of the work items evaluation. Table 2 shows the work items evaluated by each company.

Once the Global Evaluation (GE) index of criticality was obtained for the nine work items, two meetings were held to propose and validate the set of criticality ranges which would be assigned different batteries of measures and actions. These ranges were based on explicit cohorts observed after the evaluation and sensitivity analyses of the changes in the GE caused by changes in the level assigned to each criterion. It was decided that the lowest range of the GE would represent work items in which the vast majority of the criteria was assigned a level equal or lower than medium, hence, a GE≤5.0. Similarly, the highest range, i.e., the most critical, would require that the vast majority of the criteria was assigned a level equal or greater than high, hence, obtaining a GE≥8.0. Finally, the work items with a GE between 5.0 and 8.0 were assessed in detail to determine if additional divisions were needed. After the close assessment, the participants detected that an increase from "medium – 5" to "high – 8" criticality in the three most relevant criteria should require a change in the recommended batterie, which produced a third division that created four final ranges of criticality.

Table 2. Work items evaluated per company

Company	Work items	ID
1	Preparation and placement of foundation reinforcement	1.1
	Installation of basement wall formwork	1.2
	Installation of tower reinforcement	1.3
2	Anchoring of foundation piles	2.1
	Installation of basement wall formwork	2.2
	Installation of basement wall reinforcement	2.3
3	Installation of basement wall reinforcement	3.1
	Excavation of foundation piles	3.2
	Concreting of basement wall	3.3

STAGE 3: PROPOSAL OF A SET OF PREVENTIVE MEASURES

In stage 3, two workshops were held with all the participants of the stage 1 workshops. The first workshop consisted of teaching different technologies and methods to monitor and control people's behavior to mitigate the probability of COVID-19 transmission. Some of the technologies presented were capacity control of work areas, triage survey, distance detection bracelet, cameras for computer vision, video analytics, and ex-situ construction, among others. Also, methods such as the use of the Last Planner® System of production control, location-based planning, Building Information Modelling (BIM), and rule-based automated crew allocation protocols were discussed, introducing the general concepts within each of them. At the end of the workshop, construction professionals shared experiences of effectiveness and possible limitations of the different technologies and methods mentioned.

The second workshop consisted of using the four ranges of criticality obtained in state 2 to differentiate the nine items evaluated and new theoretical work items, to brainstorm, refine and validate a recommended batterie for each of them. The workshop discussed the particularities of each construction site to understand why two similar items had different levels of overall criticality in two different projects and the variance within available resources, capacity, and conditions of each project to determine general case scenarios. Finally, technologies and methods presented in WS 1° of the stage and new ones proposed by the participants were allocated to each criticality range to determine the recommended measures in each batterie.

RESULT AND DISCUSSION

EVALUATION INSTRUMENT

Table 3 describes the nine factors considered critical for evaluating a work item in a construction project and the weight assigned to each factor, obtained from the final judgment matrix. The final inconsistency ratio was 9%, hence, the eigenvector was considered representative of the relative importance of each criterion within the instrument.

Table 3. Description and weight of each criterion in the instrument

Factor	Description	Weight
The item is part of the critical path.	The item’s related schedule activities are part of the project's critical path.	21.30%
Risk personnel within the work item’s crew	Number of unvaccinated, elderly, and base disease staff within the assigned crews	16.80%
City’s expected pandemic phase	Expected phase in a 4-week horizon, on a five-level scale, according to authority-imposed restrictions	15.10%
Average possible social distance in the work area	The health authority defines the maximum capacity of a work area depending on the status of the pandemic.	11.50%
Minimum guaranteed physical distance	Average distance required to execute the tasks required to complete the work item	9.70%
Level and type of ventilation of the area	Type of ventilation of the location where the work will be carried out (open, closed, mixed)	9.00%
Relative cost of the item in budget	Work item unit price per quantity of work, multiplied by the planned work quantity, as a percent of the budget.	6.80%
Necessary specialization in the work item	Level of specialization required to perform the work item (complexity)	6.00%
Number of workers in average crew	Average number of workers per crew needed to carry out the tasks from the work item	3.80%

The participation of the work item’s related activities in the critical path, number of personnel at risk within the crew and expected phase of the pandemic in the next four weeks, based on a five-level scale, account for approximately 53% of the assessed criticality. This allowed to significantly represent the potential impacts of the risk of contagions over the construction site’s personnel and the project’s goals. Also, the average possible social distancing at the area where the work item will be carried out, the minimum guaranteed distance required to carry out the work item’s tasks and the level and type of ventilation available, which add to approximately 30% of the criticality, represent the capacity to prevent contagions while executing the work item. Finally, almost 20% is explained by the complexity of the work item, represented by its cost, required specialization and number of workers involved in its activities.

The criticality of each work item's criterion is represented by a non-linear five-level scale based on a Fibonacci sequence (1, 3, 5, 8 and 13), to help differentiate criticality levels. Specific measurable factors, which are presented in Figure 1, were assigned to each level in each criterion to facilitate the criticality assessment. These factors were based on the most relevant attributes needed by the academic and industry experts to assess the work items in each criterion and agreed upon at the end of stage 2. It must be noticed that these factors came from the use of the instrument within the Chilean context, they were generalized so that the same instrument could be applied internationally. Finally, as Figure 2 presents, higher observed factors which represent higher risks, impacts or foreseen restrictions, account to higher evaluation levels in each criterion, which are weighted and summed to obtain a General Evaluation of Criticality (GE).

Criteria levels	1 - Very low	3 - Low	5 - Medium	8 - High	13 - Very high
The item is part of the critical path.	Not part of the critical path	Between very low and medium	Yes, weight equivalent to 3%.	Between medium and very high	Yes, weight greater than 6%.
Risk staff composition of crews	None	At least one person at slight risk, none at higher levels	1 or more people at moderate risk	Between medium and very high	More than one at-risk person, at least one with high risk
City's expected pandemic phase	Phase 5 – Normal activities and movement are allowed with no capacity restrictions	Phase 4 – Normal activities and movement are allowed with slight capacity restrictions	Phase 3 – Normal activities and movement are allowed with moderate capacity restrictions	Phase 2 – Normal activities and movement are allowed with significant capacity restrictions	Phase 1 - Full lockdown or only critical activities allowed with significant capacity restrictions
Average possible social distance in the work area	More than 8 m^2 per person	More than 6 m^2 per person	More than 4 m^2 per person	More than 2 m^2 per person	Less than 2 m^2 per person
Minimum guaranteed physical distance	More than 2 meters radial	-	Between 1 and 2 meters radial	-	Less than 1 meters radial
Level and type of ventilation of the area	100% open space	-	Enclosed with natural ventilation	Enclosed with need of mechanized ventilation	Enclosed not ventilated
Relative cost of the work-item in budget	Represents 1% of the project's budget or less	Between very low and medium	Represents close to 3% of the project's budget	Between medium and very high	Represents 6% or more of the project's budget
Necessary specialization in the work-item	Does not involve specialized manpower, resources or complex procedures	Only some specific tasks require moderately specialized manpower, resources or complex proceedures	Aproximately half of the tasks require moderately specialized manpower, resources or complex proceedures, none of them high	At least some specific tasks require highly specialized manpower, resources or moderately complex proceedures	Most tasks require highly specialized manpower, resources or highly complex procedures
Number of workers in average crew	1 to 4 people	5 to 6 people	7 to 10 people	11 to 14 people	15 people or more

Figure 1. Evaluation levels and assessment factors for each criterion of the instrument

Criterion	Weight	Response	Level	Weighted level
The item is part of the critical path.	21,30%	Yes, weight greater than 6%.	13 - Very high	2,769
Risk staff composition of crews	16,80%	1 or more people at moderate risk	5 - Medium	0,84
City's expected pandemic phase	15,10%	Phase 5 – Normal activities and movement are allowed with no capacity restrictions	1 - Very low	0,151
Average possible social distance in the work area	11,50%	More than 2 m^2 per person	8 - High	0,92
Minimum guaranteed physical distance	9,70%	Between 1 and 2 meters radial	5 - Medium	0,485
Level and type of ventilation of the area	9,00%	Enclosed with natural ventilation	5 - Medium	0,45
Relative cost of the work-item in budget	6,80%	Represents close to 3% of the project's budget	5 - Medium	0,34
Necessary specialization in the work-item	6,00%	At least some specific tasks require highly specialized manpower, resources or moderately complex proceedures	8 - High	0,48
Number of workers in average crew	3,80%	5 to 6 people	3 - Low	0,114
General Evaluation of Criticality (GE)			**6,549**	

Figure 2. Example of work item evaluation using the instrument

EVALUATION OF WORK ITEMS

Table 4 shows the global evaluation of the nine items by the three construction companies. Although the criticality rating ranges from 1 to 13, the work items' GE was rated in a range of approximately 4 to 8, i.e., they have a degree of criticality between medium and high level, as presented in the rubric of factors in Figure 1.

Table 4. Global Evaluation of criticality (GE) from the nine items

ID	Work item	Global evaluation
1.1	Preparation and placement of foundation reinforcement	7.27
1.2	Installation of basement wall formwork	5.48
1.3	Installation of tower reinforcement	5.06
2.1	Anchoring of foundation piles	5.46
2.2	Installation of basement wall formwork	4.21
2.3	Installation of basement wall reinforcement	4.45
3.1	Installation of basement wall reinforcement	6.39
3.2	Excavation of foundation piles	6.05
3.3	Concreting of basement wall	5.70

A sensitivity analysis was carried out using the correlation between the GE results from the nine items, and evaluation results obtain using three sub-sets of the criteria: (1) All but the city's pandemic phase (weight = 15.10%), since authority imposed restrictions may vary over time and depending on the region, (2) All but the participation in the critical path (weight = 21.30%), since different scheduling methods may lead to different critical paths, and (3) All but the city's pandemic phase and participation on the critical path (Combined weight = 36.40%). Figure 3 presents a scatter plot where x-axis represents the GE obtained using the instrument and y-axis shows the resulting scores of the evaluation in the three cases. The linear regression trend-lines from the three cases are also presented with their correlation values represented by their R^2 results to show if the work items could be assessed without the use of the criteria.

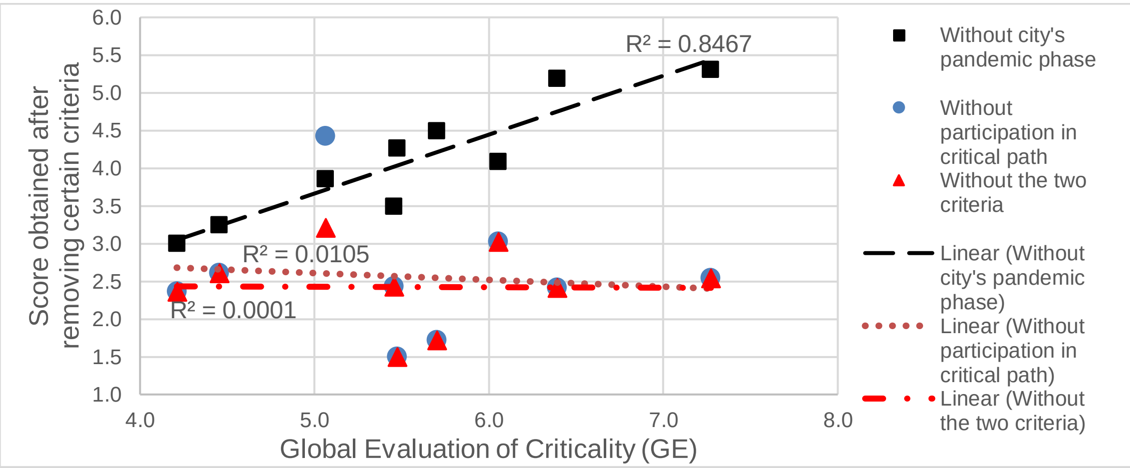

Figure 3. Sensitivity analyses of removing certain criteria from the evaluation

As Figure 3 exemplifies, removing the factors' evaluation associated with the expected pandemic phase of the city in which the project is being carried out would not drive significant differences in the evaluation. The high correlation between the GE scores and the scores obtained without considering the city's pandemic phase allows to infer that the instrument could be applied to prioritize work items from different projects in different cities, as well as assessing work items from the same project or region. On the other hand, removing the evaluation of the participation on the work item's related tasks in the critical path does affect the evaluation, as shown by the significantly low levels of correlation shown in figure 2. Hence, users should pay attention to comparing work items from projects using similar scheduling methods to prevent evaluation biases caused by the calculation of the item's weight on the critical path. Also, assessment of the item's participation and weight on the critical path should not be avoided since this criterion constitutes a fundamental element at the time of evaluating measures to mitigate project and safety risks.

CRITICALITY RANGES AND PROPOSED PREVENTIVE MEASURES

As presented in the research method section, at the end of stage 2, four criticality ranges were proposed. The first range represented the presence of mostly medium or lower-level factors in most of the criteria, hence, accounted for a GE≤5.0. On the opposite, the fourth range signaled the presence of high or very high criticality factors on most of the criteria, which would result in a GE≥8.0. The middle division was decided based on the effect caused by the three main criteria moving from a medium to high level, which represented moving for 5 to 8 points in criteria which accounted for approximately 53% of the weight. This movement would result in an increment of approximately 1.5 in the GE, hence, the middle division was set as GE=6.5, obtaining the four proposed ranges. Table 6 shows the proposed the set of measures recommended by the academic and industry experts to prevent health risks and related project impacts, depending on the criticality range of each evaluated work item.

Table 4. Set of measures proposed for each criticality range

Range	GE	Set of actions	Measures
1°	GE ≤ 5.00	Base	Implementing systematic periodic instances of planning and coordination Increasing safety equipment and sanitary protocols Implementing capacity restrictions and ensuring systematic control in work areas Implementing periodical mandatory Triage surveys Temperature measurement
2°	5.00 < GE < 6.50	Distancing	Base actions plus: Ensuring effective and efficient on-site coordination through methods such as the Last Planner® System Increasing control of interactions on specific locations through systems such as QR registration protocols Increasing social-distance prevention through use of alert systems such as distance detection bracelets
3°	6.50	Analytics	Distancing actions plus:

	< GE < 8.00		Implementing higher coordination protocols such as the use of Location Base Planning to prevent unnecessary interactions between crews Shielding at-risk crews and highly specialized crews by avoiding contact through coordination systems such as on-site Plan of Day (POD) apps Monitoring social-distancing and coordinated crew movement through systems such as Computer-vision and GPS real-time monitoring
4°	GE ≥ 8.00	Industrialization	Analytics actions plus: Using Building Information Modeling (BIM) systems to assess the opportunity to shield or extract critical elements from on-site construction Ex-situ construction or opting for the industrialized construction of the most critical activities

CONCLUSIONS

This research aims to propose a method for evaluating and prioritizing work items at the construction site, based on health risks, project impacts and current restrictions. An evaluation instrument was constructed through action research in collaboration with 11 academic and industry experts, to allow the compared assessment of work items from single or multiple projects and identify recommended preventive actions. The instrument uses a five-level nonlinear scale to rate the criticality from 9 relevant assessment criteria. These criteria were weighted through the use of Analytical Hierarchy Process in collaboration with the 11 experts, to obtain an Eigenvector representative of the compared weight of each criterion with a 91% consistency coefficient. The proposed method allows to classify each item into four criticality ranges and each of them presents a set of recommended preventive actions to minimize the risk of contagion and impacts on the project’s goals.

Considering that the risk factors for COVID-19 contagion will lose relevance with time, the method proposed in the research represents an important step to face the different challenges or scenarios for the safety and health management in construction sites. It is possible to analyze specific risks such as handling and lifting of prefabricated elements, handling of chemical elements or other factors, which based on experts and professionals will be possible to quantify, measure and propose measures to mitigate such risks. Finally, the authors recommend that researchers continue this study by applying the instrument to additional items and projects, in addition to recommending new actions based on experience and literature research.

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IMPLEMENTING LOOKAHEAD PLANNING AND DIGITAL TOOLS TO ENABLE SCALABILITY AND SET OF INFORMATION IN A MULTI-SITE LEAN IMPLEMENTATION

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ABSTRACT

This paper seeks to demonstrate the implementation of lookahead planning in the current largest construction company and developer in Latin America and how best to consolidate and manage data from a large number of construction sites. This is demonstrated starting with the planning of the implementation pilot, defining the routine model, the participants, the methodology and tools and goes on to the part of continuous improvement within the implementation cycles. The project expansion and project support stages reached 162 sites within a year. This was split into three implementation cycles, led to training 40 multipliers in the lean philosophy and the last planner system within the company in question. The article also presents difficulties encountered in the process of implementing this high volume of sites. Using the preliminary data collected in the routines, it was identified that more than 56% of the restrictions are not removed on time and these, when delayed, cause a delay of 20 days. In addition, it was identified that material correspond to approximately 55% of the total restrictions found in the survey.

KEY-WORDS

Lookahead planning, Last Planner® System, constraint analysis, application development

INTRODUCTION

Despite Lean Construction being a production philosophy applied to construction since 1992 (Koskela, 1992) and the Last Planner System having been described for the first

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time in the following years (Ballard, 1993; Ballard, 1994), its practice is still little explored. systemically, in civil construction and, when it is implemented, it is sometimes done inappropriately, without understanding the principles and concepts behind it (Ballard, 1994). According to a survey carried out by Climb Consulting in 2020 (Climb, 2020), among the planning horizons, lookahead planning is the one in which the companies that took part in the consultation have the lowest level of implementation maturity.

Several studies have already demonstrated Last Planner system implementations in companies (Formoso et al., 1998; Kalsaas et al., 2009, Hamzeh and Bergstrom, 2010, Lindhard and Wandahl, 2013, Kassab et al., 2020). Benefits from these have included greater engagement of subcontractors in the work planning, adherence to the work planning, improvements in productivity and in the cost of sites. However, the implementation of the Last Planner System presents many difficulties. Lean requires the parties involved to collaborate, which in traditional companies is in itself a barrier, as there is a veiled unfriendly competitiveness between people, thus generating a lack of mutual trust between the parties. In addition, specifically in civil construction, the development of a stable labor supply is difficult, creating work packages with their associated productivity, resistance of those involved in the process to changes, lack of commitment to carry out the activities and routines of the new system, lack of training, and lack of support from a sponsor for the project to happen (Kalsaas et al., 2009; Fernandez-Solis et al., 2013; Ryan et al., 2019; Kassab et al., 2020).

Ballard (1997) defined the lookahead as the "missing link in production control" which, since the time of its publication, is the planning stage that has the least effective execution in the construction industry and moreover, in the Brazilian scenario, this lower adherence persists (Climb, 2020). Several articles have been published specifically addressing this planning stage (Johansen and Porter, 2003; Kemmer et al., 2007; Ballard et al., 2007, Hamzeh et al., 2008; Kalsaas et al., 2009; Samudio and Alves, 2012) and several others presenting cases in which they were implemented in small and medium-sized companies and in specific and infrastructure construction sites (Formoso et al., 1998; Kemmer et al., 2007; Hamzeh et al.., 2008; Kalsaas et al., 2009; Samudio and Alves, 2012; Kassab et al., 2020). However, the development of implementation pilots and project rollout in a company with a high volume of construction sites and units produced is not explored and in terms of the scalability of the collection and processing of information in a large number of sites within the same company, permeation of information and integration with the company's other systems is still a gap in the literature.

Therefore, this article puts forward the process of implementing lookahead routines in a large construction company with a focus on consolidating, controlling and managing these routines, as there is a need for scale when managing the information gathered in these routines and digitization is presented as a solution. To do so, tools applied and insights already obtained using the data collected will be presented that covers from the analysis of the initial state to the stage of developing the routine.

LOOKAHEAD PLANNING

Ballard (2000) cited six functionalities of lookahead planning in his study, namely: Shape work flow sequence and rate; Match work flow and capacity; Decompose master schedule activities into work packages and operations; Develop detailed methods for executing work; Maintain a backlog of ready work; and Update and Review higher level schedules as needed. After planning 3 to 12 weeks, all activities are analyzed to identify constraints in order to generate a stock of activity packages that are ready to be placed in the week's

planning. This analysis of constraints is carried out so as to give the construction team enough time to anticipate the problems that constrain the activity being undertaken and can act towards finding a resolution in order to be able to meet the initial deadline.
Lookahead planning, in the horizons defined by the Last Planner System, serves to create a window of reliability in production, because, in those weeks that have been planned ahead, the flow, sequencing and workload have already been defined and there is a list of packages ready to be pulled to short-term planning. In other words, a step is introduced in planning that will collect information on what must be done, check what can be done and a list of activities that will be performed will be generated. (BALLARD, 1994). Ballard and Howell (1997) also point to lookahead planning as an essential step in production to shield the production and they only send activities to teams that really are able to perform them.

RESEARCH METHOD

Action research was the methodological approach adopted in this paper. Action research focus is on solving real problems (O'Brien 1998) and contributing to the organization's development, focusing on simultaneous action and research in a collaborative manner (Coghlan and Brannick 2001). The research was conducted through multiple iterative cycles of diagnosis and initial status following by three implementation cycles.

PROJECT CONTEXT AND INITIAL STATUS

Company A is currently the largest builder and developer in Latin America. It produces more than 40,000 housing units annually and has around 300 construction sites in simultaneous operation. The company focuses on constructing social housing, linked to the national program to promote housing in a country. Its product has a high similarity between different sites, even though they are at opposite ends of the country and the construction methodology is of the concrete wall type. Most of buildings have four to five storeys and there are some taller buildings ranging from 8 to 20 storeys.

The Lean implementation project was set to be run in one year and was structured as follows: three implementation cycles of three months each with a one-month break between each such cycle for a kaizen of the project in order to improve it as a whole for the next cycle. Besides the implementation, the project provided for training multipliers in lean philosophy and the last planner system on site so that they would become responsible for sustaining the project. In addition to this, these employees who were trained at each cycle were to be responsible for implementing the routines, tools and philosophy at other sites with each new cycle that would take place. In this way, as a geometric progression, the project expected to reach 19 states, 176 construction sites within 12 months and to train 40 multipliers. For this implementation, it was defined that each consultant would be responsible for up to four simultaneous sites and for training not more than two multipliers simultaneously.

The company had a type of lookahead planning, which identified some constraints. However, this routine was monthly and used only the Pert-CPM planning of the MS Project and this was done only between a person responsible for planning 5 other sites (on average) and the construction engineer. Thus, several constraints were not seen, field problems were not taken into account, there was a lack of visual management and collaboration to understand the sequencing of activities and service fronts, and the collaborative and social element of Last Planner did not exist.

IMPLEMENTING THE LOOKAHEAD IN THE SITES

After the company's initial diagnosis, a model of lookahead routines and tools were developed to be tested in the first implementation cycle. For this pilot, what were defined were how the meeting would take place, who were the participants and what visual management, materials and responsibilities there would be. The standard definition was an important deliverable considering the number of construction sites and the geographical distance in between each region (as shown in Figure 1) that could be a barrier for a complete lean implementation. For the start of the project, it was defined that the superstructure part of the buildings would be dealt with, thus leaving the external part of the condominiums aside for the time being. The summary of the implementation cycles defined in the project and some of the numbers of sites involved are presented in Figure 1.

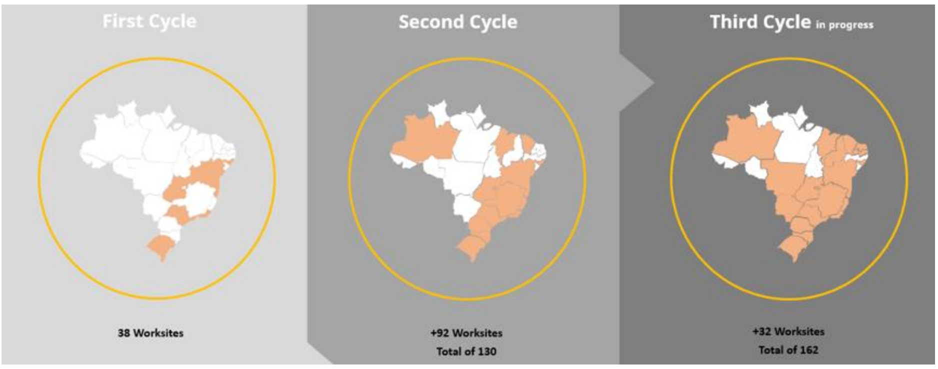

Figure 1 - Lookahead implementation cycles

Table 1 presents a summary of the main points that were generated in these meetings with regard to implementing the lookahead planning, standardizing the process and managing this information, and further on, the implementation cycles and decisions are presented in more detail.

MODEL AND FIRST IMPLEMENTATION CYCLE

The first implementation cycle was marked as a major project pilot at company A. A visual management model was defined for the Lookahead Meeting and Survey of Constraints for which wall charts and post-its were used. At this meeting, the obligation to have a construction engineer, assistants, master builder, a safety technician and a warehouseman were defined, and that, optionally, there would be a coordinator/manager of the site, a project multiplier, interns and supervisors.

As company A's product has a high level of standardization among the various sites in Brazil, work packages for all sites could be defined, in order to start the pilot of the meeting in 38 sites in 6 different Brazilian states in the most standardized way possible. For the lookahead, some tasks were grouped into packages. Thus, it is possible to be more objective when dealing with the themes. The dynamics of a lookahead meeting were initially established as follows:

- Plan the next six weeks of the sites;
- Survey constraints linked to the activity packages;
- Define an action plan for each constraint found raised with the person in charge and a deadline for its removal;
- Compile information to generate indicators of the process.

As a premise of the project, a target was set for the rhythm of production to be reached for each work package. Therefore, the concept of balancing and constructive sequence had already been incorporated into Lean Implementation. Having set the rhythm pace and standardized and sequenced packages for the six weeks, the second stage begins, which consists of detecting the constraints that may adversely impact the conduct of the planned activities. To assist in identifying and categorizing constraints, some categories of these were defined for the project, namely: (a) Manpower; (b) Material; (c) Design; (d) Accesses; (e) Equipment and Tools; (f) Safety; and (g) DAE (the acronym in Portuguese for the Department of Support to the Contractor). For this step of identifying and categorizing constraints were considered the perspective and information regarding the construction phases the following participants: engineer, interns, foreman, construction assistants, supply administrative, safety technician and planning assistant.

Table 1 - Summary of implementing lookahead planning cycles

	Cycle 01	**Cycle 02**	**Cycle 03**
Number of worksites total	38	130	162
Number of worksites using virtual Action Plan	5	49	72
Standarization of Package	Non-existent due to lack of standardizing the sequence of construction	Standardized packages for superstructure	Standardization of packages for supra and infrastructure
Constraints checklist	No	No	Yes
Access to information gathered in lookahead sessions	Local only	Remote acess to those involved in work	Remote Acess to the company
Information capture and management tool	Excel	Sharepoint List + Excel	Power Apps + Power BI
Destination of collected information	Local Only	Online Database	Enterprise Data Lake
Good feedback from the construction site's team	Greater assertiveness in the execution of work Better constraint control Good integration with the construction team and some support sectors Greater reliability in planning in generall Good visual management for the work The information digitization pilot was a success	Operational gain with new activity package split Easier and better access to information generated in the lookahead meeting	Constraints checklist brought a higher level of reliability to the lookahead process Less mature teams were able to perform the lookahead meeting with similar quality to experienced teams Reliability of the work as a whole with the inclusion of the infrastructure in the lookahead
Improvement points	Difficulty in identifying constraints	Difficulty for teams to use more digitized tools Need to include other condominium areas in the lookahead routine	Help chain structuring Draw up checklist of constraints of infrastructure activities

Once the restrictions for the period were defined, an action plan was created on a whiteboard on the wall. This generated an action for each constraint identified, with person responsible and deadline for completion. The last step was to compile this information into a spreadsheet with a dashboard on a dynamic spreadsheet, thus generating lookahead planning indicators and of the efficiency at removing constraints. The first indicators used in the project were: (a) Constraint Removal Index; (b) Constraint status per person responsible and per category; (c) Average days of delay per person responsible and per category; (d) Lists with the next constraints due to expire; and (e) List with delayed constraints. After having defined this routine and these materials and indicators, implementation began in the 38 sites of the lookahead planning and as a result, opportunities for improvement were identified:

- Lack of experience of the construction team at making a survey of constraints;
- Lack of giving support to routines when the consulting team was not present at some sites;
- Policy of not using Excel on sites to avoid sites manipulating cells and consequently, sites not being supplied with the software;
- Lack of some people's familiarity with Excel, thus making use of it was difficult;
- Teams "forget" about the action plan from its creation until the day of the next lookahead meeting;
- Difficulty accessing the action plan when outside the Obeya room;
- Difficulty that managers and directors not on site have in sharing and monitoring indicators;
- Difficulty triggering help chain via data collected.

When these difficulties were perceived by the implementation team, it was identified, that this provided the opportunity to use an online action plan. This would enable those responsible for the constraints to be alerted, and would facilitate access to the plan outside the Obeya room and would eliminate the need for sites to use Excel or to use it to manipulate data and information. Among the tools available to the company, it was decided to use the Sharepoint List, but, still, for the time being, to keep the information dashboard in Excel. However, the data entered were automatically updated in the company's cloud and everyone connected to the sites could access the data remotely.

Despite Sharepoint being one of the platform solutions already made available by the company, the teams used only the basic functions of the app. In other words, implementing the proposed virtual tool was to be done in an environment that was scarcely digital - a typical feature of much of the civil construction industry - and for a team with little familiarity with the opportunities that has already been presented to them. Hence, the implementation and use were closely guided in a pilot format with a few sites and linked to the same consultant.

Five construction sites were chosen for the pilot. The Sharepoint list allowed engineers and managers to access the action plan even off-site without using Excel, and those responsible for the actions began to receive emails informing them when the actions were created, edited or deleted. Other alerts were created according to the need noted with the use, e.g., it was noticed that some employees postponed the deadline for resolving the action so as not to appear negative in the indicators. Therefore, an alert for the engineer had to be created whenever a date limit was changed.

As a result of this first cycle of implementation, with the tools in their most basic form and an initial standardization of routines and methodology, the multipliers reported greater assertiveness in the execution of the work, better control of constraints, good integration with the working site's team and some sectors of support, greater reliability in planning in general and good visual management for the site. In addition, the information digitalization pilot was successful, so it was then expanded to other regions. As a point of improvement, what was highlighted was the difficulty that some teams - with a very young profile in this company - have in identifying and removing constraints and in implementing integration.

SECOND CYCLE OF IMPLEMENTATION

For the second cycle, training was held for everyone involved in implementing the lookahead planning in the new digital tool that had been validated in the cycle 01 pilot. This tool had already been standardized in some categories and this permitted some further data analysis. Moreover, the use of excel as a tool to control actions could be discarded. Only the panel of indicators in it was kept, while all the filling in and manipulation of data would now be in Sharepoint.

The second cycle stood out because of the large expansion of the project. In this cycle, 92 more sites were added to it. This now totaled 130 sites in 8 different states and therefore covered 14 states in Brazil. Among the new sites, implementations carried out by multipliers trained in the previous cycle, without direct assistance from an external consultancy.

There were some changes in relation to the model of the meeting implemented in cycle 01, namely, alteration of lookahead packages covering some activities initially omitted; standard sequencing for the sites was defined. Having obtained good results by using the methodology for the activities of the supra-structure, the initiative to use the methodology and tools for infrastructure arose spontaneously on some sites. Regarding the routines, their characteristics remained unchanged. Of these 92 sites, 49 advised that they would be using the new tool to include their sites in the database. This difference can be justified because there were sites that implemented the project without the direct participation of the consultancy, sites that chose not to migrate and sites that use the tool, but did not inform the person responsible for digitizing the lookahead, which covered most cases.

After collecting the data, a base was obtained with 4,793 actions recorded by the teams of the 49 adhering sites. However, as most of the fields did not place limits on their completion, as columns could be changed to meet specific demands of the sites and due to negligence when filling in the Action Plans, it became necessary to prune the database. Thus, it was reduced to include only 1,545 actions with sufficient information and clarity for all intended categorizations. Thus, a need arose for a solution that would guide how to complete fields and prevent errors.

As a result of the second cycle, for the team responsible for implementing the project, there was an operational gain with the new division and standardization at the national level of the activities in the lookahead packages. In addition, with regard to including the action plan and indicators in the company's cloud, an improvement in access to this information was reported due to using SharePoint lists. This requires only an internet connection for checking or editing, in addition to the control facilitated by notification emails.

THIRD CYCLE

For the third cycle, as an increment to the project, the lookahead routine for the infrastructure part was standardized. This routine encompassed all construction site activities from then on. Another improvement was, based on the information collected in cycle 02 and the company's manuals for standard procedures, to create a checklist of common constraints for each of the suprastructure activities. Thus, the routine becomes less dependent on the teams' experiences and ability to identify future constraints and more dependent on the process.

Finally, an app on the Power Apps platform was developed, which replaced SharePoint. This thinks about the user’s experience, linked to a series of security devices that aimed not only at greater standardization and quality of information, but also at agility in inserting data and mitigating errors due to lack of attention or negligence. The third cycle, started in January 2022 and still in effect, was focused on sustaining the project. Hence, the lookahead routines were not implemented in as many new sites as in the previous cycle and focused on guaranteeing the project's sustainability in several sites where they have already been implemented. In this cycle, 32 more sites were added to the project, which gave a total of 162 sites in 5 more different states and thus covered 19 states in Brazil. Among the new sites, there were implementations carried out by multipliers trained in previous cycles, without direct assistance from an external consultancy. These numbers may still change during the cycle due to the company's strategic decision.

With the beginning of the cycle, the use of checklist of the constraints on activities began. This tool attracted a large and rapid adhesion from the teams and there was positive feedback regarding the increase in the agility of surveying constraints, in assertiveness and in the quality of meetings. It was identified that, even at sites with less experienced teams, the result of the meeting had a much smaller gap in quality as to more experienced teams surveying constraints, due the agility and the communication flow that derives from the lookahead meeting.

Also, with the beginning of the third cycle, implementing the lookahead planning was started for the other activities of the sites (condominium areas and infrastructure). Thus, a complete visualization could be obtained, and a protection window created for the next six weeks of the sites. Hence, this generated more action plans and larger amounts of data for the company's base, thereby enriching future decision making.

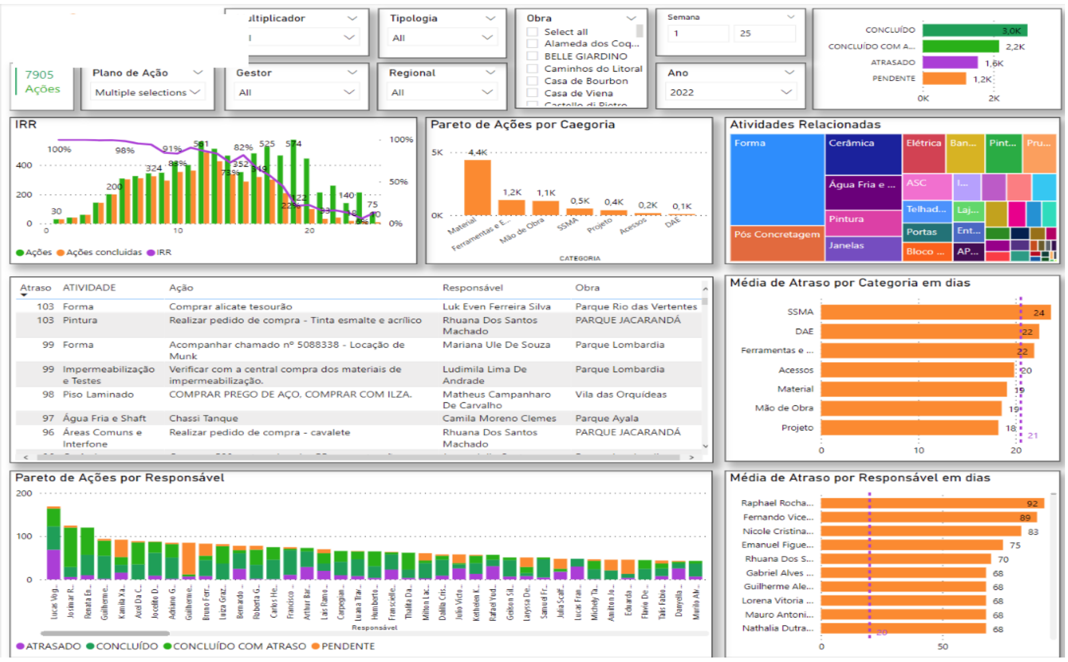

Figure 2 – 25 weeks data analysis

The use of the specially developed application was mandatory for new sites and optional for those using SharePoint lists with the option of migrating to the new solution without losing the history. This deployment format generated a large amount of data in a short time, 2363 actions raised in a month and all within the standards required for analysis. Figure 2 shows the results from the first 25 weeks of 2022.

RESULTS AND DISCUSSION

Data analysis is still preliminary, as teams are still adapting to the new tool. However, it is already possible to identify some important points for corporate analysis as shown in Figure 2:

- 56% of constraints are not removed on time. The database shows 23% of delayed actions and 42% of actions completed late with respect to the date stated in the lookahead meeting.
- 55% of the constraints refer to material, this being the main category of constraint found in sites, followed by Equipment and Tools with 15% and Manpower with 14% of the total.
- Of the related activities, 21% of the total constraints are linked to the Formwork package (the construction methodology adopted by the company) It is worth mentioning that most of the sites in which the lookahead process is being implemented using the app in this third cycle is at the beginning. However, this is a substantially higher value than those in second and third places: 8% (post-concreting) and 8% (ceramics).
- When a constriction causes a delay, the average delay is 20 days and those that cause the greatest delays are constraints related to safety at work (17 days).

NEXT STEPS

The subsequent stages to advance implementing the lookahead with a view to this being a source of data for strategic decision making, the analysis of indicators and reducing bureaucracy in the company are described below:

- Inserting data into the company's ecosystem: the capture of data from the app for the company's Data Lake was evaluated with the IT team. Thus, this will enable reports to be enriched, and to connect with any other data obtained by the various systems of the company. This process is expected to be completed by the end of the third cycle;
- Help Chain: Developing a management panel that presents the actions flagged in the appl as "help chain" and finishing structuring how this information should be passed up the other hierarchical levels of the company for quick problem resolution;
- Checklist of constraints for the other activities of the sites: The addition of the other activities of the sites in the lookahead planning and, consequently, their action plan in the apps database, will enable the checklist of constraints to be expanded. Construction teams will have access to the main constraints faced by works in progress, as well as works already completed, and thus be able to anticipate and expand the capacity to make a survey of constraints.

CONCLUSION

This article has presented the lookahead implementation project in a large construction company, and raised issues of project expansion, defining routines, a model for meetings and of tools used. The implementation in so many simultaneous sites require a great effort to standardize routines, tools and methodology on the part of those involved. The model for implementing cycles, followed by a month of reviewing standards and practices, proved to be a key point for developing the project and the continuous improvement of what was being proposed. Lessons learned in other implementations in isolated sites and in pilot format (as presented in the literature) are not enough for direct implementation in cases like this. It was possible to learn as the cycles developed and it was possible to deliver solutions that would meet the customer's needs, thereby seeking to guarantee the standardization, quality and sustainability of the project, regardless of regionalisms or peculiar characteristics of different teams.

The implementation of the lookahead generated greater integration with production support teams, production teams and administrative staff. This led to rich exchanges of information, allowing for better planning of the sites, the survey of constraints, visual management, and the engagement of employees with the established goals.

The difficulties of implementing the lookahead planning routine in a construction company and developer of such a scale were diverse. Training a large number of people is already a huge challenge and, like any change, it generated a lot of resistance. Due to the high volume of sites/consultant (up to four simultaneously), it was difficult to sustain routines, in some sites, at a time when the consultancy was not present on site. This was a reason for the lack of success at some sites, where the concepts were not fully absorbed by the field team and whenever there was no one keeping a close eye on procedures, the routines were not executed or were executed pro forma. In addition, the business environment for managing sites was not very technological and there were people who had difficulty in using online tools. The checklist developed for supra-structure activities was essential to increase the level of discussion in sites with less mature teams. However, it still greatly helped in sites with well-experienced people. This tool is always being complemented with new constraints that are pointed out weekly in feedback from sites.

Finally, it should be noted that although the solutions defined for this project were built on demand, they are not limited to use in this project. They can be used in others, even those with different characteristics that arise from some adaptations.

Regarding the data collected from the lookahead, what is demonstrated the low efficiency of the teams at removing constraints in time so as not to impact production. Altogether, 65% of constraints are not removed within the deadline and of those that are delayed, the average is 20 days. That is an important output but considering the current data we could not conclude what are the main factors that most impact on this average delay. We recommend a deeper analysis of data comparing the construction sites and the maturity of lookahead planning use to address a better understanding of the presented output.

In addition, 55% of all constraints found refer to material. In other words, more than half of the total number of constraints that impact a site refer to this category. However, there are still many restrictions that do not refer to this category of constraints (Equipment and Tolls and Manpower add up to 29% of all constraints) and they must be carefully analyzed to avoid interruptions in the flow of construction.

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FRAMEWORK FOR BLOCKCHAIN-ENABLED BUILDING INFORMATION MODELING (BIM) DATA SHARING IN CONSTRUCTION SUPPLY CHAIN

Jong Han Yoon[1], Pardis Pishdad-Bozorgi[2], Monica Viviana Sierra-Aparicio[3], and Emilio J Quintana[4]

ABSTRACT

Sharing construction project data among the construction supply chain (CSC) stakeholders (e.g., Architects, General Contractors, Subcontractors, and Suppliers) is critical for the successful delivery of construction projects within time, budget, and expected quality. Building Information Modeling (BIM) is an advanced technology for the stakeholders to create and share the construction data. However, BIM data is not effectively shared among the stakeholders because of the difficulty in determining BIM data ownership and the ambiguity in clarifying who will be responsible for BIM data inaccuracies. Consequently, the stakeholders cannot trust that their data are safe from data ownership and liability issues, hesitating to share their data. This study examines the potential of blockchain to address the limitations of BIM by analyzing blockchain use cases in construction and other industries. Furthermore, based on the findings, this paper proposes a novel framework for a blockchain-enabled BIM data sharing application to improve the quality assurance process in the CSC. This study contributes to the body of knowledge by 1) enabling the construction industry to understand the potential of blockchain through construction and other industries' blockchain use cases and 2) providing a practical framework for blockchain-enabled BIM data sharing to improve the quality assurance process in the CSC.

KEYWORDS

BIM, Blockchain, Construction Supply Chain, Data Sharing, Trust

INTRODUCTION

Sharing construction project data among the construction supply chain (CSC) stakeholders (e.g., Architects, General Contractors, Subcontractors, and Suppliers) is critical for the successful delivery of construction projects within time, budget, and expected quality (Titus & Bröchner, 2005). Building Information Modeling (BIM) is an

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advanced technology for the stakeholders to create and share the construction data (Liu et al., 2015). The technology provides a digital data platform that enables the stakeholders to transfer construction data across the supply chain with virtual 3D objects, including robust information at different stages, and deploy several collaborative instruments to drive project goals (Huang et al., 2009).

Despite the benefits, its legal and contractual systems are yet to be standardized (Arshad et al., 2019), thus leading to the difficulties in determining BIM data ownership and the ambiguity in clarifying who will be responsible for BIM data inaccuracies (Alnaqbi et al., 2022; Azhar, 2011; Enshassi et al., 2019; Oraee et al., 2019; Sun et al., 2017; Thompson & Miner, 2006).

Blockchain has the potential to address the aforementioned limitations of BIM to provide a secured platform for sharing construction data. Blockchain is a technology that can make data traceable and immutable (Hughes et al., 2019; Wickboldt & Kliewer, 2019). If we can make the data stored and shared in a BIM-based data sharing platform traceable and immutable, the CSC stakeholders can determine the data ownership and clarify who is responsible for any data inaccuracies. Consequently, the enhanced security and trust enforced through Blockchain can facilitate and promote BIM data sharing across all the CSC stakeholders in construction projects.

The purpose of this paper is to examine the potential of blockchain to address the limitations of BIM as a trusted tool for sharing data across the CSC. This research analyzes the blockchain use cases in construction and other industries, thus examining the potential of blockchain to address the BIM data ownership and liability issues. Furthermore, based on the findings, this paper proposes a novel framework for a blockchain-enabled BIM data sharing application to improve the quality assurance process in the CSC.

BLOCKCHAIN AND POTENTIAL OF BLOCKCHAIN-ENABLED BIM DATA SHARING

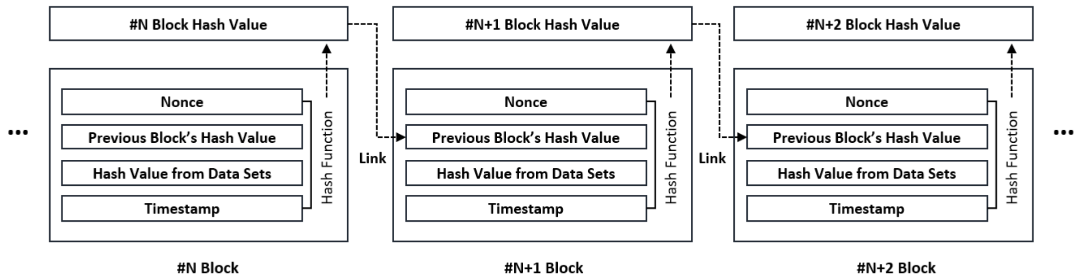

Figure1: Blockchain Components

Blockchain is a technology that can provide a digital ledger consisting of linked blocks containing data sets. The data in each block are encrypted by a hash function and changed into a unique hash value. This hash value creates a chain between blocks because each block contains the previous block's hash value (Figure 1). When a new block is added to this chain, the block must satisfy the criteria of the consensus protocol (e.g., Proof-of-Work). After data are stored in the chain through the process as mentioned above, the data are replicated and distributed to all the nodes in the blockchain, thus creating a decentralized ledger. These capabilities make the falsification of data in blockchain technically impossible. For example, for the falsification to be validated as an official modification, the entire data across the blockchain should be modified corresponding to the falsification because of the chains created by hash values. Furthermore, the process of creating the new blocks within the falsified data should be verified with the consensus protocol, which requires sufficient time and computing power. This process makes the falsified blockchain shorter than the original one, which continuously adds a new block. Accordingly, the falsified chain is discarded because the longest blockchain is determined as a valid blockchain. In summary, blockchain enables the users to have a decentralized ledger in which the stored data are immutable and traceable. This advantage has the potential to address the limitation of BIM in providing a secured and trusted platform sharing construction data.

The exploration of blockchain as a tool to enable immutable and traceable BIM data exchange among project participants is ongoing. Different scholars have identified and listed potential application scenarios. Turk & Klinc (2017) investigated the potential of blockchain to provide a trustworthy infrastructure for BIM data management during all building life-cycle stages. Mathews et al. (2017) revealed that the combination of BIM and blockchain can enhance trust among the construction stakeholders because blockchain can immutably and traceably record the BIM data-based transactions in the CSC. Erri Pradeep et al. (2019) also found that blockchain can enhance the trust among the construction stakeholders using BIM by enabling change tracking and establishing clear liabilities, which facilitates collaboration and information sharing. In addition to the trust enhancement, Nawari and Ravindran (2019) investigated how blockchain applications could be advantageous in the BIM workflow by emphasizing network security, providing more reliable data storage and management of permissions, and ensuring change tracing and data ownership.

Even though the above studies provided theoretical evidence that blockchain can facilitate BIM data sharing by making the data immutable and traceable and thus enhance trust among the construction stakeholders, the practical framework of the blockchain-enabled BIM data sharing across the CSC is in its early stages. Filling this research gap, Dounas et al. (2021) developed a framework of decentralized architectural design using BIM agents connected over blockchain. In addition, they developed a software based on the framework that enables recording all design attempts with BIM, including ones that have failed, and all positive steps towards design optimization. However, this framework is limited to the BIM data sharing in the design phase, not considering the BIM data transactions across the CSC.

RESEARCH METHODS

To develop a practical framework for the blockchain-enabled BIM data sharing across the CSC, we analyze the blockchain use cases in various industries, including healthcare, food, finance, and construction. The use case analysis reveals the practical advantages of blockchain in diverse types of supply chains and the limitation of blockchain applications in the construction industry. The identified advantages demonstrate the potential of blockchain to address the BIM data ownership and liability issues. Based on the findings from the analysis, we design a novel framework of a blockchain-enabled BIM data sharing application to practically improve the quality assurance process in the CSC.

BLOCKCHAIN USE CASES IN DIVERSE INDUSTRIES

HEALTHCARE INDUSTRY

There are a number of healthcare industry companies investing in blockchain technology (Castillo, 2019). One specific example of blockchain being used in the healthcare industry is its use in combating prescription drug fraud. A considerable portion of drug abuse in the United States of America is prescription drug abuse (Peterson, 2000). Common approaches utilized to acquire prescription drugs illicitly are doctor shopping (visiting multiple providers to unlawfully obtain prescriptions), altering prescriptions, forging prescriptions, and photocopying prescriptions (Blumenschein, 1997; Peterson, 2000).

The software company, Nuco, recognized a solution to combating prescription drug fraud using blockchain technology (Engelhardt, 2017). In their framework, the prescriber first creates the prescription on the blockchain platform. The information for the prescription (i.e., drug name, quantity, anonymized patient identity, time and date, etc.) is linked to a unique identifier in the form of machine-readable code (Engelhardt, 2017). Next, the pharmacist uses the unique identifier to fulfill the prescription on the blockchain platform. The blockchain platform documents the fulfillment effort, analyzes the blockchain for warning signals (i.e., whether the prescription has been filled previously or if the patient has multiple prescriptions from separate providers), and notifies the pharmacist if that prescription is qualified to be filled (Engelhardt, 2017). This system could drastically reduce prescription drug fraud as the blockchain would eliminate the ability to photocopy prescriptions, immediately identify any alterations, crosscheck for doctor shopping, and the patient would have to have access to prescriber's blockchain account in order to forge prescriptions. Through blockchain technology's encryption, patient privacy would be maintained while stakeholders could trust the information due to blockchain's immutability.

Another specific example of blockchain being used in the healthcare industry is in medical records. Currently, a patient's medical records are commonly disintegrated across various healthcare providers (Virginio Jr & Ricarte, 2015). Research has shown that improvements in the accuracy, availability, accessibility, and legibility of medical records improves healthcare quality and outcomes (Hong et al., 2015). One type medical record is the hospital discharge summary. Hospital discharge summaries communicate, "a patient's care plan to the post-hospital care team," and are believed essential in benefiting patient health and wellbeing when transitioning care settings (Kind & Smith, 2008). The company Medicalchain deployed a digital solution to improve the accuracy of hospital discharge summaries and worked on implementing that system on a blockchain technology platform (Engelhardt, 2017). Their current platform focuses on using blockchain technology to provide a secure, single source for patients' medical records that allows practitioners to update patient medical records in real time in a transparent, auditable, and secure way (Medicalchain, 2018).

FOOD SUPPLY INDUSTRY

As mentioned, blockchain enables supply chain stakeholders to safely store data into tamper-proof environment and share the data only with the people who are permitted to obtain the data through the peer-to-peer transaction. Food industry applies those benefits to their supply chain. As the food trade becomes globalized, verifying the safety and quality of food in the supply chain has become challenging (Aung & Chang, 2014). To solve this problem, IBM has developed an information-sharing system by using the benefits from Blockchain technology, which is called IBM *Food Trust*. This system allows authorized users to verify the freshness of food and trace records of food provenance, transaction data, and processing details.

For example, the system provides users with information about product quantity and quality at every point of the supply chain (e.g., farms, packing houses, manufacturing of goods, warehouses, distribution centers, and stores). The users can check the location of supply chain facilities with map view as well as current at-risk inventory at each facility. This helps the users examine inefficiencies in the supply chain and assess the freshness of the products in real time. In addition, the authorized users can trace every product throughout the supply chain within this system. They can verify the provenance of the products and be aware of their real-time location and condition, which helps the users identify contaminated food and respond immediately. These benefits increase customer trust in products. In addition to tracking freshness and traceability, the system facilitates holistic management of critical documents, such as authorizations, licenses, and inspection results, in a secure data storage. Traditionally, the documents have been scattered along the fragmented supply chain and are difficult to manage because of their quantity, complexity, and variety. However, the novel system allows users to gather them into the distributed database by Blockchain, which simplifies the tracing of information such as issuers and issue dates in a tamper-proof environment. A more detailed explanation of the system can be found at IBM (2019).

FINANCIAL SERVICES AND BUSINESS INDUSTRY

After the emergence of Bitcoin in 2009, the blockchain applications for financial services have been extended in a prominent way. Among the Finance use cases addressed by the book Blockchain: A Practical Guide to Developing Business, Law, and Technology Solutions (Bambara et al., 2018), two categories can be identified: customer-related and Smart Property approaches.

Within the first group, the Know Your Customer (KYC) scenario provides an automated customer identification and transaction history validation before enrolling him/her with a financial institution. To perform this, "the customer's personal information is encrypted and added as a block in the blockchain" (Bambara et al., 2018). After that, the financial institution refers the customer to its block, so that the customer allows access to his/her KYC data. Later on, the financial institution validates the provided information and decides to approve or not the customer's admission. The customer's block remains intact and in the blockchain, available for other financial institutions by the time a potential customer provides them with access. This approach was tested in the ASEAN (Association of Southeast Asian Nations) region on spring 2017 by a consortium between a Singapore government body and various banks that include HSBC and Mitsubishi UFJ Financial Group, Inc. (Sharma, 2019). Meanwhile, different financial institutions such as Santander, PNC, and SABB applied blockchain to improve the global payment process through the Ripple protocol. This pact allows the use of blockchain technology for cross-border payments, currency exchanges and the access to a broad exchange network. Ripple relies on a distributed ledger technology, or a database shared and updated within multiple entities (regardless of their geographic information) and whose transactions besides being public, require the use of a native currency called ripples. It enables cross-border payments between multiple participants of the network and direct customers. A common transfer requires the Global Payment hand over from the first Financial Institution to the Ripple's digital asset XPR, where a bilateral clearing or risk arrangement between the exchange parties takes place under the light of fee across (FX) traders, followed by the fund's relocation at the Targeted Institution in the required currency. This approach shortens the payment cycle, enhances currency conversions, offers global affordable money transfers and allows the incorporation of alternative payment options for customers (Bambara et al., 2018).

For the Smart Property approach, the most outstanding use cases include the creation of Smart Property (to trace and control physical assets) and Transferring the Ownership of Smart Property (as a new method for procuring Smart Property and transferring the information attached with it). Different Real Estate companies are currently applying blockchain to enhance the search, procurement and sale of properties (Harbor, Managego, Property Club).

CONSTRUCTION INDUSTRY

The construction industry has investigated the potential of blockchain applications to various sectors across the construction value chain, such as property management, information sharing management, supply chain management, construction management, and payment management (Dakhli et al., 2019; Perera et al., 2020).

The use cases show two prominent trends. First, blockchain is applied for data immutability and traceability in the CSC. For example, blockchain can help trace the supply chain of precast construction projects, improving the prompt delivery of precast components and enabling stakeholders to track the reasons for disputes in the supply chain (Wang et al., 2020). Second, blockchain is used to embody smart contracts that can expedite construction payment across the CSC by automatically processing the payment. For example, the digital data of construction performance can be collected by BIM or other data capture systems and used to process the interim payment based on the predefined algorithm written in a blockchain-enabled smart contract (Hamledari & Fischer, 2021). Despite the valuable trends, integrating BIM with blockchain to facilitate data sharing and developing a framework of blockchain-enabled BIM data sharing to improve the CSC is still in its exploration stages.

DISCUSSION

The above analysis of the blockchain use cases reveals that blockchain can generate cryptographically secured, tamper-proof and traceable data sharing platforms across the supply chain, thus creating a trustworthy environment for information sharing. It shows the potential of the blockchain-based platforms to address the BIM data ownership and liability issues. Despite this potential, integrating BIM with blockchain to facilitate data sharing and developing a framework of blockchain-enabled BIM data sharing to improve the CSC are still in their exploration stages. Addressing this research gap, this study proposes a novel framework for a blockchain-enabled BIM data sharing application to practically improve the quality assurance process in the CSC, which will not only reduce the time and cost of the quality assurance process but also increase the accuracy of the assurance through the integration of BIM and Blockchain.

FRAMEWORK FOR BLOCKCHAIN-ENABLED BIM DATA SHARING IN CONSTRUCTION SUPPLY CHAIN

The proposed framework (Figure 2) improves the quality assurance process of the CSC by leveraging blockchain-enabled BIM data sharing. In the current process, a general contractor manually compares the information in the quality documents provided by subcontractors or suppliers with the predefined quality standard in the specification from architects. However, in the proposed framework, the detailed information of products or construction work and the quality standard will be stored into a BIM model and can be compared digitally and automatically. This will not only reduce the time and cost of the quality assurance process but also increase the accuracy of the assurance, thus preventing mistakes or defects in construction phase. Blockchain platform in the framework is a key element to enable this digital and automatic quality assurance system using BIM data. Because it can provide a cryptographically secured, tamper-proof and traceable data sharing platform, the stakeholders including architects, general contractor, subcontractors, and suppliers can input their data into the BIM model without any concerns about the BIM data ownership or liability issues. Consequently, instead of the document-based manual quality assurance process, the system enables the digital and automatic quality assurance process using a BIM model. This will not only reduce the time and cost of the quality assurance process but also increase the accuracy of the assurance by using the BIM data, which can store very sophisticated and detailed construction information into a 3D model.

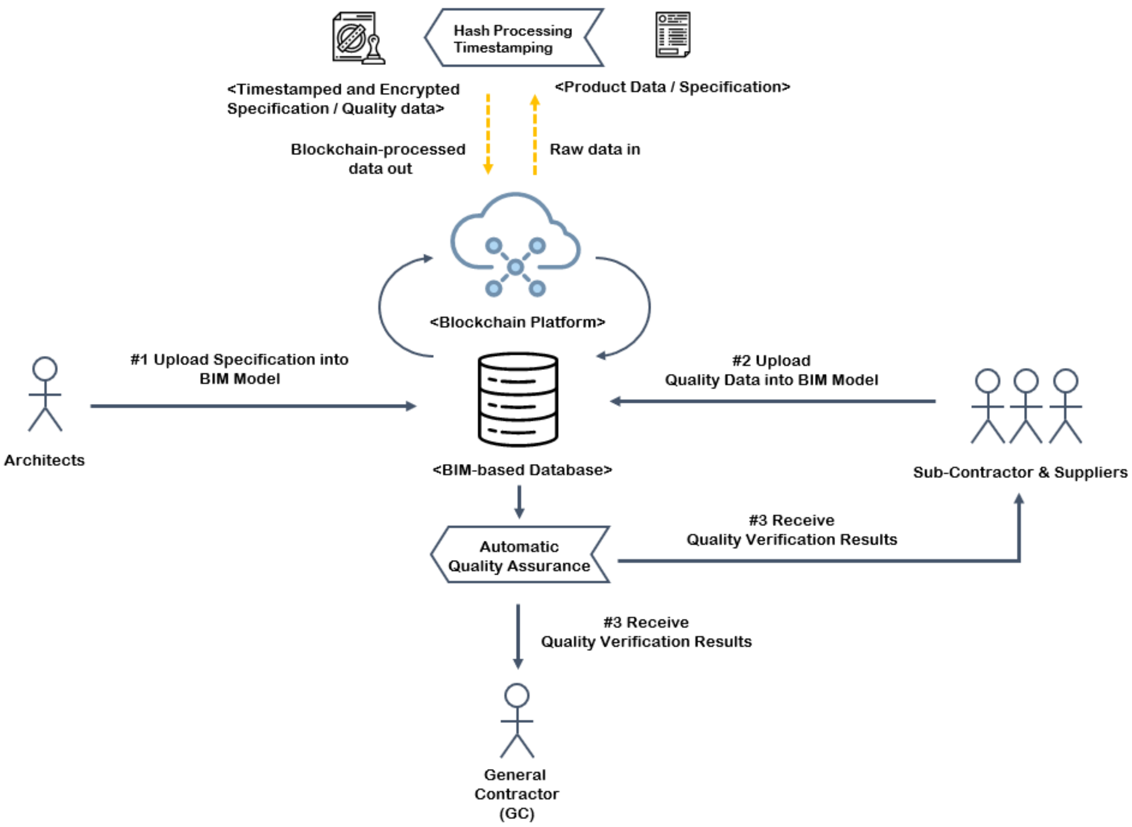

Figure 2: Automatic Quality Assurance using Blockchain-enabled BIM data Sharing

LIMITATION AND FUTURE STUDIES

This study involves development of a conceptual framework for blockchain-enabled BIM data sharing to improve the quality assurance process in the CSC. Accordingly, future studies will focus on developing a pilot system based on the framework and validating its effectiveness by conducting a few pilot tests in the real-world construction projects. Moreover, future studies are needed to investigate the potential of the proposed framework in expediting and facilitating cash flow across the CSC. The existing studies on blockchain applications in cash flow of construction projects (Ahmadisheykhsarmast

& Sonmez, 2020; Das et al., 2020; Elghaish et al., 2020; Hamledari & Fischer, 2021) can be integrated with the proposed framework to create new insight into the cash flow management of the CSC.

CONCLUSIONS

This paper has examined the potential of Blockchain to facilitate sharing of BIM data across the CSC by analyzing blockchain use cases in construction and other industries. The analysis shows that Blockchain can generate cryptographically secured, tamper-proof and traceable data sharing platforms across the supply chain, thus creating a trustworthy environment for information sharing. These advantages can effectively address the critical limitations of BIM data sharing, which are the BIM data ownership and liability issues in the CSC. Based on the findings, this paper also proposed a novel framework for Blockchain-enabled BIM data sharing to improve the quality assurance process in the CSC. The framework enables the CSC stakeholders to leverage their BIM-based data for quality assurance process because the framework employs blockchain to enable BIM data sharing by removing the BIM data ownership and liability issues. Subsequently, the BIM-based digital data in the framework allows the stakeholders to leverage the automatic quality assurance system, which can reduce the time and cost of the quality assurance process and also increase the accuracy of the assurance. As a result, this study contributes to the body of knowledge by 1) enabling the construction industry to understand the potential of Blockchain through construction and other industries' blockchain use cases and 2) providing a practical framework for blockchain-enabled BIM data sharing to improve the quality assurance process in the CSC.

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SENSEMAKING OF GUIDING PRINCIPLES IN CONSTRUCTION PROJECTS

John Skaar[1]

ABSTRACT

Processes and operations can be supported, improved, or scrutinized as an active response to guiding principles that challenge the status quo. When it comes to the subject of complexity vs simplicity the principles can contradict each other, and even flow tends to work towards simplicity while value generation adds complexity. By addressing the importance of awareness of their counter effects they can be used with care and gain even larger value as a result. Done in ignorance their use might create chaos, project loss, or production failure. The sensemaking tool, Cynefin, is used together with some core principles of lean to illustrate and explain the intent of the paper. A fundamental difference in viewpoint of a project's nature is addressed since the right sensemaking of appropriate domain in Cynefin is important for the right use of lean principles. A discussion on a fundamentally different understanding of the phenomenon of projects adds to the ontological training urged by other IGLC members. This paper argues that projects are fundamentally unpredictable and hence should be more often sensed in the complex domain, rather than in the complicated or simple domain.

KEYWORDS

Simplicity, complexity, transformation-flow-value, continuous improvement, Cynefin.

INTRODUCTION

Lean construction can relate to multiple lean principles that give meaning in accordance with the lean "way of thinking" (Hines et al., 2004). Some lean construction principles can be recognized in the keyword list for the 2022 IGLC conference. "Continuous improvement/kaizen", "standardization", "production pull" "pull planning", "takt planning", "collaboration", "trust", "flow", "waste", "relational", "reliable promising", "value stream", "visual management", and "concurrent" are all examples of spelled or close to being spelled principles (Skaar et al., 2020) that partially work as explanations for the "concept" (Koskela & Kagioglou., 2005) of lean construction. Lean is an ambiguous concept and since it has mainly been coined after inductive reasoning from observations it cannot be concluded as a certainty, especially since it is reshaped within different industries and contexts. In this paper, we will see processview (Koskela & Kagioglou., 2005) as a metaphysical ingredient in lean thinking, also supported and represented by a selection of lean principles. We use the Cynefin framework (Snowden, 2007) to discuss the phenomenon of a construction project regarding both design and production. The nature of a project and whether we should sense it as complex or

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complicated are most debated for production. The reasoning behind this is that the use and intention behind lean principles or lean thinking will vary depending on where a project is by nature. As an example, if we use “takt” as a principle and sense a project as complicated, hence in an ordered system, we can use sufficient planning resources and plan it in detail and predict the progress of the project. If the project is complex on the other hand we should build in enabling constraints and enable the resources for emergent practice to deal with deviations and unforeseen events to maintain or gain “takt”.

THEORY

THE CYNEFIN FRAMEWORK

The Cynefin framework (Snowden, 2002, Kurtz and Snowden 2003, Snowden and Boone 2007, Snowden 2010) is a sensemaking framework with five domains, see figure 1. The Cynefin framework is divided into an ordered system, with domains of simple and complicated and unordered system with the domains complex and chaotic, in addition, disorder is the fifth domain for the state when you have not made sense of where you are.

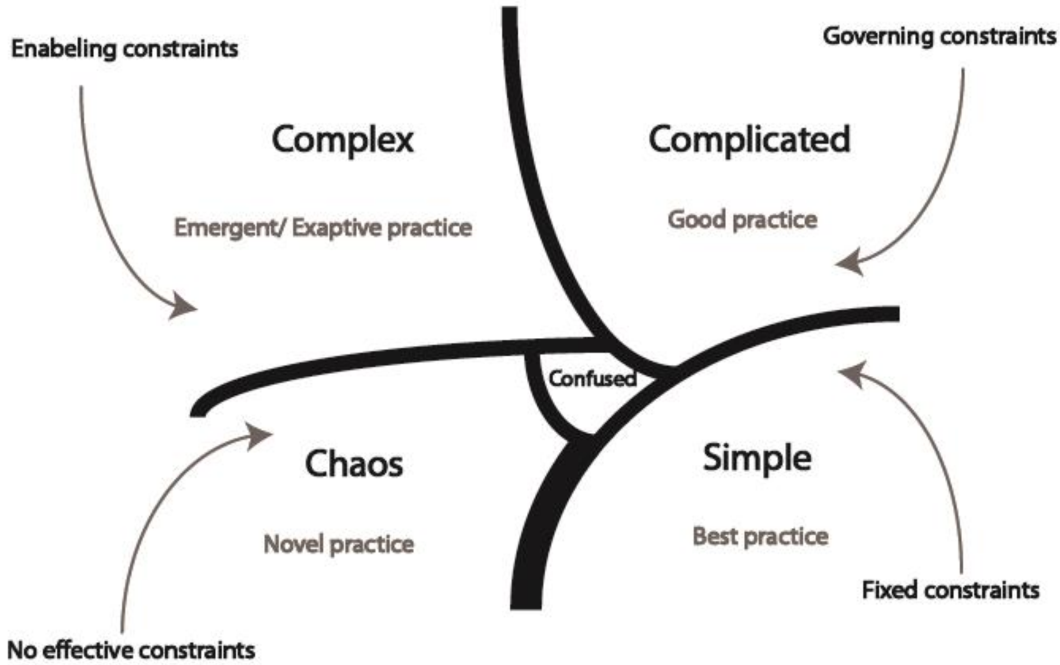

Figure 1; Cynefin framework with 5 domains and suggested constraints and practice. Based and converted from Turner, Snowden & Thurlow (2022) with copyrights to Cognitive Edge

Snowden makes a point of the Cynefin framework not being a categorization framework, but a sense-making framework. The point is to try to figure out or make sense of the world to act in accordance with the domain you are in. The need for sense-making is continuous since the context or problem you are dealing with may change because of changing situations and circumstances and hence move into a different domain.

The Cynefin framework has been mentioned in earlier papers within the IGLC network (Koskela et al., 2005, Xu & Tsao, 2012, Biton & Howell, 2013).

LEAN THINKING AND GUIDING PRINCIPLES

Lean thinking can be seen as a way of reasoning with lean principles, but what are those principles and how should they be applied? The principles representing lean thinking are not limited (Koskela, 2004) to the five principles by Womack & Jones (1990) that first coined the term “Lean thinking”. As an example, the original five principles do not make any reference to people (Bicheno & Holweg, 2016), which is part of Toyota's official principles in their lean house (Liker, 2003). If we define lean thinking as a process viewed (Koskela & Kagioglou, 2005) mindset and a challenger of the domination of thing- or substance view the principles should be a guide for this change. The TFV theory of production (Koskela, 2000) acknowledges transformations, value generation, and flow as valuable for production, but lean principles often represent a counterweight to the domination of thing view and hence become a guide towards more use of flow and value generation. Lean thinking will in this paper be defined as using all principles that can enable a more process viewed look at the world, a process viewpoint will be preferred or at least challenge a more thing viewed interpretation. Table 1, shows some sources of inspiration for principles that can guide towards a process viewpoint.

Table 1: Some references to principles that can support a process viewpoint.

Reference	Principles
Liker, 2003	14 Management Principles and Toyota’s official lean house principles
Deming, 2018	Demings 14 points (principles) for management
Ballard Tommelein, 2021	Principles for LPS
Fowler& Highsmith, 2001	12 principles of Agile software
Womack and Jones (1990)	5 principles of “lean thinking”

Principles enabling a process viewpoint can be applied to the way we think but indirectly also act on the world, so by using the principles in our narrative and active management as constraints they can guide change towards reduction of waste and increased value creation.

METHOD

This paper is based on a literature review on Complexity and Cynefin in the IGLC conference papers and also the status of development of the Cynefin framework in published literature. It is mainly based on a conceptualization (Jaakkola, 2020) of the meeting point between Cynefin and process view principles and the phenomenon of design and production in construction. The theoretical approach to the phenomenon of construction is mainly inspired by the work of Sven Bertelsen and Lauri Koskela with different co-authors in the IGLC community. The discussion is about placing this phenomenon into the Cynefin framework and linking it to the use of guiding principles. The work is a part of a Ph.D. thesis that uses guiding principles as an important part of an organizational framework for process viewed and changing environments, now testing the theory as a pilot among different Norwegian executive teams.

DISCUSSION

THE DOMAIN OF DISORDER

The domain of disorder in the Cynefin framework is the domain or state of not knowing what type of system you are in (Snowden, 2007). Based on the literature we can spot that there are fundamental differences in sensing what kind of system construction projects are. The different opinions can be recognized in the difference between Flyberg and Hirshman (Kreiner, 2020), these differences are also earlier acknowledged in IGLC about cost management (Koskela & Ballard, 2021). In short, Flyberg sees an emerging problem or issue in construction as a lack of planning, while Hirshman claimed that projects have an inherent and genuine uncertainty that the actions and outcomes cannot be known in advance, only forecasted (Kreiner, 2020). Design as a phenomenon is easier to acknowledge as a mainly complex endeavour since it among others contains reciprocal interdependencies (Kalsaas, 2020; Thompson, 2003), has more than one solution (Reinertsen, 1997), and is maturing as it develops from the start to finish (Nesensohn et al., 2014) and might be considered to be a “wicked problem” (Rittel & Webber, 1974; Buchanan, 1992). A more debatable question is whether production in construction “after design” is complex or complicated (Annweiler, 2019; Kreiner, 2020), we will add to that discussion later in this paper. Principles like “Focus control on the complete process” (Alarcón, 1997) and “doing the right things and gaining the Big Picture” (Bicheno & Holweg, 2016) is about understanding and reasoning about the situation and can be used to initiate action (Skaar et al., 2020) in favor of gaining an overview from the domain of disorder.

THE SIMPLE DOMAIN

In the simple or obvious domain, cause-effect relationships exist and are evident and predictable, hence rigid constraints can be applied (Snowden & Boone, 2007). If construction projects are in the simple domain you only need to sense then categorize and then respond. The phenomenon of design does not fit in the simple domain just argued by the fact that design has multiple solutions. And for production, there are variables that no project can truly ignore, human interactions, weather, geographical conditions, surroundings, etc. People’s tendency to be biased towards simplification (Bazerman, 2001; Bertelsen, 2003) also gives warnings against placing projects in the simple domain.

We argue that a construction project should therefore never be treated as a simple endeavour. What does the claim mean in practice?

1. You cannot make a recipe/ plan for one project and use it again for the next project, it needs at least experts to sense and analyse the context, and then make a new plan (respond). The claim is made also for projects where design is done and only production is left.
2. Best practices do not exist for coordinating design or production, not even the smallest task should be treated as simple if you want to avoid emergent deviations. There is always room for improvement from a process viewpoint, so best practice should in lean thinking not be used.

3. The principle “Simplify” can be used to simplify by minimizing the number of steps, parts, and linkages (Alarcon, 2014), to make it less complex or complicated and/or reduce waste, but no activity should be fundamentally treated as simple.
4. If participants sense that a project is in the simple domain, they should move to disorder and sense again to avoid a collapse into the chaos domain. Especially if rigid constraints are used. Treating something as simple will de facto not give room for improvement, but to be efficient everything cannot be improved all the time. So for pure transformation activities that seem stable, they can be looked into fixed constraints and just transformed, but the main point is that they should not be sensed as simple only treated as simple. A cost/benefit evaluation on necessary available resources to cope with deviations should be made.

If a project is sensed to be in the simple domain principles like “lower the water to expose and remove the rocks” (Schonberger, 2014) or ”Find problems where you think none exist” (Davey, 2017) can move you over to a more complicated domain and hence create more value since experts are available in a typical construction project. Both mentioned principles are metaphors for the attitude of making things tougher or more ambitious to see the obstacles that hinder the improvement. “Lowering the water” can be translated into more actionable ambitions like “Reduce construction time on projects to half the normal time” and “The rocks exposed” is a metaphor for the constraints that must be dealt with or removed to fulfil the ambitions.

THE COMPLICATED DOMAIN

To be in the complicated domain you should be able to sense, analyse and respond. Cause-effect relationships exist in the complicated domain, and there is a right answer though not self-evident. Experts should be able to put the system in the correct order and postpone the events. Governing constraints together with good practice can be applied to control the system. Whether construction projects normally are here or in the complex domain can be debated as earlier mentioned. Even within IGLC publications differences in this viewpoint can be spotted, where one view claims the world to be mathematically identifiable, hence predictable and deduced (Kenley, 2005) and the other view is that claiming a project is more complex and unpredictable (Bertelsen & Koskela, 2002, Bertelsen, 2003). Kenley (2005) agrees that projects are complex, but at the same time argues that on-site processes only appear complex. Aligned with the Cynefin framework things that are predictable are by definition not in the complex category, so even if Kenley recognizes the complexity of human interaction is it right to interpret his claim that they do not influence the effectuation of on-site activities?

Critical Path Method (CPM) combined with the more visual Location-Based Management Systems (LBMS) can be preferred if projects should be fundamentally perceived as complicated, as stated by Kenley (2005). If construction projects by nature are ordered and predictable sufficient planning resources should be applied to the projects since the consequences of not making a detailed enough plan are costly. The underlying assumption if a project should be perceived as a complicated project is that experts can postpone everything. From the experience of the use of Percent Plan Complete (PPC) in construction projects, this often seems not to be the case. Ballard reported a PPC of around 50% in his thesis (Ballard, 2000) on the projects that did not use the Last Planner System. We claim that emerging matters are a reflection of the complexity of the phenomenon of construction projects not just a lack of planning.

If we sense a construction project to be fundamentally complex (Bertelsen, 2003), and more emerging the use of CPM will have fewer arguments. Then the production control principle (Ballard et al., 2009), "Plan in greater detail as closer you get to the work" will be resource efficient, a principle the Last Planner System uses in the plan hierarchy from milestone plan to a detailed production plan. But even though construction projects are fundamentally complex trying to move them into the domain of complicated can reduce waste. Many of the activities of a project in production can "go as planned". Flow, takt, production pull, continuous improvement, etc. are easier to cope with and can be applied even though the project is sensed to be complex. The Cynefin framework makes a differentiation between governing constraints for the complicated domain and enabling constraints for the complex domain.

Governing constraints are boundaries and can as an example be defined rules, standards, or procedures. If takt is applied as a governing constraint, takt becomes a "rule". This might work even if projects are sensed as fundamentally complex, but must be used with caution to avoid conflicts and emerging events. If takt is applied as an enabling constraint it will be implemented as a principle and a challenger of the status quo. Takt, flow, and standardisation are principles that work toward simplification. Principles that make it more complex to manage, like involvement, can be combined with simplifying principles to cope with emergent matters. The use of backlogs with prepared activities is a practical example of measures that can be used actively to cope with the inevitable emergence in today's business. From a process viewpoint, even a planned plan can be challenged and improved further. A plan that is not challenged to be improved mainly goes as planned or goes worse, the opportunities are ignored with a thing view.

THE COMPLEX DOMAIN

In the complex domain, the environment is in constant flux and unpredictable. Cause-effect relationships are not clear but could be observable in retrospect.

Introducing a process view into construction (Bertelsen, 2003), makes a clearer argument that reality is fundamentally complex especially applicable to the social world. An underlying complex world underpins the need for awareness of complications if simplification is done. This does not mean that a plan should not be made, it means that a plan should never be mistaken to be the truth, put in other metaphorical words the plan must be adjusted to the "terrain", not the "terrain" to be adjusted to the plan. There is a fine distinction here, but a typical attitude after an unforeseen event is that the cause was a lack of sufficient planning. If a project is fundamentally complex all events that may emerge in a project cannot be planned for. So instead of trying to make a comprehensive list of all events, a shift towards more flexible methods to cope with emergent events is a better attitude and can be more efficient.

Many human biases that ignore the complexity of the world have been noted (Bazerman, 2001; Kahneman, 2011; Kahneman et al., 2021), two of the most relevant for this discussion might be:

1. Attribute substitution: Humans tend to substitute an answer to a complex question with an answer to a more simple question.
2. Hindsight bias: After an event has occurred humans tend to see the event as predictable, despite having little or no objective basis for predicting it.

So why can projects be in the complex domain? The part of production that consists of transformation can be argued to be in the complicated and even simple domain for small clear projects. From a thing viewpoint seeing transformation, it should be sensed only as complicated since it before assembly consists of defined building blocks, with sequential dependencies and solutions that experts should be able to identify. In production, the value creation can be limited and hence be less complicated to cope with.

Since the nature of construction is about unique products in temporary organizations (Ballard & Howell, 1998; Bølviken, 2012). The uniqueness of the product can be argued to be less complex since many of the processes and activities are the same from one project to the next, but variables like weather, geography, geology, and existing infrastructure increase the possibility of emergence and are unpredictable events (Bertelsen, 2002).

A key reason for added complexity in a construction project lies in the complexity gained because of people's interaction. Leading people is a complex matter. Construction projects consist of different organizations and people often without any track record or possibility to analyse and predict the new constellations' behavioural patterns.

Because of the underlying complexity emerging and unplanned events are inevitable and should not come as a surprise. The leader’s narrative should adapt to this and actors doing their best should not be blamed as a consequence. Projects not hitting their targets are as a consequence, not a “thing” that you necessarily can identify on the project level and eliminate upfront. “Bad construction projects” is not a thing it's a set of processes done in a complex world, that can be improved.

The complex domain calls for enabling constraints. Guiding principles (Skaar, 2019; Skaar et al., 2020) on both strategic, tactical, and operational levels (Clausewitz, 2003; Covey, 1992) or organizational, managerial, interpersonal, and personal levels (Clausewitz, 2003; Covey, 1992) are enabling at all those levels and can be used as constraints in an organizational framework. “Plan in greater detail as the closer you get to the work” (Ballard et al., 2009) is such an adaptation of guiding principles or principles recognizing a complex world.

THE CHAOS DOMAIN

In the chaos domain, no cause and effect relationships are perceivable, the preferred behaviour is to act, then sense ,and then respond. Meaning no reasoning towards the context is recommended, so if the fire alarm wakes you up in the middle of the night you might sense chaos and could then follow the predetermined procedure that enables acting, but if that procedure is sensed not to be appropriate, new responses are required. If a situation like this becomes unstable you are entering the domain of chaos, and stability is the goal if you want to get out of the domain.

A lead product designer in Norway has been interviewed by the author of this paper. He claims he liked to stay in the chaos domain as much as possible because he was much more creative there. He liked though requirements and objectives, they often triggered the need to be even more creative. He used time in the beginning with the customer but did not involve the customer at all in the creative process. His statement contradicts the lean notion that you should involve and get feedback from the customer to test your product. A reflection made based on this was that letting in the customer in an already complex to chaotic process could make the process too chaotic to handle. The designer believed that the value the customer got was greater if the team could work undisturbed, he is thereby making a controlled environment where he allows chaos or highly creative processes to enter.

A high level of creativity is often welcomed at the beginning of the design of a construction project and in the early evaluation of production methods, but in a relatively short period into the project, it becomes a treat to uncontrolled chaos and creativity is limited. The actual production phase of a construction project focuses more on the reduction of internal waste through flow and transformation than perceived value creation (Hines et al., 2004). Ongoing production should avoid the chaos domain.

CONCLUSIVE DISCUSSIONS AND FINDINGS

THE CONFLICTING USE OF PRINCIPLES

Under the chapter "Lean thinking and guiding principles" we defined lean construction principles to be principles that can enable a process viewpoint. This is also a crucial point when actively using the principles, a principle like standardization can in a thing view perspective be interpreted as trying to make processes static, rule-based, and restrictive while in a process viewpoint a standard can be interpreted as a systematic and temporarily steppingstone for process improvement with a dynamic nature (Spear & Bowen, 1999).

Is there a logic in using the principles to work towards simplification of some areas and towards complexity in other areas in the same project? Or does this reflect a different viewpoint of the users of the principles? Since many tools, methods, systems, and practitioners can combine principles with this contradiction, are they doing it wrong? It might not be intuitively logical to combine principles like standardizing and "creating flow" together with principles like involving, continuously improving, and welcoming change. The first set of principles limits variation, stabilize, and simplifies the process, and the latter set of principles tend to make it less defined, and create more tension and complexity? The use of conflicting qualities has previously been used intentionally, Lexus "Yet" philosophy is an example of this. Where seemingly contradicting or conflicting qualities are put together, like "Fast, yet fuel-efficient" and creates a more constrained environment, in a way it can be compared with increasing the distance between the intended and achieved purpose (Koskela et al, 2019).

If we acknowledge the world as a complex world an attempt to stabilize a process can at least gain three different positive effects;

1. Stabilization simplifies the process so that emergent situations and variability within the process can be recognized more clearly.
2. Stabilization of one process can shift resources to other processes with more potential for value creation.
3. Stabilization can in itself create end value through reduction of cost (reduced resources, storage, etc), higher efficiency (accurate and fast delivery time), and quality (fewer errors, higher safety, etc).

On the downside, stabilizations limit the dynamic and flexibility that can gain value creation of more novel and enhancing character. So stabilization and simplification should be challenged to deliver more customer perceived value creation. Having high ambitions, "pushing the envelope" (Miles, 1997), and "never accepting the status quo" (Davey, 2017) are principles that seek higher value creation.

Principles that are used for more value generation might as a consequence move the process towards more complexity, while principles that are used to move the processes towards simplification, are mainly done for waste reduction or preparation for transformation, see figure 2.

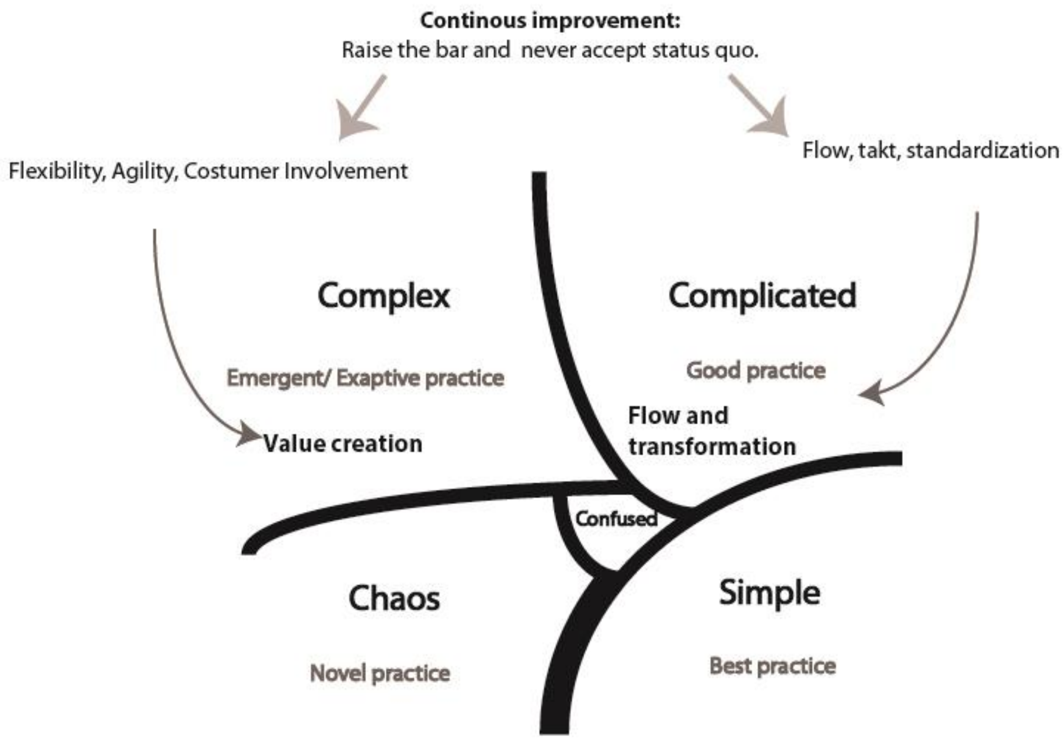

Figure 2; Modified Cynefin framework with guiding principles for flow and value creation, based and converted from Turner, Snowden & Thurlow (2022) with copyrights to Cognitive Edge

The opportunities that lie in value generation from the complex domain, are an argument for staying in the complex domain, even if the stabilization of a project makes it feasible to draw it towards the complicated domain. An example of value creation in production can be constantly trying to increase production as a team beyond the current schedule.

FUTURE RESEARCH

Further research can be done on what domain project management sense their projects and see if differences in this viewpoint affect project conflicts, manager's narrative, the team spirit, and motivation for team members.

Research can also be conducted on how a combination of guiding principles can be used together with more governing constraints in a project where all project members sense the project to be in the complex domain. How can knowledge on the subject of differences in project sensing influence a project team's attitude towards emerging opportunities and negative risks?

Further research and conceptualization on the differences in a deterministic view on task durations vs a stochastic view and how this can be related to thing- vs processview and sensing of domains in the Cynefin framework will also be possible progress.

CONCLUSIONS

This paper claims that we live in a complex world and that this should also be the ontological attitude we take towards construction projects. An understanding of the different domain's capabilities might enable projects to seek the discomfort of value generation in more complex contexts and even within contained chaos, but at the same time seek possibilities for waste reduction by constraining parts of the project towards simplification to stabilize the project. Since principles in their nature are enabling they should be used like principles down to the operational level. Principles like flow, takt, and standardization can be used to enable action to reduce waste and prepare for transformation. To manage these principles they are often presented by the management as governing constraints, if done so the project leaders should be very aware that it is done as an effort to constrain an underlying complexity. Awareness of complexity might change the narrative of how governing constraints are presented to the project team and might enable the use of principles like involvement even though the sensed complexity initially increases. We call for higher use of flexible and relational principles that support complexity in combination with the use of principles that enable simplicity. Project teams with a high understanding of the underlying complexity might also be better to take advantage of opportunities that emerge in addition to a more agile response to emerging risks.

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INVESTIGATION OF THE CONSTRUCTION SUPPLY CHAIN VULNERABILITIES UNDER AN UNFAVORABLE MACRO-ENVIRONMENTAL CONTEXT

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ABSTRACT

International trades rely on robust supply chains. However, supply chains are vulnerable to disruptions. Before implementing lean construction, identifying construction supply chain vulnerabilities (CSCV) is crucial to avoid failure. Meanwhile, an unfavorable macro-environmental context (e.g., challenging economic and political situations) can potentially affect the behavior of CSCV. This paper aims to identify and prioritize CSCV under an unfavorable macro-environmental context in a real-world case and then analyze the changes in CSCV in a period coinciding with the Covid-19 outbreak. A literature review led us to extract 26 variables that were then prioritized using the responses from questionnaires distributed among 72 participants in the studied country. A descriptive statistical approach was used to analyze the results, which showed that unlike the normal contexts mentioned in previous studies, under an unfavorable context, such CSCV as "price and exchange rate fluctuations", "supply-demand volatility", "financial issues", and "political challenges" gained priority. Moreover, analyzing the changes in CSCV indicated that the studied construction supply chain has become more vulnerable in the mentioned period. Considering the identified CSCV, this paper suggests that managers focus more on tools such as the Last Planner System and value stream mapping when implementing lean.

KEYWORDS

Construction Supply Chain Vulnerabilities (CSCV), Lean Construction, Unfavorable macro-environmental context

INTRODUCTION

Instability or volatility of economic, political, environmental, technological, legal, and social factors worldwide can disrupt the performance of local and international supply chains (SCs). For example, war, pandemics outbreaks, imposing sanctions on a specific

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economy, or even climate can make the supply chains around the world vulnerable to disruption. On average, companies' losses on account of different sources of disruptions in supply chains equal 45% of one year's profits for a decade (McKinsey Global Institute, 2020). The construction industry is not an exception in facing supply chain vulnerabilities (SCV). Due to the nature of this industry, it can even be more complicated for it to manage such sources of disruption (Loosemore, 2000), especially if the industry plans to deploy lean principles. As discussed later in this paper, implementing lean construction practices exhibits varying relationships with the performance and vulnerability of construction supply chains. Thus, accounting for SCV before implementing lean construction practices can support making better managerial decisions in supply chains and a smoother transition from tradition to modernity.

The SCV can impact supply chains in interconnected global markets. However, there seem to be distinctions regarding the context of isolated economies where specific rules are applied. For instance, in a country like Iran, which has been under severe international sanctions and disconnected from the global markets for years, monopolies have become prevalent in different echelons of supply chains (Jahantigh et al., 2015). So, some severe macro-environmental factors (i.e., sanctions, economic isolation, corruption, fraud, and prevalence of monopolies) can affect the behavior of construction SCV and their importance in different economies and their associated contexts. However, no study has been conducted to date to consider the vulnerabilities of the construction supply chains under an unfavorable macro-environmental context.

In this study, we take Iran as a benchmark for an unfavorable macro-environmental context to identify and prioritize the construction supply chain vulnerabilities (CSCV). Then, we analyze the changes in CSCV in the past two years, which coincide with the Covid-19 outbreak. The results act as a decision-making tool for supply chain participants and researchers to consider lean practices or resilience concepts in the construction supply chains struggling with difficult macro-environmental situations.

LITERATURE REVIEW

LEAN CONSTRUCTION AND CONSTRUCTION SUPPLY CHAIN

Akintoye et al. (2000) considered construction supply chain management as a strategic management process that manages the information flow and activities among networks of organizations and linkages to deliver construction products and services to the clients. They introduced the upstream and downstream linkages in construction supply chain management. Upstream linkage is interpreted as activities related to the production preparation on site. On the other hand, the downstream linkage consists of activities in the delivery process of construction products. Each construction supply chain comprises different phases, including planning and design, procurement, and construction and delivery (Le et al., 2020). As Loosemore (2000) states, the supply chain in construction is different from that of other industries, as the construction industry has a transient nature and imposes broader risks than other sectors.

Some researchers have considered lean construction as a means for supply chain improvement. For instance, the application of some lean tools and aspects such as partnering and collaboration (Ballard & Howell, 2003; Green & May, 2005), the Last Planner System (Fernandez-Solis et al., 2013), and value stream mapping (Pasqualini & Zawislak, 2005) can improve SCs. Erik Eriksson (2010) showed that lean construction could result in monetary savings due to efficient coordination and utilization of shared resources among SC partners. The maturity process of supply chains consists of six stages, and "lean" is the third stage of this process (Stevens & Johnson, 2016). On the other hand, since lean thinking focuses on eliminating waste through the minimization of resources, the implementation of lean construction principles can strain supply chains (Azevedo et al., 2008), as discussed in the rest of this study.

CONSTRUCTION SUPPLY CHAIN VULNERABILITIES (CSCV)

Pettit et al. (2010) proposed a two-dimensional outlook for assessing supply chain resilience: vulnerabilities and capabilities, the former of which will be considered in the context of Iran in this paper. Christopher & Peck (2004) considered the origins of supply chain vulnerabilities as internal and external factors. Internal factors rise within the organizations and their supply chains, while external factors are out of the control of the supply chain networks. Recently, determining the SCV and analyzing their impacts on the supply chains has motivated the interest of some researchers. For instance, Elleuch et al. (2016) and Ekanayake et al. (2020) have reviewed the related literature in this area.

The construction industry can be affected directly and indirectly by the vulnerabilities of its supply chains, as they play a crucial role in this industry; therefore, any SC disruption can cause irreparable costs in construction projects (Zainal Abidin & Ingirige, 2018a, 2018b). Zainal Abidin & Ingirige (2018b) studied the vulnerabilities affecting the construction supply chain of Malaysia by proposing a layered framework that shows the cascading impacts of SCV.

Another significance of CSCV can be sought in their role in applying lean construction principles. Previous research shows that lean practices will result in more vulnerabilities for construction supply chains (Ponomarov & Holcomb, 2009; Ruiz-Benítez et al., 2018). Applying lean practices means maintaining very little inventory and relying on integrating supplier relationships to decrease costs and create SC efficiencies. The supply/demand volatility, the cost minimization, and increased dependency among supply chain participants, which all result from lean, contribute to a lack of responsiveness to the adverse effects of disturbances. Consequently, commitment to lean principles can make the supply chains more vulnerable to disruptions (Azevedo et al., 2008). In other words, when implementing lean, a trade-off between lean practices and vulnerabilities should be established in supply chains (Maslaric et al., 2013; Govindan et al., 2015). Furthermore, Christopher & Rutherford (2004) mentioned that managing supply chain vulnerabilities will be a challenge for continuous improvements, a core element of lean (Green & May, 2005; Jørgensen & Emmitt, 2009). So, identifying construction SCV is critical before implementing lean concepts in the construction supply chains.

As mentioned previously, some specific tools and aspects of lean contribute to SC improvements when implementing lean. On the other hand, areas in which lean construction can cause SCV have been pointed out in the literature. So, identifying CSCV will provide the SC managers with a guide for an optimized selection of lean tools in such a way as to decrease the vulnerabilities of construction SCs.

IRANIAN CONSTRUCTION SUPPLY CHAIN

Located in the Middle East, Iran is a developing country whose construction industry accounted for 5.5% of Iran's GDP in 2019 (Central Bank of Iran, 2019). After a period of decline, the output value of the country's construction sector is expected to grow at an annual average rate of 4.4% until 2023. This growth is due to the government's efforts to invest in transportation, energy, and infrastructure projects (GlobalData, 2019). However, official figures indicate that the industry is experiencing fluctuations throughout the Covid-19 outbreak, followed by a decline and contraction from November 2021 to January 2022 (Iran Chamber of Commerce, Industries, Mines and Agriculture, 2022). This underachievement can be rooted in chronic problems originating in Iran's political, economic, and regulatory bodies (Asnaashari et al., 2009).

In this paper, we identify and prioritize the vulnerabilities of the construction supply chains considering an unfavorable macro-environmental context to see the effects of such factors on the behavior of CSCV. We chose Iran as a country that best fits such situations. Then, we analyze the changes in these vulnerabilities over the past two years (coincident with the outbreak of Covid-19).

RESEARCH METHOD

This research conducted a review to extract the SCV in the global context. The authors utilized the keywords "*Construction*" AND "*Supply Chain*" AND "*Vulnerable*" and "*Supply Chain*" AND "*Resilient*" through the target databases of Scopus, Science Direct, and Google Scholar (as a searchable Engine) within a time bracket from 2000 onward. At this stage, 120 pieces of research, including journal and conference papers, thesis, and books, were collected. Afterward, the results were scrutinized by reading their abstracts, which excluded some of them for further consideration. The results were refined to those focused merely on supply chain vulnerabilities in this step. Then, a thematic analysis was conducted to obtain common SCV in the literature.

After determining the SCV using 40 pieces of research, a questionnaire containing the identified SCV was designed. Respondents were solicited to answer two questions regarding each SCV:

- The effect of CSCV in the past two years, and
- The effect of CSCV in general

The reason for separating the questions into two parts is that the outbreak of Covid-19 (in the past two years) impacted supply chains in different ways (Alicke et al., 2021), which can bias the respondents' minds on the general effects of CSCV. The responses were received using a five-point Likert comprising very low (1), low (2), moderate (3), high (4), and very high (5). The scores were then averaged and compared to identify how the priority of CSCV differs under the dominance of an unfavorable macro-environmental context. The scores were also utilized to realize how recent conditions (including the outbreak of the COVID-19) have changed the priority of CSCV.

In the last section of the questionnaire, respondents were also requested to declare a further three CSCV other than those presented by the questionnaire, allowing the authors to tune the results and recognize any factors not identified through the literature. Before distribution among respondents, the questionnaire was approved by an academic professional in the construction industry.

By analyzing the results through a descriptive statistical analysis method, a prioritized list of construction supply chain vulnerabilities and their changes in the last two years under an unfavorable macro-environmental context is obtained.

SAMPLING SPECIFICATIONS

The data-gathering period took place from December 2021 to January 2022, and the data were solicited from the respondents through online questionnaires based on a random sampling approach. The online questionnaire was shared via the social networking platforms LinkedIn™, WhatsApp™, and Telegram™. The authors applied two criteria for selecting respondents: 1) being an active participant in the construction supply chain and 2) having more than two years of experience in this industry. The use of the online questionnaire made it impracticable to account for the response rate. A total number of 72 responses were received through the online questionnaire. Figure 1 shows the respondents' background information in the first section of the questionnaire. The charts indicate that most of the respondents were highly educated and experienced. They also show that the respondents were chosen from a wide array of Iranian construction sectors and were from multiple provinces indicating the validity and generalisability of the research results.

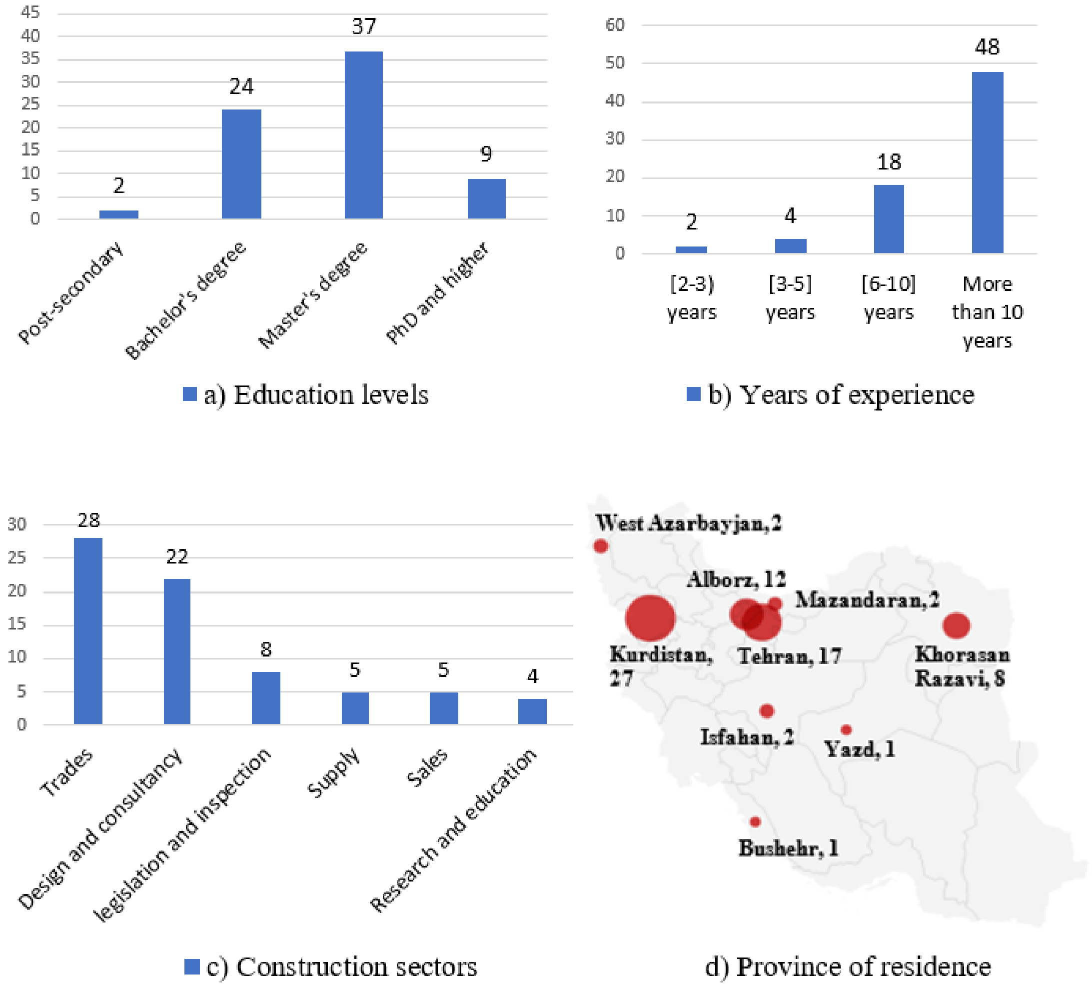

Figure 1- Information of Respondents

SCV IN THE LITERATURE

This study utilized 40 screened papers to extract a list of supply chain vulnerabilities. We scrutinized these papers to achieve a list of 26 vulnerabilities that were either precisely common or conveyed the same concept with nuances in expression among the screened papers. Consequently, we subsumed some vulnerabilities in the literature under more inclusive categories. The identified 26 vulnerabilities with their frequency in the reviewed literature are listed in Table 1.

Table 1- Categorized SCV extracted from the literature

Rank	SCV Category	Brief Description	Freq.	References No.
1	Natural disasters and environmental issues	e.g., flood, earthquake, famine, and environmental pollution leading to a lockdown	20	[1] [2] [4] [6] [7] [8] [15] [16] [17] [18] [19] [21] [23] [25] [28] [30] [32] [36] [37] [39]
2	Human resources issues	e.g., strikes, job-quitting, dissatisfaction, unskilled HR	14	[2] [3] [4] [7] [11] [12] [15] [20] [21] [23] [28] [29] [34] [39]
3	Machinery and IT breakdown	due to improper maintenance or no upgrading	14	[4] [7] [13] [15] [18] [21] [22] [23] [24] [25] [31] [33] [38] [40]
4	Political challenges	e.g., international sanctions, nepotism, lack of meritocracy, and mafia.	14	[4] [7] [8] [9] [10] [15] [19] [21] [23] [25] [27] [28] [29] [37]
5	Supply-demand volatility	market pressure due to supply and demand mismatch	12	[2] [4] [7] [8] [10] [11] [12] [15] [21] [23] [25] [37]
6	Inadequate communication and poor information flow	SC stakeholders fail to access up-to-date info. due to communication breakdowns	11	[1] [7] [10] [13] [15] [22] [23] [24] [33] [38] [40]
7	Data Breach	violating confidentiality protocols	11	[4] [7] [13] [18] [22] [24] [25] [33] [38] [39] [40]
8	Terrorism/war	war outbreak and terrorist attacks	10	[4] [14] [15] [19] [21] [28] [29] [34] [36] [37]
9	Disruption of logistics	inbound/outbound logistic and transportation problems	9	[3] [4] [5] [7] [12] [15] [18] [23] [39]
10	Information mishandling	inadequate data analysis and improper forecasting causing the bullwhip effect	9	[13] [18] [21] [22] [24] [25] [33] [38] [39]
11	Poor product quality	material, products, and services fail to meet customers' requirements	8	[3] [4] [7] [18] [21] [22] [23] [25]
12	Financial issues	e.g., bankruptcy, budget non-realization, problems in financing the projects	8	[3] [4] [7] [8] [9] [10] [12] [23]
13	Corporates dropout	closure of companies supplying materials, products, and services	7	[2] [3] [7] [11] [23] [27] [31]
14	Distrust among stakeholders	due to the prevalence of fraud and non-transparency among SC participants	7	[1] [7] [9] [15] [22] [23] [25]
15	Rework and change orders	due to changing customers' preferences in construction projects	7	[4] [11] [15] [21] [22] [29] [31]
16	Unreliable IT systems	IT systems fail to conform to project preferences	7	[4] [11] [12] [15] [21] [22] [25]
17	Severe weather	harsh climatic situations that disrupt construction projects	6	[4] [12] [15] [21] [27] [40]

Rank	SCV Category	Brief Description	Freq.	References No.
18	New legislation	the implication of new governmental rules	6	[4] [8] [10] [15] [18] [29]
19	Poor integration due to outsourcing	unmanaged outsourcings that lead to loss of SC connectivity	5	[7] [10] [15] [21] [37]
20	Utility disruptions and energy scarcity	power and Internet service outages, together with fuel shortages	5	[4] [7] [8] [11] [39]
21	Infrastructure damage due to accidents	accidents such as the explosion at the workshop or the supplier companies	5	[4] [7] [11] [23] [36]
22	Health and safety issues	occupational health and safety incidents, including accidents and near misses	4	[7] [9] [15] [21]
23	Theft and sabotage	e.g., cyber-attacks and deliberately damaging or thieving projects assets	4	[8] [15] [21] [25]
24	Biological threats	e.g., infectious diseases outbreak	3	[7] [15] [35]
25	Price and exchange rate fluctuations	unstable local currencies that affect the prices and cause an inflation bubble or recession	2	[3] [10]
26	Negative media	e.g., social media causing an interruption in SCs by the propagation of exaggerated or biased news	2	[4] [29]

References utilized are: 1=(Zavala-Alcívar et al., 2020); 2=(Wang et al., 2018); 3=(Truong & Hara, 2018); 4=(Bevilacqua et al., 2018); 5=(Zavala et al., 2018); 6=(Chaghooshi et al., 2018); 7=(Zainal Abidin & Ingirige, 2018b); 8=(Kochan & Nowicki, 2018); 9=(Zainal Abidin & Ingirige, 2018a); 10=(Zainal Abidin, 2018); 11=(Meinel & Abegg, 2017); 12=(Ali et al., 2017); 13=(Huong Tran et al., 2016); 14=(Annarelli & Nonino, 2016); 15=(Fiksel 2015); 16=(Mensah et al., 2015); 17=(Bruno & Clegg, 2015); 18=(Green, 2015); 19=(Bueno-Solano & Cedillo-Campos, 2014); 20=(Scholten et al., 2014); 21=(Pettit et al., 2013); 22=(Aloini et al., 2012); 23=(Chowdhury et al., 2012); 24=(Tummala & Schoenherr, 2011); 25=(Xiao et al., 2011); 26=(Wedawatta et al., 2011); 27=(Wedawatta et al., 2010); 28=(Boin et al., 2010); 29=(Pettit, 2008); 30=(Stolker et al., 2008); 31=(Berry & Collier, 2007); 32=(Kumar & Viswanadham, 2007); 33=(Cucchiella & Gastaldi, 2006); 34=(Tang, 2006); 35=(Peck, 2005); 36=(Sheffi & Rice Jr, 2005); 37=(Christopher & Peck, 2004); 38=(Chopras, 2004); 39=(Chopra & Sodhi, 2004); 40=(Handfield et al., 2002);

RESULTS AND ANALYSIS

In this section, the responses indicate that the four most and least concerning SCV have not changed during the past two years in the construction industry of the studied country. Accordingly, "price and exchange rate fluctuations", "supply-demand volatility", "financial issues", and "political challenges" are the prime disruptors of the country's construction supply chain in descending order. These are followed by "corporate dropouts", "distrust among stakeholders", and "poor product quality". However, in the case of the past two years, "biological threats" have taken the sixth position in the most prior CSCV in Table 2. On the other hand, the least concerning CSCV have not changed in the past two years. They include "natural disasters and environmental issues", "infrastructure damage", "data breach", and "terrorism/war" in descending order. The factors are sorted by their priority from highest to lowest. They are indicated by their rank in the literature -as the global context- in Figure 2.

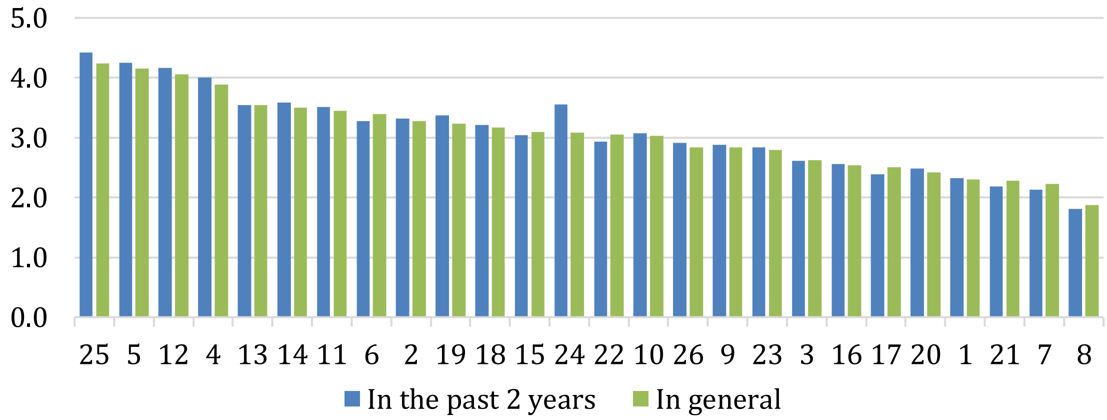

Figure 2- CSCV by their rank in general and the past two years in Iran

The data also shows that the priority of the majority of the CSCV has not considerably changed within the past two years. If one step change in rank is regarded as negligible, the priority of only five CSCV has changed over the past two years. Thereby, three CSCV have lost their priority which include "corporates dropout", "inadequate communication", and "rework and change orders". Also, two CSCV have gained priority during this period: "biological threats" and "information mishandling". The most considerable changes belong to "biological threats" and "inadequate communications". This information is indicated in Table 2.

Table 2- Factors with the most significant change in priority in the past two years

CSCV	General Rank	Rank in the past two years	Change
Biological threats	13	6	7 up ↑
Information mishandling	15	13	2 up ↑
Corporates dropout	5	7	2 down ↓
Rework and change orders	12	14	2 down ↓
Inadequate communication	8	11	3 down ↓

The changes in the score of CSCV are calculated to indicate the extent to which they have gained or lost significance. Hence the in-general scores are subtracted from the past-two-year score. Hence the average general and past two years' scores are subtracted for CSCV to calculate the change measure. It is illustrated in Figure 3. As can be seen, "biological threats" have gained the highest amount of importance in the past two years, and this is followed by "price and exchange rate fluctuations", "poor integration", "financial issues", and "supply-demand volatility". In contrast, concerns regarding certain CSCV have been reduced within the past two years. This group of CSCV is comprised of "health and safety issues", "inadequate communication", "severe weather", "infrastructure damage", "data breach", "terrorism/war", "rework and change orders", and "machinery and its breakdown" in ascending order of score change. Only "corporate dropout" exhibited no change in score in the study period. It should be noted here that the aforementioned score changes ranged from the lowest of -0.11 to the highest of 0.47.

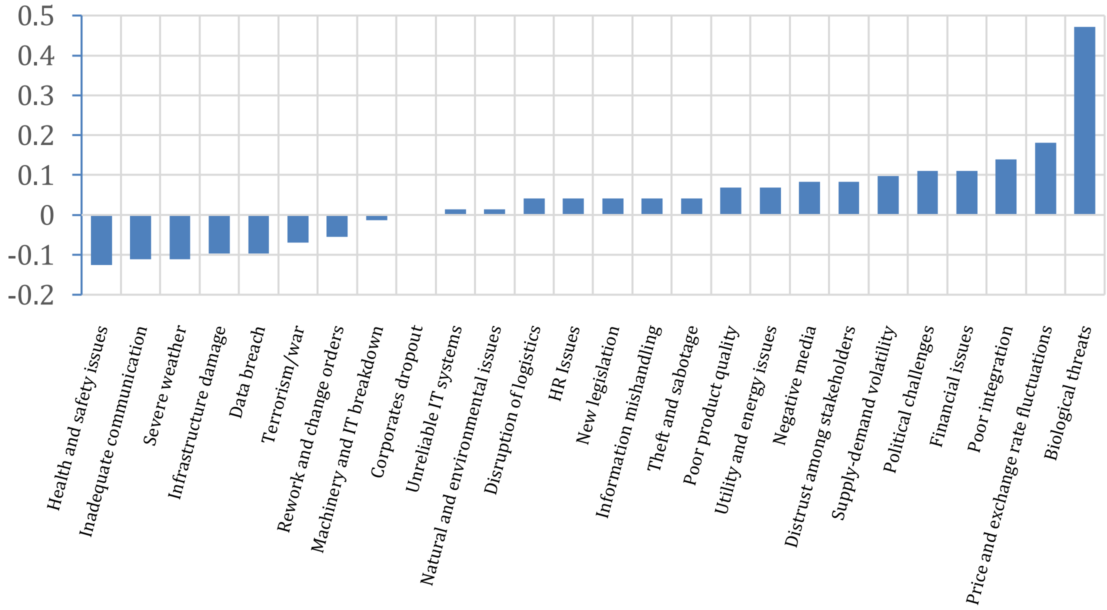

Figure 3- Change in the importance of CSCV in Iran in the past two years

The respondents were asked to point out any CSCV missing from the questionnaire through open-ended questions. A total of 16 responses were received, which were analyzed qualitatively. The most-cited concerns are listed below, respectively:

1) corruption of regulatory and supervisory bodies (typically referred to as bribery)
2) incompetency of the regulatory and supervisory entities to enact regulations and circulars
3) little use of new technology
4) the role of monopolists (especially in the supply of cement as a strategic material in the construction industry)
5) the role of intermediaries and middle persons.

It should be noted that, due to space limitations, only the top and bottom four CSCV are investigated and discussed in the rest of this essay.

DISCUSSION

The primary variable in the studied country was "price and exchange rate fluctuations". It can be attributed to the country's economic crisis due to international sanctions[5] that have caused the national currency to lose its value and drop by around eight times[6], resulting in massive inflation during recent past years[7]. This variable makes investors keep their capital in any form other than cash, which cannot sometimes be readily liquidated. Further, investors make significant losses due to these conversions in many cases. The second most crucial variable in the presence of an unfavorable macro-environmental context, "supply-demand volatility", also appears to have links with the economic crisis. This mainly happens due to the shortage of raw materials and the influence of monopolists, especially cement suppliers, limiting the market supply to

[5] Carnegie Endowment for International Peace. *The Geopolitical Roots of Iran's Economic Crisis*. (https://carnegieendowment.org/sada/83350)
[6] https://www.tgju.org/archive/price_dollar_rl
[7] Inflation, consumer prices (annual %) - Iran, Islamic Rep. (https://data.worldbank.org/indicator/FP.CPI.TOTL.ZG?locations=IR)

increase the prices or export their products when they perceive higher profit in exports. These all cause the demand to react impulsively to supply fluctuations that deteriorate market balance. The third most important variable was "financial issues", which again stem from the country's economic situation. "Political challenges" was identified as the fourth most important variable associated mainly with the foreign policies of the studied country. Although these CSCV have not changed their priority during the past two years, their significance has increased in this period. It can be related to the deteriorating economic-political conditions of the studied country.

Another subject worth mentioning here is "biological threats", whose priority has changed meaningfully from 13 to 6 during the past two years. It has happened due to the outbreak of the COVID-19, indicating that the pandemic has resulted in higher vulnerability in the construction supply chain of the studied country. Other changes that occurred to the priority of the CSCV indicated in Table 2 do not appear to convey any meaningful information.

Moreover, the changes in the score of the CSCV in the past two years indicate that the COVID-19 has been a significant issue during this time. It is also evident that the most prior CSCV of the studied construction supply chain have gained the highest significance levels during this period. Thus, it can be inferred that the construction supply chain of the studied country has become more vulnerable in the past two years.

CONCLUSION AND FUTURE RESEARCH

In this paper, for the first time, we studied the construction supply chain vulnerabilities (CSCV) in the presence of an unfavorable macro-environmental context (e.g., difficult political, economic, and legal situations). Also, we analyzed the changes in such vulnerabilities in a period coincident with the outbreak of the Covid-19. The country which best fit the study's situation was Iran, where crippling international sanctions have brought about economic isolation and the prevalence of monopolists. The results showed that under unfavorable macro-environmental factors, such CSCV as "price and exchange rate fluctuations", "supply-demand volatility", "financial issues", and "political challenges" gained priority over others. These ramifications, which differ from those in normal contexts mentioned in previous research, imply the significance of considering the specific supply chain context in identifying the CSCV. They also provide a proper tool for supply chain decision-makers when facing challenging macro-environmental factors.

Furthermore, this study analyzed the changes of the identified CSCV in a period coincident with the outbreak of the Covid-19 pandemic. The results of analyzing these changes indicated that the impacts of the pandemic in line with the unfavorable macro-environmental context have made the studied construction supply chain more vulnerable to disruption. Moreover, this paper has introduced four more CSCV specific to the abovementioned context. The limitation of this study refers to considering only one country, i.e., Iran, to simulate an unfavorable macro-environmental context. However, the results can provide a decision-making tool for supply chain managers before implementing lean principles. In other words, since lean has twofold effects on SCs (i.e., improving SCs' performance while making them more vulnerable to disruption), the CSCV provided in this paper help managers focus more on lean tools such as the Last Planner System and value stream mapping which cause less vulnerability in SCs.

Further research can be done to determine the capabilities in supply chains operating under unfavorable macro-environmental contexts to counter the CSCV for making the supply chain resilient. Moreover, future studies can focus on the role of each lean tool on the vulnerability of construction SCs and consider separating internal and external vulnerabilities.

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EMPIRICAL VALIDATION OF LEAN IMPLEMENTATION BARRIERS IN ENGINEER-TO-ORDER COMPANIES: AN EXPLORATORY STUDY

Felix Schulze[1] and Patrick Dallasega[2]

ABSTRACT

Enterprises employing an Engineer-to-Order (ETO) manufacturing strategy produce complex products designed specifically to customer requirements, on a project basis, under time and cost constraints. As a result of this complexity, wastes and inefficiency occur within the internal and external supply chain. To improve productivity, companies are striving to implement Lean practices in ETO environments but encounter implementation barriers. Based on the comprehensive literature study on Lean implementation barriers in ETO companies, this study empirically validates the occurrence of these barriers in practice. For this purpose, empirical evidence was gathered using a survey questionnaire followed by semi-structured interviews with 15 companies from the ETO sector in construction, mechanical engineering, and shipbuilding. As a result, the barriers mentioned in the literature are compared with the barriers that occur in practice. Simultaneously, new barriers not described in the literature are also identified. This study can guide Lean professionals in the ETO environment in their Lean efforts to identify corresponding barriers in their own organizations while trying to understand the relevant causes and fields of action to mitigate them. Future research should aim to explore other methods and strategies along with emerging technologies of Industry 4.0 that could help overcome Lean implementation barriers.

KEYWORDS

Lean construction, barriers, engineer-to-order (ETO), complexity, waste

INTRODUCTION

Engineer-to-Order (ETO) companies design and manufacture highly customized products such as machines, plants, buildings, and ships according to customer requirements. These goods are often characterized by low volumes, a low rate of order recurrence and project-by-project procedure (Løkkegaard et al., 2022). ETO projects are characterized by high cost and delivery time pressure, a high degree of individualization, and high complexity in relation to planning and coordination activities, which lead to a large proportion of non-value-added activities resulting in productivity losses and lower competitiveness (Aslam et al., 2020; Schulze & Dallasega, 2021).

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To remain competitive and improve efficiency, ETO companies are forced to rethink their operation strategies and reassess the implementation of verified approaches and technologies to improve productivity (Mayr et al., 2018; Sanders et al., 2016; Schulze & Dallasega, 2021; Strandhagen et al., 2018). The improvement in productivity and reduction of waste in companies with an ETO strategy using Lean thinking has already been shown in various studies (Buer et al., 2018; Sanders et al., 2016; Schulze & Dallasega, 2021; Strandhagen et al., 2018). Originally developed in the automotive industry, Lean processes and principles are applied in mainly product-centered repetitive production settings characterized by stable demand for large volumes of related products (Jünge et al., 2021; Schulze & Dallasega, 2021). Lean thinking, also known as Lean Manufacturing or Lean Construction, intends to maximize customer value by reducing non-value adding activities, forming a pull-based flow induced by customer requirements, and reducing excessive process variability (Jünge et al., 2021; Salem et al., 2006).

However, the adoption of Lean methods and tools to the ETO environment is limited and very challenging due to the low volume of customized products and non-repetitive manufacturing setting (Schulze & Dallasega, 2021). Some of the Lean tools and principles are suitable to the ETO environment, while others require adaptation (Schulze & Dallasega, 2021), still most ETO companies face barriers in implementing Lean in their environment (Kumar & Kumar, 2014; Schulze & Dallasega, 2020; Zhang et al., 2017). These implementation barriers can be related to organization, management, knowledge, culture, finance, as well as non-context causes (Schulze & Dallasega, 2021).

The literature on barriers when implementing Lean methods and tools in companies with an ETO strategy is relatively limited in comparison to industries with repetitive manufacturing strategies (Birkie & Trucco, 2016; Schulze & Dallasega, 2021) and a framework that discusses inputs, tools, techniques and barriers regarding Lean for the ETO sector is still missing (Basu & Dan, 2020). Therefore, research discussing Lean implementation barriers in repetitive manufacturing does not support for conclusions to be drawn for non-repetitive environments like ETO.

This paper aims to empirically validate the barriers to Lean implementation that companies in the ETO environment face in practice. Based on a detailed literature review (Schulze & Dallasega, 2021) this paper proposes an empirical validation of Lean implementation barriers in the ETO-industry. For this aim, a survey questionnaire followed by semi-structured interviews with 15 companies from the construction, mechanical engineering, and shipbuilding sectors were used. As such, this article contributes to the growing body of research discussing Lean principles and their implementation in the ETO environment.

LITERATURE REVIEW

In previous research seven Lean implementation barrier categories were identified by means of a systematic literature review (SLR) (Schulze & Dallasega, 2021). The Scopus database has been used with a search string containing the following keywords: "Lean" OR several Lean methods such as 'LPS', 'LMBS', 'Kanban / CIP', 'JIT', 'Poka-Yoke', 'Prefabrication', 'Modularization', 'Pull scheduling', 'Pull planning', 'Visual Management', 'IPD', AND "barrier" OR synonyms such as 'obstacles', 'difficulties', 'constraints', 'failure factors', 'challenges', 'hurdles', 'hindrances', and 'critical success factors', AND "Engineer-to-Order" OR "ETO". From a total of 362 articles identified, 115 article were duplicates, leaving 247 papers to be analyzed according to title and abstract fitness. Inclusion criteria were applied to identify relevant works for the content analysis. These included: articles referring to the ETO industry, articles focusing on the implementation of the searched Lean tools and methods, articles reporting on the barriers during the implementation process, articles published in scientific journals and conference proceedings, articles published within the time range between 2010 and 2020. As a result, 79 articles were deemed inadequate topics leaving 168 articles to be further analyzed. Based on an independently chosen selection of articles, which were analyzed in-depth by the two authors, further inclusion criteria were applied: articles listing implementation barriers supported by data and articles describing barriers with reference to an ETO context. Consequently, 113 were excluded, leaving 55 articles for an in-depth content analysis. 19 articles were further included via backward and forward snowballing, a search strategy using the references and the citations respectively, resulting in a final set of 74 articles for an in-depth content analysis.

The following section briefly summarizes the barrier groups and subgroups identified in the SLR.

1. Organization related barriers relate to the lack of a supportive organizational culture for Lean. These include the (1.1) resistance of the workforce to change to new ways of working and unwillingness to engage in Lean processes (Huaman-Orosco & Erazo-Rondinel, 2021; Lodgaard et al., 2016; Murguia, 2019; Salonitis & Tsinopoulos, 2016). Another factor is the (1.2) lack of effort to build a supportive organizational culture for a successful Lean adoption (Abu et al., 2019; Haque et al., 2003; Lodgaard et al., 2016). Further, companies in the ETO sector often (1.3) ignore the systematic approach of Lean by only concentrating on certain tools (Almeida Marodin & Saurin, 2014; Zhang et al., 2017). A (1.4) lack of communication of all Lean efforts and results across the organization is another organizational related barrier (Almeida Marodin & Saurin, 2014; Bayhan et al., 2019).

2. Management related barriers include the (2.1) absence of commitment from the top management to the Lean implementation process, which is critical factor for a successful Lean adoption (Huaman-Orosco & Erazo-Rondinel, 2021; Lodgaard et al., 2016; Valente et al., 2020; Zhang et al., 2017). Also, top management often only (2.2) focuses on short-term results rather than the implementation process (Huaman-Orosco & Erazo-Rondinel, 2021; Salonitis & Tsinopoulos, 2016; Tezel et al., 2017). In addition, (2.3) different hierarchical levels must deal with contrasting views on Lean implementation barriers during their day-to-day operations, making adoption even more difficult (Lodgaard et al., 2016; Salonitis & Tsinopoulos, 2016).

3. Knowledge related barriers consist of an (3.1) insufficient understanding of Lean concepts and tools as well as a lack of implementation know-how and practices (Abu et al., 2019; Huaman-Orosco & Erazo-Rondinel, 2021; Salonitis & Tsinopoulos, 2016; Valente et al., 2020; Walter et al., 2020). In addition, ETO companies often neglect to properly (3.2) train employees (Abu et al., 2019; Lodgaard et al., 2016). Another aspect is that managers often (3.3) lack the ability to quantify the benefits of the implemented Lean methods in terms of key performance figures (KPIs) (Almeida Marodin & Saurin, 2014; Erthal & Marques, 2018).

4. Cultural related barriers entail a (4.1) lack of awareness and understanding of Lean and the corresponding change in one’s own organization towards a Lean culture (Haque et al., 2003; Lodgaard et al., 2016). Employees are often not empowered enough to adapt to certain Lean methods (Aslam et al., 2020; Huaman-Orosco & Erazo-Rondinel, 2021). Additionally, (4.2) organizational cultures that emphasize internal competition and corporate hierarchy are less conducive to implementing Lean than those that favor collaboration and teamwork (Dominici & Palumbo, 2013; Erthal & Marques, 2018).

5. Financial related barriers comprise of a (5.1) lack of financial resources for training the workforce or external consultants and investment in innovation (Gupta & Jain, 2013; Zhang et al., 2017). Further, not all Lean methods implemented generate (5.2) quantifiable advantages, but rather intangible benefits such as employee satisfaction and improved safety (Zhang et al., 2017).

6. Non-context specific related barriers are those barriers that cannot be assigned to any of the other barrier groups. These include obstacles such as a (6.1) lack of Lean adaption from the repetitive production environment to the non-repetitive setting of ETO firms (Birkie & Trucco, 2016; Huaman-Orosco & Erazo-Rondinel, 2021; Tezel et al., 2017). The low volumes, wide variety of products, and lack of long-term forecasting make it difficult for an ETO organization to sustain Lean implementation processes (Salonitis & Tsinopoulos, 2016). In addition, companies with an ETO strategy are affected by high environmental uncertainty, such as unpredictable customer and demand fluctuations, varying performances of suppliers and subcontractors, and ever-changing rate of innovation (Birkie et al., 2017). This (6.2) lack of process reliability poses another barrier for implementing Lean.

7. Customer related barriers include either the (7.1) lack of customer support in Lean implementation efforts or pressure from clients to implement Lean. This (7.2) forced approach often leads to futile implementations due to a lack of motivation, assistance, and determination from ETOs management (Hussain, 2016; Zhang et al., 2017).

RESEARCH METHODOLOGY

Design: A sequential explanatory mixed-method design was adopted to collect data using survey questionnaire and qualitative semi-structured interviews. Survey methods targeted to collect primary data from the participants (Mathers et al., 2013), while semi-structured interviews gathered qualitative data that enabled the exploration of subjective experiences, understanding, and personal beliefs (Bray et al., 2014). First, the quantitative data was collected by sending a questionnaire to the targeted key individuals, followed by semi-structured interviews which were conducted with the companies' participants to gain a better in depth understanding of their answers (Harrell & Bradley, 2009).

Data Collection: A structured survey questionnaire was used to gather self-reported data on the Lean implementation barriers encountered in practice to the participants. The questionnaires and interviews were collected between the end of November 2021 and the end of February 2022.

Development of questionnaire: To collect data for this study, a questionnaire was developed consisting of various parts including: (A) the background information provided by the respondents and the company itself, (B) the occurrence of losses and wastes during an ETO project, (C) the Lean methods and tools applied, and (D) the actual Lean implementation barriers encountered, which were structured according to the barrier groups and subgroups summarized in the previous chapter. Useful information about the study is contained in the header part of the questionnaire. The last part of each segment has some space for the interviewees to provide some comments or additional information if any. The questions were designed to be simple yet easy to understand for the respondents.

Sample selection: Based on the realization that companies in the ETO environment are reluctant to share confidential information, the research is exploratory, and the findings are preliminary, justifying the use of non-probability sampling (Malhotra, 2008). Purposive sampling was utilized to select the companies to be questioned, as this non-random technique allows respondents to be explicitly selected based on the necessary information they can provide on the concepts and topics at question (Campbell et al., 2020; Tongco, 2007). Furthermore, purposive sampling helps to better match the objectives of the research with the sample, thereby increasing the rigidity of the study and the reliability of the data and results (Campbell et al., 2020). Table 1 shows the companies that participated to the study using code names to protect identity. A total of 15 companies from the ETO sector, namely construction (7 companies), mechanical engineering (4 companies), and ship building (4 companies), were selected. The ETO companies are located in Italy, Germany, and Norway. About half of the companies are small and medium sized enterprises (SMEs) with 60 to 500 employees and annual sales between €10 million and €500 million. The other half are large companies with more than 500 employees and annual turnover between €700 million and €4.6 billion. Since the barriers of Lean implementation were to be researched, the respective companies interviewed assigned us the relevant persons responsible for the subject of Lean. Respondents were typically the corresponding 'Lean experts' or 'Lean managers' in their company, or held equivalent positions, such as 'Production manager' or 'Head of digitization and innovation management' occasionally also the respective high-level business executives of the company. Interviewees' work experience ranges from 5 to 28 years.

Table 1: Sampled companies

Case company	ETO sector	Size	Country	Interviewee's position	Expe-rience
A	Construction	SME	Germany	Head of BIM and Innovation	7
B	Construction	Large	Germany	Expert Production Systems	10
C	Construction	SME	Germany	Head of Lean Management	10
D	Construction	Large	Germany	Head of BIM Department	16
E	Construction	Large	Germany	Head of Lean Construction	8
F	Construction	SME	Germany	Head of Project Management	20
G	Construction	SME	Norway	CEO	20
I	Mech. Engineering	Large	Italy	Production Manager	26
J	Mech. Engineering	Large	Italy	Head of work preparation	16
K	Mech. Engineering	SME	Italy	Production Manager	12
L	Mech. Engineering	Large	Germany	Production Manager	28
Q	Shipbuilding	SME	Germany	CEO	18
R	Shipbuilding	Large	Germany	Digitization / Innovation head	20
S	Shipbuilding	SME	Germany	Process & Project Manager	5
T	Shipbuilding	Large	Norway	Deputy Managing Director	15

Testing and validation of the questionnaire: After the structure and questions were defined, this instrument was validated against the criteria by experts from different ETO companies, who assessed and scored the entire questionnaire. Any corrections and suggestions were implemented accordingly in the questionnaire.

Interviews: To examine the collected primary survey data, as well as to explore the participants subjective experiences and believes, individual interviews were conducted in a semi-structured form. Semi-structured interviews (SSI), which are both a data collection strategy and a qualitative research method (McIntosh & Morse, 2015) aim to establish and verify the perspective of participants in order to confirm, correct or discover new knowledge related to the focus of the research (McIntosh & Morse, 2015). The interviews were conducted by the two members of the research team either face to face in the interviewed company or over the internet via a video conferencing tool depending on the participants' preference and location. All interviews were audio or video recorded with the participant's consent.

Data Analysis: After the interview, the data collected from the semi-structured interviews was summarized in a protocol and sent back to the interviewees for validation. The validated protocols and questionnaires were then summarized and analyzed. The responses received were compiled in an Excel spreadsheet and the data analyzed using quantitative research methodologies.

RESULTS

To achieve the main objective of this study, respondents were asked about the specific Lean implementation barriers that they encounter in their organization. The results are shown in Table 2 and ranked according to their frequency of mentioning.

Amongst the (1) organizational related barriers, (1.1) "Employee's resistance to change" is the most frequently cited barrier subgroup amongst the interviewees. "*At first it was difficult to gain the acceptance of the employees and especially the suppliers for Lean*", Case company R quotes the first phase of Lean implementation in their organization. Similarly, case company A describes that "*The traditional way of working is a major obstacle*" is a major hindrance to their Lean efforts. Furthermore, the barrier subgroup (1.3) "Fragmented implementation" is named by case company K as: "*Isolated solutions are a barrier to the introduction of Lean with us*".

The barrier subsection (1.4) "Insufficient information management" was especially emphasized by bigger construction companies. Case company E takes this into account with the quote: "*The size of the company means that Lean efforts spread differently and therefore more slowly in the various company units*". Case company B also openly addresses this barrier by saying: "*Each area has its own Lean boss, which requires a lot of communication effort*". (2.1) "Limited management commitment" is the most discussed barrier subsection under (2) management related barriers. This becomes clear in case companies I and G, which state: "*Mainly, the interest of the top management in Lean is missing*" and "*We lack the commitment from the management*". Even after the successful introduction of some lean methods and tools, company S still complains: "*The lack of top management commitment is still a problem […] Support is missing in certain areas, but it is also there in certain areas*".

(3.3) "Missing quantitative measurement indicators" is the most stated barrier subcategory amongst the (3) knowledge related barriers. This becomes clear in case study C, which perceives the improvements of Lean but cannot measure them directly: "*Qualitative indicators are also missing. Lean provides what feels like better processes but no increased financial output*". This is also emphasized by companies B and J: "*It is difficult to measure the added value of Lean methods*" and "*It's hard to identify measurable benefits from certain Lean practices*". Company Q complains that Lean-related improvements in important key figures are not directly measurable: "*We are observing difficulty quantifying of lead time and improved adherence to deadlines*".

Table 2: List of Lean implementation barriers in ETO companies

Barrier	Case Company	# Mentions
6.2 Lack of process reliability	A, B, C, D, E, G, J, L, Q, S, T	11
3.3 Missing quantitative measurement indicators	A, B, D, E, F, I, K, Q, S, T	10
1.1 Employee's resistance to change	A, B, D, E, F, G, Q, R, S	9
4.1 Lack of Lean culture	A, B, D, E, J, L, Q, R, T	9
6.1 Lack of adaptability of Lean methods from other production environments	A, B, G, J, Q, R, S, T	8
1.2 Insufficient organizational structure for Lean	B, E, J, K, Q, R, S	7
1.3 Fragmented implementation	C, E, F, Q, R, T	6
2.1 Limited management commitment	E, F, G, I, Q, S	6
2.2 Short-term focus	C, F, Q, R, S, T	6
3.2 Insufficient training of workforce for Lean	A, D, I, L, Q, T	6
5.2 No direct financial advantage	A, E, J, K, Q, T	6
1.4 Insufficient information management	B, D, L, Q, T	5
3.1 Insufficient know-how about Lean	A, J, I, Q, T	5
4.2 Country related cultural differences	Q, S, T	3
5.1 Lack of financial resources	A, E, J, K, Q, T	3
7.1 Lack of customer support	E, G	2
3.4 *Internal fluctuation of key Lean personal*	C, E	2
3.5 *Long Project duration*	D, E	2
7.2 Forced Lean adoption by customer	Q	1
2.3 Hierarchical differences	D	1

The barrier subsection (3.1) "Insufficient know how" is stated by case company I as one of the crucial obstacles in their Lean efforts: "*There is a lack of knowledge to introduce Lean in our production*". The issue of (3.2) "Insufficient training of workforce for Lean" is emphasized by Company E: *"Due to the long duration of the projects, it takes time for learning effects to set in regarding Lean*".

When it comes to (4) cultural related barriers, (4.1) "Lack of Lean culture" is the most mentioned hurdle. The interviewed case company G points out that Lean thinking is mostly missing in all areas in their organizations: "*Lean methods are easy to understand, but hard to implement, which makes it difficult to gain its acceptance throughout the company*". (5.1) "Lack of financial resources" is the frequent cited barrier subgroup among (5) financial related barriers. As case company Q addresses the issue in terms of finances and involvement of top management for Lean: "*Lean implementations often lack short-term successes, but they are necessary for its acceptance. […] But if these two goals [more sales and lower costs] are addressed with the increase in efficiency [via Lean tools], then the management is also interested in Lean*".

In the (6) non-context related barrier group, the barrier subgroup (6.2) "Lack of process reliability" was cited the most amongst the interviewed companies. Especially the interviewed construction companies emphasized this barrier. As case company B puts it: "*A lack of process reliability in the construction industry is a major barrier to Lean*". Case company E emphasizes the subject of fluctuating subcontractors: "*Due to the high fluctuation of the subcontractors, there is a lack of process stability*". "*Every project is different, which makes it difficult to compare established Lean methods*" is described by case company Q as a decisive issue in this regard. Case company J adds here: "*Own improvements, achieved through Lean, are difficult to pass on to subcontractors*".

In the barrier group (7) customer related barriers, the interviewed companies mention the (71.) "Lack of customer support" in their Lean endeavors. Case companies C and K complain about the lack of customer support: "*On the customer side, almost nothing is demanded or supported in terms of Lean*" and "*The customer is needed for Lean, but they often do not participate*". The additional effort involved in proving certain lean certificates is often not appreciated by customers: "*Customer orders nowadays require more and more evidence of Lean, but rarely support implementation*", as case company G criticizes.

During the interviews several new implementation barriers emerged, previously not mentioned in the literature, especially among the construction companies. (3.4) "Internal fluctuation of key Lean personal" is described by case company E: "*Important employees who are familiar with Lean often change companies, which means that there is a lack of sustainability in Lean activities.*" Further, (3.5) "Long Project duration" was described as an issue for case company D: "*Due to the fact that the construction project often run for several years, the learning effects and best practices [regarding Lean] that have been gained cannot be processed and passed on quickly enough to other projects*".

DISCUSSION

As the survey findings indicated, (6.2) "lack of process reliability" is the primary obstacle mentioned by the ETO companies surveyed, indicating that the non-repetitive environment of ETO characterized by high complexity and unpredictable demand fluctuations still represents a key hindrance to the implementation of Lean methods and tools from the repetitive manufacturing setting. This was also confirmed in the work of Birkie et al. (2017) and Alfnes et al., (2016), who observed that complexity (varying factors that influence decision making) and dynamism (degree to which these factors change) in ETO organizations have a strong influence on the implementation of Lean.

The survey results also implied that (3.3) "missing quantitative measurement indicators" is a major obstacle for ETO companies to evaluate the benefits of Lean and therefore to implement it. As interviewee T expressed it: "*However, the great difficulty of Lean is measuring the monetary and qualitative benefits*". This finding is consistent with the statement from the literature that managers often cannot measure the impact and benefits of most Lean methods (Almeida Marodin & Saurin, 2014; Erthal & Marques, 2018; Schulze & Dallasega, 2021; Tezel et al., 2017).

The study findings also indicate that (1.1) "Employee's resistance to change" is a key barrier mentioned by the interviewees. As interviewee S stated: "*I encounter resistance to change regarding Lean practices daily in my work*", and also mentioned by Interviewee D: "*Getting the workforce behind Lean is crucial*". This is also evident in the literature, where employee's adherence to traditional working methods and skepticism towards new processes and technologies are one of the biggest barriers to the introduction of Lean in an organization (Gupta & Jain, 2013; Lodgaard et al., 2016; Salonitis & Tsinopoulos, 2016; Schulze & Dallasega, 2021). Previous research shows that employees resist implementing Lean practices and tend to revert to pre-Lean habits in the absence of a clear vision, commitment from top management, and an understanding of the underlying performance benefits (Birkie et al., 2017).

An operational implication of this study is that managers who want to implement Lean in their organizations should use the results obtained here as starting points for their own Lean activities. Any efforts to mitigate Lean implementation barriers should not only focus on the barriers mentioned most often in this study, but also on considering the respective specific situation of the company, researching the underlying causes of the barriers, and looking at possible connections between the barriers. For example, the barrier "Lack of process reliability" can have different causes, such as frequent customer changes, the fragmentation of the construction industry, low level of standardization and digitization, which must be considered separately

This study also has limitations. As an empirical study in a profoundly dynamic and intricate environment, 15 ETO cases were used via questionnaire surveys and semi-structured interviews. Responses from all respondents relate to their individual company and situation and there may be different perspectives within the broader ETO sector. Further, due to the Covid-19 situation, some interviews could only be conducted online. The specific company tour was missing here, where internal organization issues could have been better explained.

Future research may continuing investigate the occurrence of Lean implementation barriers in different sectors of ETO businesses. Companies with and ETO strategy in different sectors are so diverse that it is not easy to generalize findings. More empirical validation is recommended. Further, research may examine other strategies and methodologies besides Lean to overcome barriers in Lean implementation. Further investigation could also explore the potential of new technologies such as virtual and augmented reality, big data, artificial intelligence and other Industry 4.0 tools and concepts to overcome traditional barriers to lean implementation.

CONCLUSIONS

This study examined the real-world occurrence of Lean implementation barriers in Engineer-to-Order (ETO) companies. The Lean implementation barriers were determined through a literature review, mainly based on the work of Schulze & Dallasega (2021). The study was conducted based on questionnaire survey and subsequent semi-structured interviews developed to collect data with 15 companies from the ETO sector. The key contribution of this research is the empirical validation of the occurrence of Lean implementation barriers in companies with an ETO strategy practice. Further, new barriers not previously mentioned in the literature have also been identified through this research, which should be further investigated in theory and practice. The findings of this study could be used as a starting point to help researchers, practitioners, and companies in the ETO environment seeking to mitigate their own Lean implementation barriers, by investigating the exact causes and interrelationships of the barriers in their organizations.

Limitations of this research are the size of the sample, which can affect the validity and reliability of the research findings, as well as that not all interviews could be conducted on site in person. Future research would include exploring the occurrence of Lean implementation barriers in practice and in different sectors of ETO, also investigating methods and strategies, as well as new technologies to mitigate Lean implementation barriers.

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PREPARING CONSTRUCTION EMPLOYERS FOR THE GEN-Z WORKFORCE: A CASE STUDY

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ABSTRACT

The construction industry has been facing many challenges in the recent years such as labour shortage, aging workforce, productivity decline, and resistance to change. These challenges have pushed both practitioners and academicians to investigate and invest in new transformations that can alter the industry's traditional business-as-usual model. To successfully address the challenges and create an industry that successfully adapts to and fits in the changing environment, construction employers must prioritize attracting, recruiting, and retaining the new workforce generation. Thus, it becomes important to understand the expectations that construction students are looking for in organizations after graduation. Such studies are still missing, notably on Generation-Z and the construction industry in USA. This paper attempts to fill the gap through providing the first case study on Gen-Z students graduating from of the state of Kentucky and wanting to join the construction industry. A total of 51 students were surveyed and asked to evaluate the importance of 27 factors when accepting a job offer, describe their ideal workplace, and elaborate on whether the COVID-19 pandemic shifted their perspective on the workplace. Findings of this paper can help construction employers in and around the state of Kentucky in preparing for the Generation-Z workforce.

KEYWORDS

Generation-Z workforce; workplace; construction industry; employer of choice; Lean construction

BACKGROUND

Work environments in the 21st century have been described as both dynamic and complex, which is intensifying the natural and unique stress levels that workplaces have on their employees (Darling & Whitty, 2020). In the last couple of years, stress levels reached staggering peaks as industries continue to navigate the effects of the COVID-19 pandemic which riddled every work environment (Borg et al., 2021). The construction industry is

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no exception: the pandemic impacted the schedule of projects, increased costs, scarcened materials, and created a spike in workforce concerns and complaints (Alsharef et al., 2021; Bou Hatoum et al., 2021). The pandemic, while a major challenge for the construction industry on its own, has also aggravated the long-standing problems of lagging productivity, the pressing needs to reduce fragmentation and integrate technology, and the urge to address labour and talent shortage that have been dauting the construction industry for decades (Barbosa et al., 2017; Bou Hatoum et al., 2020).

A key aspect for overcoming the challenges faced by the construction industry is the need to attract, recruit, and retain the young workforce (Ammar & Nassereddine, 2022; Borg et al., 2021; Hatoum et al., 2021). Like other industries, construction employers should be ready for the wave of Generation-Z (Gen-Z) graduates that already started making their way into the workplace (Schroth, 2019). As explained by the Pew Research Center (PWC), Gen-Z represents people born between 1997 and 2012 (Dimock, 2019). A major distinction between Gen-Z and previous generations is that Gen-Z are “digital natives”, meaning that they were born into an era dominated by technology (Dimock, 2019). Research on Gen-Z shows that they are motivated, self-confident, and ambitious, with a strong sense of autonomy and solid opinions on matters that they care about (Horton, 2021). Another important finding about Gen-Z is that financial compensations are not its major drive for work, implying that Gen-Z is ready to switch and leave a workplace when a sense of belonging no longer exists (Deloitte, 2021). Thus, not only should the construction employers appeal to the Gen-Z and utilize their talent, they should also dedicate resources to secure their loyalty and address their needs (Borg et al., 2021).

Research on the Gen-Z workforce joining the construction industry are starting to rise, with recent publications from Australia, United Kingdom, and Spain (Denny-Smith et al., 2021; Turner et al., 2021) – but not USA. Therefore, this study was initiated to address the gap through launching a nation-wide survey to understand the needs of young Gen-Z students who will join the construction industry. This paper is the first publication from this study, which provides the preliminary findings of insights collected from construction management students in the state of Kentucky.

OBJECTIVE AND METHODOLOGY

This study aims to understand the expectations of the new construction management Gen-Z workforce that is joining the construction industry. The study is conducted with students in the state of Kentucky. Findings of the paper can help employers in the construction industry, including those that self-identify as lean organizations, in attracting and retaining the new workforce. The paper answers the following questions:

- What are the factors that Gen-Z consider when accepting job offers?
- How does Gen-Z paint their ideal workplace?
- Did the COVID-19 pandemic shift Gen-Z perspective on an ideal workplace?
- How does the Gen-Z ideal workplace reflect on Lean construction ideologies and principles?

To answer the research questions, a survey was developed to ask students to: (1) evaluate the importance of 27 factors when accepting a job offer, (2) describe their ideal workplace, (3) describe their non-ideal workplace, and (4) elaborate on whether the COVID-19 pandemic shifted their perspective on the workplace. Respondents were also asked to identify whether they have experience in the construction industry, and whether they have close or distant relatives working within the industry. These two binary variables were used to study their impact on the importance of the 27 factors. Once the data was collected, statistical tests including k-means clustering and non-parametric pairwise comparisons were employed to analyse the input collected from close-ended questions, and thematic analysis was applied to analyse the open-ended questions.

FACTORS OF INTEREST

To identify factors that students consider when selecting their preferable employer, a Scopus search for the key-terms "employer of choice" in "construction industry" yielded only two studies (Denny-Smith et al., 2021; Sedighi & Loosemore, 2012). Both studies alongside Branham (2005) – the most cited paper on "employer of choice" – were used to comprehensively compile the list of 27 factors listed and defined in Table 1.

Table 1: Factors analyzed in the survey

Factor	Definition
Benefits	Offer includes paid time off, retirement plans, bonuses, etc.
Clarity	Organization is clear about your roles and responsibilities
Competition	Organization creates a competitive environment between workers/ teams
Compensation	The financial salaries that the organization offers
Creativity	Organization allows workers to be creative and provides them with means to express their opinions and thoughts
Collaboration	Tasks are teamwork oriented
Diversity	Organization supports the presence of different race, gender, religion, sexual orientation, socioeconomic status, ethnicity, nationality, age, etc.
Education Offering	Organization provides online or in-person academies to take classes
Fairness	Organization is fair in compensation and benefits
Flexibility	Offer allows flexible work hours as long as the contract hours are met
Freedom	Organization allows workers to work on their own pace
Growth	Organization offers opportunities to advance and/or get promoted quickly
Honesty	Organization's mission and vision are well-defined
Innovation	The organization has an "innovative" reputation when compared to others
Relocation	The need to relocate in order to join the organization
Location Stability	The potential need to relocate to another state over the course of the career with the organization
Mentoring	Organization assigns a mentor within the organization for support, advice, and growth
Professional Development	Organization provides support to gain certificates, licenses, graduate studies, etc.
Recognition	Organization has a system of rewards for accomplishments
Realistic	Realistic work expectations and tasks have realistic deadlines
Respect	Respect for people
Safety	Hazard free; proper protection; safety manuals; safety training
Job Security	Organization provides a sense of relief in terms of job loss

Standardization	Organization provides clear instructions on how to perform tasks
Technology	Organization is advanced when it comes to the use of technology
Wellbeing	Organization is aware of mental health and cares for the wellbeing
Work-Life Balance	Roles and responsibilities maintain a balance between life and work

SAMPLE SIZE

According to recent data, an estimated 150 students graduate annually with a construction management degree or civil engineering with construction management emphasis from the five main universities in the state of Kentucky (Data USA, 2022a, 2022b).The survey was shared with students studying civil engineering with an emphasis on construction management. Thus, using the finite population equation for sample size, the 51 data points collected for this paper are enough to have 95% confidence that the real value of every measured metric is within ±10% of the measured/surveyed value. The age of the participants ranged between 19 and 24, indicating that all students were born in the Generation-Z era between 1997 and 2012 (Dimock, 2019). In terms of gender, 73% of students were male and 27% were female. Most of the students were undergraduates (86%) and 14% were graduate students doing their masters. Moreover, 12% of students were non-white, 6% were married, and 6% identified as part of the LGBTQIA+ community.

ANALYSIS OF FACTORS

As the factors were ranked on a 3-point scale, Cronbach's Alpha was calculated to measure the internal consistency of the scale and estimate the measurement accuracy (i.e. reliability) of the factors (Taber, 2018). The calculations yielded a value of α_{cron} equals to 0.898, indicating good reliability (George & Mallery, 2019).

For every factor, an Average Weighted Index (AWI) was calculated using the following equation:

$$AWI = \frac{1}{n}(\omega_{NI} \times NI + \omega_I \times I + \omega_{VI} \times VI)$$

Where:

- NI is the number of respondents who chose "Not Important" multiplied by a weight of $\omega_{NI} = 1$;
- I is the number of respondents who chose "Important" multiplied by a weight of $\omega_I = 2$;
- VI is the number of respondents who chose "Very Important" multiplied by a weight of $\omega_{VI} = 3$;
- n is the total number of respondents who ranked the factor.

Next, k-means clustering was employed to group factors and break them into multiple tiers based on their AWI. To determine the number of clusters, the elbow method was used as seen in Figure 1. The scree plot of the variation of within sum of square errors (SSE) as a function of clusters shows that the variance within-group sum of squares decreased as the number of clusters increased. Based on the elbow method, the elbow at cluster three represents the optimal balance between minimizing the number of clusters and the variance within each cluster, indicating that the data can be clustered into three clusters. Results were verified using the "KneeLocators" function in *python* (Arvai, 2021).

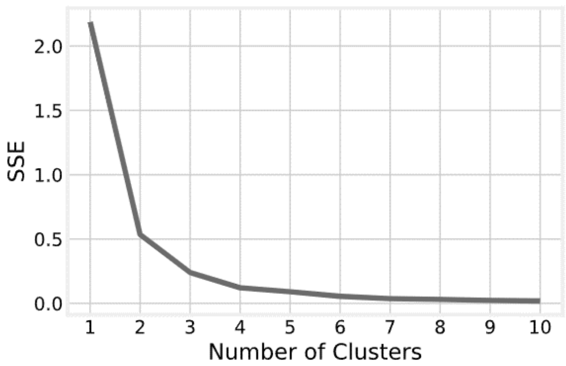

Figure 1. Scree plot for the k-means cluster analysis of the factors' AWI.

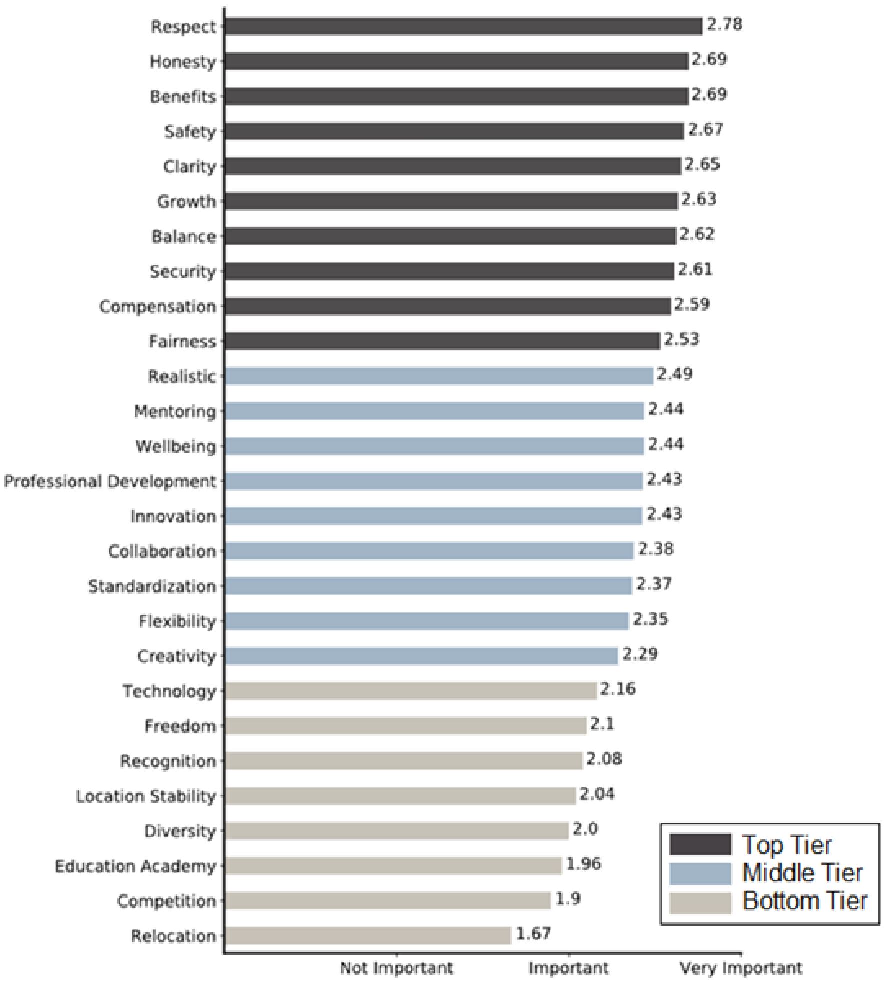

Figure 2. Factors with their AWI and clusters.

The three clusters were referred to as *Top Tier*, *Middle Tier*, and *Bottom Tier*. Results for the AWI and the k-means clustering are shown in Figure 2.

As shown in figure 2, most of the factors had an AWI between *Important* and *Very Important* except for "Education Academy" (AWI=1.96), "Competition" (AWI=1.9), and "Relocation" (AWI=1.67). Overall, students ranked "Respect" (AWI=2.78), "Honesty" (AWI=2.69), and "Benefits" (AWI=2.69) as the highest three factors of importance when accepting job offers, leading the *Top Tier* factors.

ANALYSIS BY **C**ONSTRUCTION **E**XPERIENCE

Respondents were asked to specify whether they have experience in the construction industry or not. Results showed that 76% of students did have an experience, while 24% did not. This distribution warranted testing the following hypothesis: *Students with experience in the construction industry have different perception of the factors that play a role in joining an organization than those with no experience.*

Two tests were performed for the hypothesis. First, k-means cluster analysis was performed on the data of every group, and the *Top Tier* cluster was compiled and presented in an alphabetical order as shown in Figure 3. Then, pairwise comparisons using Mann-Whitney test (non-parametric t-test) were performed on all 27 factors to detect significant differences between the two groups, and the significant comparisons are highlighted in Table 2.

Figure 3 plots the AWI of *Top Tier* factors of each group. The AWI values vary between 2 (i.e., Important as illustrated at the center of the chart) and 3 (i.e., Very Important as illustrated by the outer circle of the chart). As shown in Figure 3, "Respect" and "Clarity" led the *Top Tier* for students with construction experience, while "Respect" and "Benefits" led the *Top Tier* for students without experience. Moreover, students with construction experience had "Balance", "Clarity", and "Fairness" exclusively in their *Top Tier*, while students with no experience has "Realistic [expectations]" in theirs.

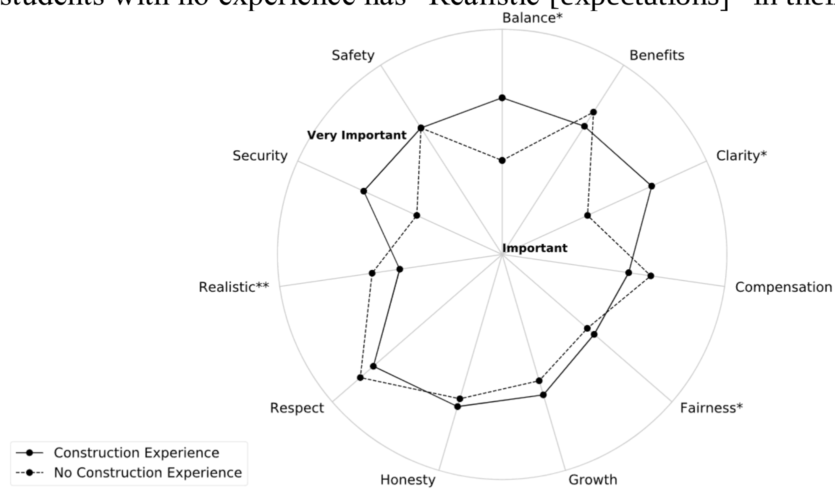

Figure 3. *Top Tier* factors for the students with Construction Experience (solid line) and students without Construction Experience (dashed line). Note that (*) implies that the factor was in the *Top Tier* for "Construction Experience" only, while (**) implies that the factor was in the *Top Tier* for "No Construction Experience" only.

As for the significant pairwise comparisons (Table 2), students with experience in the construction industry ranked "Clarity", "[job] Security", and "[work-life] Balance" significantly higher than students with no experience.

Table 2. Significant comparisons of the pairwise comparisons across the 27 factors.

Factor	Construction Experience (AWI)	No Experience (AWI)	P-value	Significance
Clarity	2.729	2.416	0.056	Significant at 90%
Security	2.675	2.416	0.058	Significant at 90%
Balance	2.694	2.416	0.038	Significant at 95%

ANALYSIS BY INDUSTRY RELATIVES

Respondents were asked to specify whether they have family members working in the construction industry. The collected responses showed that 55% said yes while 45% said no. The distribution warranted testing the following hypothesis: *Students who have family relatives in the construction industry have different perception of the factors that play a role in joining an organization than those who do not have family members in the construction industry.*

K-means clustering and pairwise comparisons were performed, with the *Top Tier* clusters and the significant comparisons presented in an alphabetical order as shown in Figure 4 and Table 3 respectively. Similar to Figure 3, the AWI values vary between 2 and 3. As shown in Figure 4, "Respect", "Honesty" and "Clarity" led the *Top Tier* for students with relatives working in the construction industry, while "Benefits", "Safety", and "Respect" led the *Top Tier* for students with no relatives working in the construction industry. Moreover, students with relatives in the construction industry distinctly had "Collaboration", "Innovation", "Mentoring", "Professional Development", "Realistic [expectations]", "Standardization", and "Wellbeing" in their *Top Tier*.

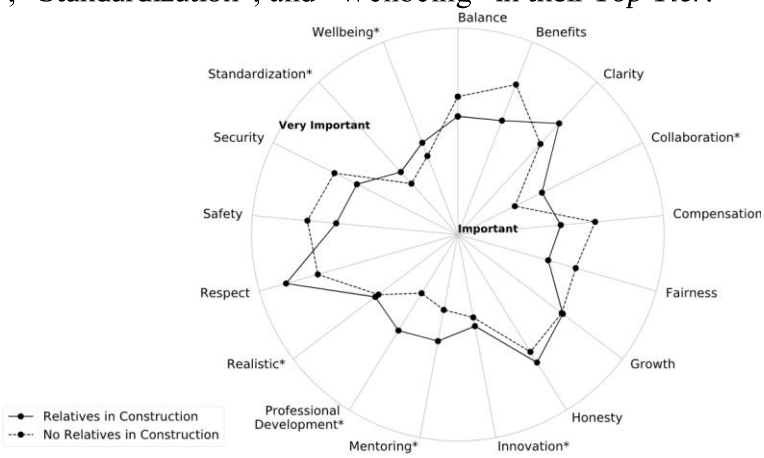

Figure 4. *Top Tier* factors for students who have relatives in the construction industry (solid line) and students who do not have relatives in the construction industry (dashed line). Note that (*) implies that the factor was in the *Top Tier* for "Relatives in the Construction Industry" only.

As for the significant pairwise comparisons (Table 3), students who have relatives in the industry ranked "Respect" and "Professional Development" significantly higher, while students with no relatives ranked "Benefits", "Compensation", and "Safety" higher.

Table 3. Significant comparisons of the pairwise comparisons across the 27 factors.

Factor	Family in Construction (AWI)	No Family in Construction (AWI)	P-value	Significance
Benefits	2.591	2.777	0.057	Significant at 90%
Compensation	2.500	2.666	0.098	Significant at 90%
Respect	2.863	2.703	0.095	Significant at 90%
Safety	2.526	2.760	0.092	Significant at 90%
Professional Development	2.545	2.333	0.096	Significant at 90%

THE IDEAL WORK CULTURE

Respondents were asked to elaborate in their own words on the ideal environment that they would want to work in, and the environment that they would like to avoid. A thematic analysis approach was used to analyse the descriptions, yielding six themes as shown in Figure 5: colleagues, managers, culture, workplace, personal preferences, and projects.

Figure 5. Thematic Analysis of Ideal and Non-Ideal Work Environment as Discussed by the Students (Figure was designed using icons from Flaticon.com; author attributes provided in "Remarks" section)

IMPACT OF THE COVID-19 PANDEMIC

Students were asked whether the COVID-19 pandemic impacted their perception of an ideal working environment. Results showed that 49% chose “Yes”, 45% chose “No”, and 6% had “No Opinion”. Elaborations on their choices were mostly limited to discussions on in-person versus remote working.

Starting with students who chose “Yes”, discussions revolved around the success they perceived from working remotely, and the personal benefits of working from home. Some major highlights:

- The pandemic proved that many tasks could transition from in-person to remote work, in contradiction to the popular belief that the industry cannot operate in a remote or hybrid model.
- Significant reduction in congested meetings, where large assemblies are carried remotely instead of people crowding-up and standing “elbow to elbow”.
- Significant reduction in travel time between the office and construction site or between sites, especially when the outcome of the visit can be sorted remotely or by using technology.
- Some companies transitioned to hybrid models where students were able to balance between working from home and commuting to the workplace.
- Increased attention on health and safety practices including sanitization, cleanliness, personal-protective equipment, availability of vaccines, and healthcare benefits.
- Highlighted personal benefits of working from home such as convenience, wellbeing, less paid-time off due to sickness, flexible schedules, and increase in family time.

As for the students who chose “No”, discussions revolved around the benefits of in-person work. Some major highlights:

- Working fully-remotely lacks the social aspect of working closely with colleagues and having genuine conversations.
- The nature of some tasks cannot be done remotely, and certain positions such as a “project manager” require on-site presence.
- Visiting construction sites remains essential, as it helps with career development.
- Some students experienced a decrease in productivity when working fully remotely, and they would rather have the option to commute to the workplace.
- Students also highlighted that the perception before and after the pandemic did not change because their career goals and motivations remain intact. Whether working remotely or in-person, they still care about excelling at their jobs, gaining recognition, and being treated with respect.

REFLECTION OF FINDINGS ON LEAN CONSTRUCTION

Findings of the survey highlighted the importance of multiple aspects that are supported by Lean Construction. Starting with the results of Figure 2, the high importance of *Top Tier* factors including respect, honesty, clarity, growth, and fairness are all dimensions of a Lean culture (Osman et al., 2021). Respect – which leads the *Top Tier* group in terms of overall importance and surpassed any other factor when ranked by students with construction experience, students with no construction experience, and students with relatives in the construction industry – is at the center of any Lean environment. More precisely, respect for people is a main pillar for any "real Lean environment", and is critical to enable continuous improvement, another critical pillar for successful organizations (Seed, 2015).

The features of an ideal work environment articulated by the students are, for the most part, achieved and facilitated through the following three Lean principles defined by (Liker, 2021):

- Process-related principles such as principles 2 (continuous flow), 4 (levelling), and 5 (standardization) facilitate features discussed on "colleagues", "managers", and "culture" (Figure 5) such as communication, collaboration, inclusion, shared and balanced roles and responsibilities, and constructive criticism.
- People-related principles such as principles 9 (grow leaders) and 10 (develop people and teams) facilitate features discussed in "personal preferences" (Figure 5) where students emphasized personal aspirations like continuous learning, professional development, promotions, and work-life balance.
- Problem solving-related principles like principle 13 (align goals) facilitate features discussed in "projects" (Figure 5) where students highlighted the importance of aligned goals, quality, and progress checks in projects.

One additional insight from the analysis of the input concerns the "workplace", where students emphasized their preference for collaborative spaces and functional furniture instead of rows of isolated cubicles. This finding is aligned with multiple Lean studies that highlight the importance of places and spaces in organizations, and how "Lean offices" can provide benefits for individuals' professional development, behaviours, attitudes, and skills (Bodin Danielsson, 2013; Freitas et al., 2018) .

Regarding the impact of COVID-19, great emphasis was placed by many students on the ability to work remotely and successfully to complete tasks that do not require commute to a workplace. This reflects on Liker's eighth principle, which calls organizations to adopt technology that support people and processes (Liker, 2021). This observation also reflects on major transformations affecting the construction industry such as Lean Construction 4.0, which highlights how technology needs to serve the organization and address human needs (Hamzeh, González, Alarcon, & Khalife, 2021).

Finally, it can be stated that findings discussed in this paper highlight long-term thinking – the first main Lean principle and the foundation of a Lean environment (Liker, 2021). Long-term thinking was reflected on in students' emphasis on career aspirations, excelling at jobs, gaining recognition, professional development, and continuous learning.

CONCLUSIONS, LIMITATIONS, AND FURTHER STUDIES

This paper provided insights into Gen-Z of Kentucky wanting to join the construction industry. Through a survey, students were asked to rank the importance of 27 factors when selecting a job, describe their ideal workplace, and elaborate on whether the COVID-19 pandemic shifted their perception of the workplace. It is important to note that the findings present a case study on the state of Kentucky and are based on the gathered responses from the construction management students in Kentucky. The next step in this research effort is to conduct a nation-wide survey to help US construction employers prepare for the new wave of the Gen-Z workforce, attract new talent, and establish a culture that meets fresh graduates' expectations.

REMARKS

Figure 5 was designed using icons from Flaticon.com including: “Participation” icon created by Eucalyp, ‘Manager’ icon created by Monkik, ‘Team’ icon created by Eucalyp, ‘Workplace’ icon created by Linector, ‘Opinion’ icon created by Freepik, ‘Project Management’ icon created by Ultimatearm.

Study was approved by University of Kentucky’s Institutional Research Board (IRB) – protocol #76068. All findings and opinions expressed in this paper are those of the authors, and do not necessarily reflect the University of Kentucky.

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THE NEED FOR A HUMAN CENTRIC APPROACH IN C4.0 TECHNOLOGIES

Karim Noueihed[1], Farook Hamzeh[2]

ABSTRACT

Construction industry is amidst a radical shift towards digitalization. The promising benefits of Construction 4.0 (C4.0) are yet to be harvested; however, the implications of the C4.0 technologies are still being explored after adoption. Among the various impacts of adoption are social impacts, which have been overlooked in this fast-paced revolution despite their grave consequences on the industry and the people involved. This paper explores the literature on the social impacts of these technologies and tackles artificial intelligence as a specific case. This study compares different findings, analyzes them, and reflects on how practitioners need to consider a more humane approach when implementing new technologies.

KEYWORDS

Construction 4.0, human-centric, social impacts, Lean Construction, artificial intelligence

INTRODUCTION

Over the course of history, humans managed to disruptively innovate and evolve throughout different industries, improving their overall wellbeing and the lives of their succeeding generations. In the first industrial revolution, production became mechanized using water and steam. The second revolution included mass production using electrical energy. The third revolution was about production automation using information technology and electronics (Majumdar et al., 2018). The fourth revolution, Industry 4.0, includes the use of cyber-physical systems and advanced digital technologies (Sawhney et al., 2020). Culot et al. (2020) stated that Industry 4.0 is an “announced revolution”. It is an encompassing concept for a list of technologies and applications applied in different contexts. Embarking on this fourth revolution, the potentiality is not yet actualized. In the context of construction, the term Construction 4.0 (C4.0) is used. Sawhney et al. (2020) described C4.0 as a paradigm that uses cyber-physical systems (such as robots, actuators, and drones), industrial production (such as 3D printing and off-site manufacture), and digital technologies (such as BIM, internet of things, and artificial intelligence). As defined by the authors: “Construction 4.0 aims to create interconnected environment integrating organizations, processes, and information to efficiently design, construct and operate assets.”

An overlooked aspect amidst this revolution is the social aspect. Scholars addressed the impact of several C4.0 technologies on humans as individuals and the social structure

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in the industry. Studies categorize C4.0 technologies differently based on their application and level of digitalization and innovation. However, most studies tend to generalize and deduce impacts, influences, and implications of specific technologies among others under the umbrella of Construction 4.0. Many researchers shed light on the negative impact, while others showed the bright side that came with the implementations. This indicates the potential benefits that can be harvested from implementing these technologies, as well as the collateral damage that may be left behind. This paper explores the literature found on the social impacts of C4.0 and how the industry is coping and approaching this inevitable shift to address the following research questions: (1) What are the social impacts of C4.0 technologies on people in the construction industry? (2) How is the industry coping with this digital shift? The paper explores these impacts under the title of "C4.0 technologies" and investigates artificial intelligence in more details. The study aims to provoke discussion and reflection on the impact of existing and promising technologies on humans, and emphasizes the need for a human-centric approach for their adoption. The paper is divided into the following sections: Research methodology, social impacts of C4.0, investigating AI, different approaches to C4.0 adoption, the need for a novel human-centric approach, and conclusion.

RESEARCH METHODOLOGY

Due to the controversial and abstractive nature of the topic, a synthetic literature review was used. A synthetic literature review is a methodology used to critically analyse a specific topic to identify trends and patterns in the literature, analyze and pinpoint discrepancies in the body of knowledge, and propose recommendations and next steps for future research (Schirmer, 2018).

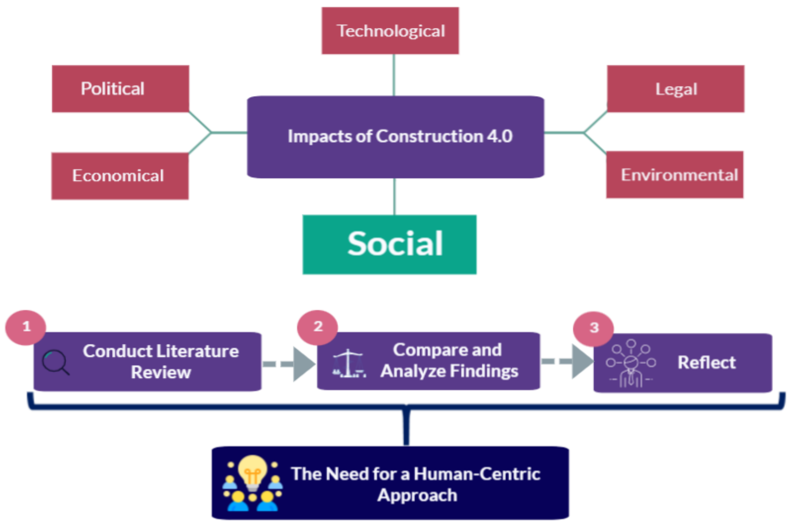

Figure 1: Research Methodology

As shown in figure 1, the social impact was the main focus in this study among other types of impacts (political, technological, legal, environmental, and economical). The first step was conducting a literature review to understand the state of the knowledge in terms of *what* the social impacts of Construction 4.0 technologies on people are, and *how* they are being addressed. The review process is linked to the research questions stated in the introduction, with the aim to highlight different views on the social impact of C4.0 and the industry's approach to adopt C4.0. The next step was conducting a comparative analysis between different views on the topic to capture any specific trend in the impacts and the current methodologies carried out to address them. This sparked reflection that was expressed after the analysis; reflections were in form of statements and questions that would trigger more thought on the topic. Moreover, the findings were linked to studies and theories in other fields and sciences, such as psychology and neuroscience. The same steps were followed to address artificial intelligence as a specific case of C4.0 technologies. This paved the way for expressing the need for a more humane approach for embracing C4.0.

SOCIAL IMPACTS OF C4.0

The social impacts spanned from impacts on organizational structures and companies as a whole to impacts on people and individuals. Table 1 summarizes the findings on the social impacts of C4.0, the social considerations in C4.0 adoption, and the questions raised to reflect on them. The questions are labeled in the table and referenced in the section.

Table 1: Summary of C4.0 Social Impacts

Authors	Main Findings	Questions Raised
Balasubramanian et al. (2021)	C4.0 might lead to small and medium-sized enterprises (SME) running out of business due to the monopolization of technologies by bigger companies Cyber-Physical Systems (CPS) may reduce employees' creativity, professional autonomy, self-worth, and morale	**Q1:** Is there a standardized method for organizations to assess the impact of these technologies on their employees? **Q2:** How is this radical change managed? **Q3:** Is it too late to track these impacts?
Lokovitis (2021) Sherratt et al. (2020)	C4.0 does not support the nature of architects' work (art and culture) and might cause disruption	**Q4:** Is it a positive thing to automate or delegate creativity, brainstorming, intuition, and other humane tasks to machines? **Q5:** What would be the consequences of achieving that?
Ness (2009) Forcael et al. (2020) Chan (2020) Balasubramanian et al. (2021)	C4.0 imposes the risk of automating and replacing the jobs of blue-collar workers C4.0 technologies lead to safer environments Companies can upskill their workers	**Q6:** Which jobs are compromised? **Q7:** What jobs are created? **Q8:** How can the affected people fill the gap in the new opportunities that technology create? **Q9:** What is the strategy to upskill people?
Oesterreich & Teuteberg (2016) Alaloul et al. (2020)	Most companies adopt a techno-centric approach for adopting C4,0 The social and ethical factors are barely addressed in the adoption of I4.0 technologies in construction Social and technical factors are the most critical in delaying the implementation of C4.0 technologies.	**Q10:** What if companies start with the root cause, the social factor, and address it as a basis for their approach to digitalization? **Q11:** What if this "hindrance" is the solution for a successful and healthy adoption?

Balasubramanian et al. (2021) studied the current and future state of C4.0 technologies in the industry and how they are disrupting the sector. The authors used extensive literature review and surveys to assess different technologies. They reflected on the social, economic, and environmental sustainability impact. With respect to the social impacts, organizational structures are expected to radically change, where big companies will monopolize the market and SME are at risk of being left out of the game. Moreover, the impacts were also expressed at the level of individuals. For example, the study showed that Cyber-Physical Systems may reduce the creativity of employees. Also, AI and machine learning were indicated to negatively affect professional autonomy and creativity of employees. From the interviews conducted in the study, the interviewees voiced the concern that technologies are truly shaping and limiting free thinking, creativity, and skill utilization. Furthermore, C4.0 technologies were viewed to affect employee's perceived self-worth and morale. These alarming issues are hard to detect as they are abstract and subjective; however, their repercussions may ripple from individual performance to an entire organization's existence. The subtlety of the problem is a much bigger problem. *Q1:* Is there a standardized method for organizations to assess the impact of these technologies on their employees? *Q2:* How is this radical change managed? *Q3:* Is it too late to track these impacts?

Lokovitis (2021) investigated the integration of C4.0 in the Greek AEC industry using interviews with experts from the architecture, engineering, and construction field. Interestingly, experts with an architectural background reflected that C4.0 innovative technologies do not align with the nature of their work. They opined that architectural work still focuses on creativity and brainstorming which are not yet supported by these technologies. The interviewees emphasized on aspects such as art and culture, which cannot be reshaped by C4.0 technologies. *Q4:* Is it a positive thing to automate or delegate creativity, brainstorming, intuition, and other humane tasks to machines? *Q5:* What would be the consequences of achieving that?

Sherratt et al. (2020) used the term technocratic optimism to describe the negligence and passivity in accepting technologies without any consideration of their social impacts. In their study, the authors argued how C4.0 technologies are close to reshaping the whole workforce eliminating the people who actually build the projects in real life. Moreover, the authors expressed concerns regarding the impacts of C4.0 technologies on reshaping the work of architects. This digital shift was said to lead to projects being built to meet and fit technological advancements in the industry, rather than being a product of creativity, humanity, and imagination of architects. Besides reshaping the nature of jobs, some are risked to be replaced or even lost. Whether due to industry 4.0 technologies (Morrar et al. 2017; Berriman 2017) or construction 4.0 technologies, jobs of manual workers and blue collars are anticipated to become redundant and automated. (Ness, 2009; Forcael et al., 2020; Chan, 2020; Balasubramanian et al. 2021). On the other hand, other studies reflect optimism regarding the impact on jobs. During the interviews conducted by Balasubramanian et al. (2021), some interviewees mentioned initiatives in their companies to upskill blue collar workers to knowledge workers, where their jobs will not be as physically intensive as before. Blue collar workers would shift from an unsafe and harsh environment to a safer and more controlled one. They would supervise and transfer their experience to robotic systems. Robots and automation are predicted to produce new roles and opportunities (Garcia de soto et al., 2019). Although these contradicting views may both be true, what is most important is the need for proactive measures. Before adopting these technologies, considerate questions of their impact should be asked first.

Q6: Which jobs are compromised? *Q7:* What jobs are created? *Q8:* How can the affected people fill the gap in the new opportunities that technology create? *Q9:* What is the strategy to upskill people? These are few preliminary questions that should be raised and more effort should be put to address them.

Oesterreich & Teuteberg (2016) conducted a systematic literature review (SLR) and multiple case analysis to explore the benefits, challenges, and state of Industry 4.0 technologies in the construction industry. The authors used PESTEL framework to aggregate findings (benefits and challenges) and categorize them as political, economic, social, technological, environmental, and legal. From the 9 case studies conducted (each case study addressed a different construction company), only one showed a human-centric approach to the adoption of technology. The company explained that innovation and work environment redesign springs from their own workforce, fitting technologies adopted to what people saw helpful and healthy. This is what deemed the approach human-centric; innovation and change come from people who are doing the work to fit their needs. From the SLR conducted, the authors found that the analyzed articles mostly address technical aspects of I4.0 technologies adoption in the construction industry. The social and ethical aspects were barely addressed. A comprehensive literature review was performed by Alaloul et al. (2020) to identify causes of delay in implementing I4.0 technologies in the construction industry. The findings of the study state that social and technical factors were the most critical factors in delaying the implementation of these technologies. This highlights a paradoxical trend, where social factors are considered as hindrance for C4.0 technologies on one hand, and on the other hand are barely addressed in adoption frameworks, models, and methodologies. *Q10:* What if companies start with the root cause, the social factor, and address it as a basis for their approach to digitalization? *Q11:* What if this “hindrance” is the solution for a successful and healthy adoption?

Among different C4.0 technologies breaking through the industry, artificial intelligence (AI) is one of the quickest in reaching maturity. A significant number of studies focused on the current state of this technology, its prospective benefits and challenges, and its impact on humans. Therefore, it is chosen to be discussed as a specific case in the following section.

INVESTIGATING AI

Technology has different levels of disruption depending on what the technology is able to offer, and how drastic its impact is on the latest practice. Clerck (2017) explained the difference between digitization, digitalization, and digital transformation. Digitization is the move from paper to digital data. It is the creation of digital version of physical things. Digitalization is the automation of processes where machines replace human labor. Digital transformation is the integration of different digital technologies leading to radical change across industries, organizations, and people. It is considered to be beyond a technological phenomenon.

Artificial intelligence is a branch of science and technology that creates intelligent machines and computer programs to perform various tasks which requires human intelligence (PK, 1984). AI is one of the most influencing digital transformations disrupting almost all industries. With respect to construction, the technology can potentially infiltrate any aspect of the industry and is addressed in particular by many scholars and researchers. Arroyo et al. (2021) discussed the uses of AI in the industry and the ethical and social dilemmas that arise from using it. The authors highlighted provoking questions that spark reflection and thought about how impactful AI is on industry practitioners. For example, if AI would take over, how would team structure and collaboration look like? A construction project binds effort of various trades. Project success is highly related to how harmonized the trades are with each other. Can AI algorithms come up with decisions that take social context into the equation? Would it compromise these bonds that tie people in a construction project?

McAleenan (2020) tackled moral issues and considerations of the use of AI in construction. The author stated that transparency is crucial for human liberty and well-being. However, the AI systems designed are still far from being transparent to both creators and users. The AI could be several AIs within an AI, obscuring transparency further and leading to more difficulty in finding the root causes of distrust and mistrust between the human and the machine (Abbas, 2019). Taking the best-case scenario, where the intentions of inventors are noble in trying to improve construction productivity, there are unintended consequences of these inventions (Arroyo et al., 2021; McAleenan, 2020). Schia (2019) explored the impact of AI on human behavior in the construction industry. The study included interviews with people from contracting and subcontracting companies to discuss the digital shift and its impact on the human behavior. ALICE, which is an AI-powered construction scheduling application, is one of the technologies that the interviewees assessed. The assessment was based on technology, process, and culture. It was evident that there was no clear strategy of how ALICE should be implemented (process). Moreover, the cultural aspect (visibility of the utility, willingness to use, sense of achievement, and ownership) is missing. It is difficult for a worker to understand the output coming out of the application, let alone trusting it. Klien et al. (2004) reflected on the challenges for making automation a "team player". Even today, nearly 18 years after publishing the paper, challenges such as the ability to negotiate, ability to interpret signal of status and intentions, ability to reach mutual predictability, and ability to collaborate are far from reached. This gap is both exciting and scary; if not closed, it can lead to a lot of conflict between human and machine.

Wang and Siau (2018) categorized AI as being either weak or strong. Weak AI performs specific tasks with high involvement of human in terms of decision making and supervision. While strong AI is the performance of tasks with human-like intelligence and decision-making abilities. In 2014, Google Deepmind developed AlphaGo, an AI algorithm that competes in the world's oldest board game developed in China: Go. Go is an abstract strategy board game with simple rules; however, the possible configurations of the Go board are more than the number of atoms in the universe. Therefore, it is impossible for any existing computer to compute all possible variations. Thus, as described by Go players, most of the times intuition drives their decisions to move the stones on the board. This challenge of mimicking human intuition using AI was picked up by the researchers and developers of Deepmind. In 2016, AlphaGo won 4 out of 5 games against 18-time world champion Lee Sedol. The caveat lies in analysis of AlphaGo's moves as the games were progressing. A lot of moves were judged as unreasonable and stupid but turned out to be genius as the game unfolded. However, other moves were also judged as unreasonable and stupid and turned out to be so. In 2017, a newer version of AlphaGo defeated its predecessor 100 times (Du Sautoy, 2019). The technology is maturing faster than what we can comprehend, making the adaptation process more challenging and threatening in terms of disruption. As these decisions might be unreasonable for human brains, how can we judge a decision made by algorithm as right or wrong? Developing human-like autonomous AI applications like AlphaGo in the construction industry is not far from possible; how can users ensure transparency and develop trust with such a technology?

Construction projects can be viewed a network of commitments where reliable promising is at the heart of project success (Howell & Macomber, 2006). In his theory of Multiple Intelligences, psychologist Howard Gardner defined 8 types of intelligence (Gardner, 2011). With an artificial intelligence depicting one (Logical-Mathematical intelligence) out of 8 types of intelligence and disregarding all intrinsically human views of intelligence, how can rapport be built and decisions be agreed on when dealing with a strong AI? How can reliable *promising* be made with no emotional connection? How can trust be developed facing an emotionless machine? Who will be making the promise and based on what? Technology can be supplementary in a sense that it doesn't overtake what humans are meant to do but rather support it. Delegating tasks that are cognitive and humane to an algorithm sets the limit of what humans can achieve.

DIFFERENT APPROACHES FOR C4.0 ADOPTION

Goodrum et al. (2011) developed a predictive model to assess and estimate the potential impact of a technology on construction productivity. The authors used analytical hierarchy process (AHP) to weigh the input of experts on 4 main categories: Strategic economic analysis, technical feasibility, technology usage issues, and technical impact (attributes that have been found to directly influence construction productivity). The model built was successfully validated based on the preset criteria. However, social factors were not mentioned or used in the model. Hossain & Nadeem (2019) developed a framework describing steps to adopt the concept of C4.0 among construction companies. Although the authors stated that "digital culture" and training are the major hindrances in the adoption of C4.0 technologies, the framework did not include any measure of assessment on human impact. The framework is considered to lead to positive increase in productivity, quality, efficiency, and process integration. The factors used are critical in assessing a technology; however, they are incomplete. If socio-cultural and human factors are usually considered an impedance on the adoption, what is the solution?

Simon Sinek, a well-known entrepreneur, inspirational speaker, and author, tackles a well-known phenomenon in business which highly relates to construction. He explains the relationship between performance and trust, and how organizations measure success (Sinek, 2019). He highlights that performance metrics are not wrong; however, they are incomplete. If an organization hits a financial goal by the end of a year, people in the organization get incentivized without knowing how they got there. Meaning, even if team members kept quitting and their morale kept fluctuating abruptly, as long as the goal is met, people (whoever is remaining of the team) would get a bonus. Simon discusses that on the long run, measuring performance leads to diminishing returns because metrics such as momentum, trust, and morale are out of the equation of success. Tying this back to construction, whether measuring project performance, or assessing impact of C4.0 technologies, the metrics are lopsided. There are uncountable metrics to measure performance, but negligible to zero metrics to measure elusive yet highly critical human factors such as trustworthiness and morale. The focus on potential benefits in terms of productivity and profit reaped from adoption of C4.0 technologies may lead to the inconsideration of any social, human, and ethical consequences (Sherratt et al., 2020). If only monetary metrics are used to assess the implementation of a technology (productivity, profit, cost, time, etc..), then this would be similar to the attempt to optimize the parts of a system rather than the whole.

Hatoum et al. (2021) proposed a framework to assist companies in reengineering their processes with construction 4.0 technologies. The framework integrates Lean Construction and Construction 4.0 transformations. People-process-technology triad is used as a basis; the assessment of current state, vision of a future state, and the implementation are all based on the triad. Moreover, the authors leveraged lean principles to describe the philosophy and motivation behind the steps presented in the framework. The framework encompasses both sides of the equation: human and technology. Overlooking one and emphasizing the other gives false hopes and incomplete information about what the technology is expected to achieve. Does lean construction bridge this gap? Is it a healthy methodology that balances all factors?

THE NEED FOR A NOVEL HUMAN-CENTRIC APPROACH

The comparison between different point of views indicates an inevitable trade-off of gains and losses from adopting C4.0 technologies. The vocal concerns about technological dominancy are not an attempt to run away from it, but rather an urge to embrace it in a healthy fashion preserving both: control and humanity. Control is an external factor, meaning that humans should have the predictability and control of the physical output of any technology. Technology should serve what the human wants and not the opposite. Humanity is an internal factor, meaning that humans must flourish and succeed, not only projects. Technology are means of support, not dominancy.

The study of qualitative, subjective, and abstract factors such as motivation, collaboration, satisfaction, or any human related factor is very challenging. Assessing such factors in the construction industry makes it even harder and appeared to be limited in the literature as this study was conducted. However, the impact of digitalization on our brain is highly discussed in neuroscience, psychology, and sociology. Brain coach Jim Kwik elaborated in his book *Limitless* (Kwik, 2021) on what he named “digital villains”: digital dementia (coined by neuroscientist Manfred Spitzer), digital deluge, digital distraction, and digital deduction. The most relevant to the impacts of C4.0 technologies are digital dementia and digital deduction. Digital dementia is the breakdown of cognitive abilities (such as planning, reasoning, critical thinking, etc..) due to the overuse of technology. Just as people’s route processing abilities diminish with the reliance on GPS, the ability to do proper project planning (which is an art), scheduling, and control will wane if these technologies take over. This also relates to digital deduction, which is the automation of deduction. With a matured technology, such as AI in planning and scheduling, one click would solve almost every question a practitioner might have. There would be no deduction made on how the technology arrived to the solution and why it is the right one. This means that critical faculties such as problem solving and creativity are now delegated to a machine. How can the industry innovate, evolve, create, and thrive when such skills are being automated? Wouldn’t that limit our abilities? What is more alarming is the direct exposure of these technologies to the new generation. People with previous actual practical experience have the potential to judge a decision made by a technology; they have the “hunch”. This privilege is not available for the upcoming generations, meaning that a gradual extinction of such knowledge is occurring without us being aware.

The “bigger, faster, stronger” mentality in disrupting construction with no proactive measures may backfire. Albert Einstein once said, “It has become appallingly obvious that our technology has exceeded our humanity.” As scholars and professionals in construction, we owe ourselves to raise the concern of preserving humanity in face of everything, not just technology. Lean construction, in its essence, bridges the gap between technology and people. Hamzeh et al. (2021) introduced Lean Construction 4.0 which embraces the shift toward digitalization maintaining the people-process-technology triad as a foundation. The philosophy behind Lean Construction 4.0 is human-centered rather than being technologically-centered. Both white- and blue-collar people drive the design and implementation of these technologies in any organization, making sure these technologies fit their needs and preserve their rights of performing their work freely, efficiently, and humanely.

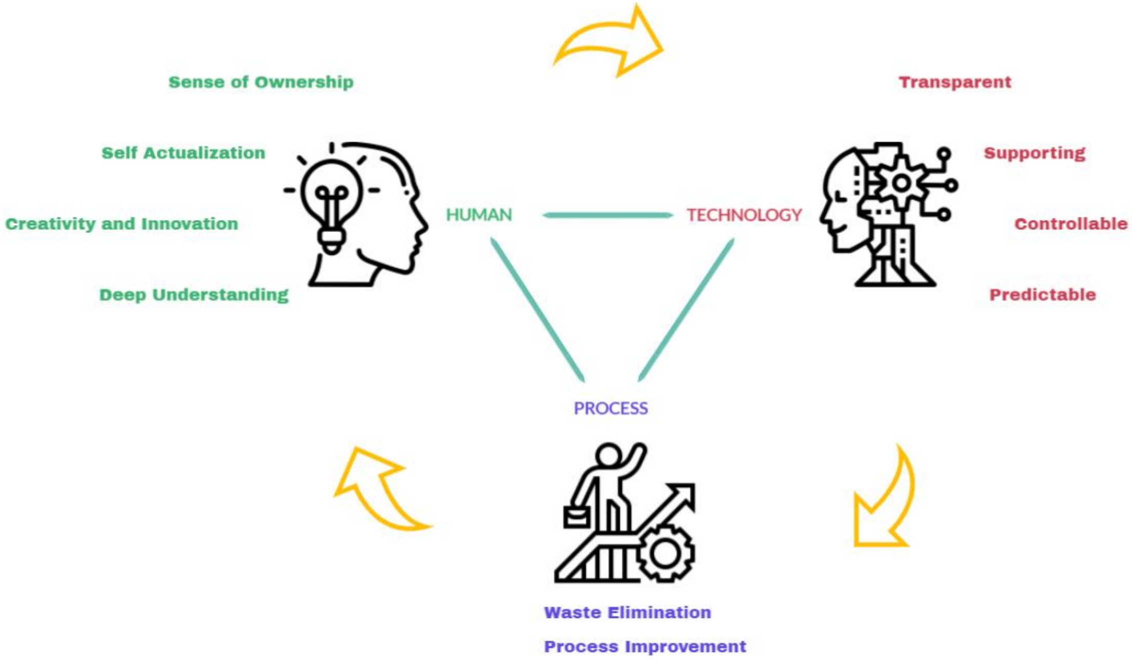

Figure 2: Human-centric Approach

"Industry 5.0", coined by the European Commission, is starting to gain momentum. This new industrial revolution is considered to be "value-driven" compared to the 4th industrial revolution which is technology-driven. Its core values center around human-centricity, sustainability, and resilience. The reason behind introducing a new industrial revolution is the assumption that I4.0 overlooks sustainability and social fairness, and focuses on digitalization for production improvement (Xu et al., 2021). Industry 5.0 is considered a shift in perspective, where the same technology used in I4.0 is now designed and used to serve people and societies meeting the needs of industry workers. Industry workers are considered "investments" rather than "costs". (Lu et al, 2021). Lean construction encircles similar principles and core values. Besides maximizing value and minimizing waste in production, Lean Construction puts people first and safeguards their autonomy and privacy. The Last Planner System (LPS) (Ballard, 2000) serves the best example of the beforementioned statement. With the goal of reducing variability and uncertainty in construction operations, successful implementation of LPS in any organization cannot happen without the embracement of "lean" philosophy by all stakeholders involved (Hamzeh, 2011). Liker (2004) emphasizes the importance of people and culture over technologies and methods in implementing any lean tool.Principle 8 in the Toyota way states that technology is to support people and not to replace them (Liker, 2004). This mindset brings to surface any hidden harm a technology can bring on both people and processes. It regulates current and future applications of any technology and preserves the human element. Therefore, it can be said that Lean Construction 4.0 is a masked expression of a newly announced industrial revolution 5.0 in the context of construction. They are similar means to the same end. The key is to believe in these values and transform them into actions.

CONCLUSION

The shift to digitalization promises a lot of benefits such as improvements in productivity, safety, quality, just to name a few. However, even if the benefits are actualized, the social impacts of Construction 4.0 technologies are overlooked in the pre-adoption and post-adoption phases of these technologies. Like fire, technology changed our lives, but a fire can cook your food or burn your home down. The light side of technology empowers practitioners and organizations, supports them, and helps them to thrive. However, unconscious consumption and disruption of such technologies may backfire and lead to permanent consequences that would degrades our industry further. The paper aimed to explore the literature on that subject, compare and analyze different findings, and reflect on the endeavors made to adopt C4.0 technologies. The paper also addressed artificial intelligence as a specific case. The findings showed that the industry's approach to adopt C4.0 technologies overlooks the social factor and social impacts of their adoption The paper projects reflections made as statements and questions to provoke questions and thoughts on this topic. Moreover, the paper highlights the need for a human-centric approach, such as Lean Construction 4.0, to preserve the social aspect amidst this revolution. With respect to the research limitations, the authors acknowledge that the study only covers a part of the body of knowledge found in the literature. Moreover, the research tackled AI as a specific case and can be extended to cover a wider range of technologies. This paper calls for future research to investigate the social impacts of the latest technologies in the construction industry. Also, research should be done to assess and compare frameworks and methodologies used to adopt different C4.0 technologies.

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CATEGORIZATION OF CONSTRUCTION TASKS FOR ROBOTICS USING LEAN VS VALUE-ADDED EFFECTIVENESS FRAMEWORK

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ABSTRACT

Robotics and automation are still considered a novelty in the U.S. construction industry, as compared to manufacturing, despite its proven advantages for production. Due to the continuing advancement of technology needed, there are limited applications of robotics in construction to date. To better identify the potential tasks that would benefit from the use of robotics on construction sites, we consider methods for assessing the craft labor tasks that occur in construction. In this paper, we decompose construction tasks of an observed activity of installation of stone veneer system and compared two systems of categorizing the construction tasks based on value added assessment and lean (waste) assessment of tasks. The analysis compares the two categorization systems using a matrix which highlights consistency in the alignment of value adding tasks, such as final placement, as well as ineffective tasks with type two muda, but discrepancies emerge regarding the idea of contributory tasks related to logistical support of construction activities. The focus of the discussion is derived from the intersection of contributory tasks with type one muda tasks. The contributory tasks offer an opportunity to reduce the use of craft labor for wasteful tasks elimination by leveraging automation and robotics.

KEYWORDS

Wastes, value, lean, construction tasks categorization.

INTRODUCTION

In the US construction industry adoption of robotics and automation has begun but is still in its infancy compared to Japan where the first construction robots appeared on sites in 1980s (Bock, 2007). With the current state of US construction industry's shortcomings in productivity, safety, and availability of labor, robots and automation offer at least a partial solution. The primary principle of adopting lean is to avoid and reduce waste and non-value adding activities. However, the nature of construction projects, with in situ work specific to the site of a given facility, creates challenges for

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ensuring efficient and value-added production to the extent seen in manufacturing contexts. With automation and robotics performing as the actors instead of human workforce in future, their deployment could be used to allow the craft labor to focus their efforts on the value-adding tasks for delivering a given project or could further hamper production and increase the waste if applied poorly.

Waste reduction has still not succeeded in the construction industry (Koskela & Bolviken, 2016). To effectively study the application of robotics for the purpose of reducing waste in craft labor tasks in construction, the tasks need to be decomposed in sufficient detail to assess the sub-tasks for a given construction activity for the level robots would contribute. Wastes could also be classified into seven types, compiled by Ohno and Bodek (1988) and Lai et al. (2019) and the type of Muda (Womack & Jones, 1996).

In this paper we utilize two existing methods of classifying the construction sub-tasks. The first was value added assessment of construction tasks, introduced by Pregenzer et al. (1999) to build upon the classical productivity research emerging from the construction domain. The second categorizes them by the commonly used seven types of wastes, as well as including recognition of value-adding tasks. A time study of installation of stone veneer as part of façade system of a construction project was conducted. After defining the decomposition using the two classifications, they are cross compared using a matrix framework to highlight discrepancies in how tasks are categorized under the parallel systems in pursuit of a framework for identifying tasks appropriate for leveraging robotics and automation.

LITERATURE REVIEW

The construction industry, with its inherited characteristics or peculiarities of site production, temporary organization, and bespoke designs (Vrijhoef & Koskela, 2005) is slow to adopt technology, traditionally unsafe and known for its low productivity and quality challenges. The nature of in situ construction industry requires balancing logistical support to bring all materials, labor, and equipment to a project with the effort to perform on the on-site work efficiently. A per Chang et al. (2004) the nature of construction industry resembles a unit production system dependent still mostly on jobsite activities with small batches of production and inherent with uniqueness of its projects due to varying needs and requirements of owners and designers. Research has pointed to numerous solutions like computer integrated construction, off-site and modular construction, automation and robotics, immersive technologies, and lean construction to overcome these problems.

Automated systems in the Japanese construction industry have increased the productivity, operator safety and work quality (Taylor et al., 2003). In construction, automation and robotics can be helpful in improving the quality of work thus adding value and reducing the wastes. Llale et al. (2019) conducted a more recent review of the advantages and disadvantages of the use of automation and robotics for the South African construction industry which revealed the potential of increased safety, productivity, and sustainability. However, the prioritization of tasks specific to site construction has not yet been identified.

Lean construction is formulated on the principles of lean production based upon the realization of the shortcomings of traditional project management (Ballard et al. 2007). Lean principles that were developed for the manufacturing industry have been adopted for the construction industry. As per literature review by Babalola et al. (2019) the predominant purpose of lean methods is to utilize minimum resources and efforts to attain maximum benefits and value for the customer. Lean Construction generates the product by maximizing value and minimizing waste while considering the construction project as a temporary production system (Ballard & Howell, 2003). Waste reduction is the core emphasis of lean. Within that approach, waste is defined as anything that does not add value. As per Porter (1985), "Value is what buyers are willing to pay" and as per Bolviken et al. (2014), "value is the wanted output, the usefulness of the product, functionality, utility and benefit and it is for the customer or client." Waste reduction and value generation are closely but inversely related. Identifying the wastes and then decreasing or removing them would be tantamount to adding value in a construction project. In construction there is a significant amount of waste that stays hidden, unworkable and is caused by rework or non-value adding activities, such as waiting, moving, accidents and repeated activities (Koskela, 1992).

TASK CATEGORIZATION AS PER SEVEN TYPES OF WASTES

Compiled definitions of the seven types of waste in lean manufacturing is shown in Table 1 based upon Ohno and Bodek (1988) and Lai et al. (2019). Construction sub-tasks could be categorized into the types of waste using this classification. The characterization of wastes supports concept within continuous improvement, it offers a lens for identifying tasks that can be adjusted or removed to improve the value-adding emphasis of production steps.

Table 1: Seven types of Wastes, based upon Ohno and Bodek (1988) and Lai et al. (2019)

Waste	Summarized Definitions
Over-production	Producing too much/ when not needed / without actual orders
Waiting	Waste of time or delays, idling or unable to process due to unforeseen reasons
Transportation	Waste of movement of material or product unessential to the production process
Over-processing	Unnecessary steps taken to produce the product, produce anything that is not valued / required nu customer
Inventory	Waste due to excess work in progress (WIP) / stocks / materials finish or unfinished
Unnecessary motion	Waste due to movements that do not add value to the product
Defects	Waste from making products that is defective, unacceptable quality or require corrective rework to be accepted by customer

TASK CATEGORIZATION AS PER LEAN ASSESSMENT

Womack and Jones (1996) provided a different perspective to study the value stream by decomposing the value stream into different actions (tasks) and segregating them in value adding or muda. Muda is the Japanese word for wastefulness. Within this classification there are three categories; (1) Value adding – which create value as required by the customer; (2) Type One Muda – which are steps that do not create value but are required for the process and cannot be excluded; and (3) Type Two Muda – which do not create value as required by the customer ad can be directly removed.

TASK CATEGORIZATION USING VALUE ADDED ASSESSMENT

Building upon traditional construction categorization, this method defined by Pregenzer et al. (1999) of classifying construction activities leverages the previous works of Thomas (1983) and Oglesby et al. (1989) by introducing contributory and ineffective tasks. The resulting value-added effectiveness framework (VAEF) contains a set of nine rules, demonstrated in Figure 1. The VAEF can be used to assist in identification of value adding, contributory and ineffective tasks. Tasks that do not qualify for the specific decision node keep going down the chain and settle at the bottom in the category of ineffective tasks.

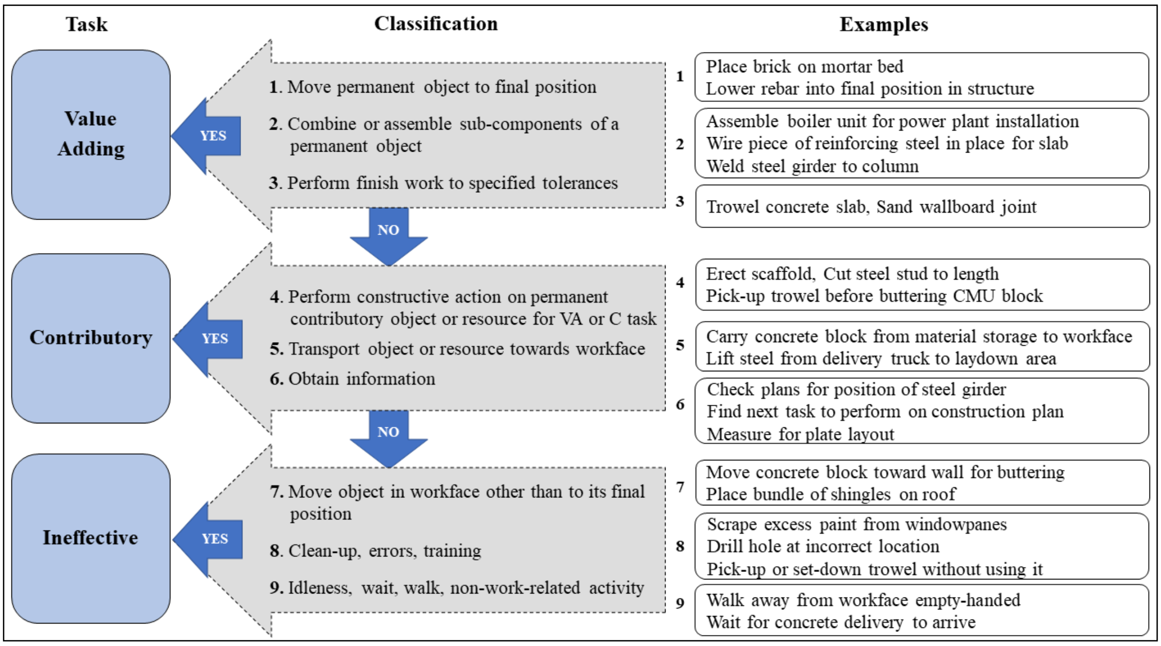

Figure 1: VAEF Flow Chart for Nine Decision Nodes (from Pregenzer et al. 1999)

METHODOLOGY

TEST CASE

To compare the application of these alternative classification systems to construction tasks, a test case was performed for the installation of a stone veneer system as part of the façade works at a residential building project. The author used a handheld video recorder to observe and record video of the workers installing stone veneer system on a local project. A subset of the recording and resulting analysis are presented using 10 minutes and 22 seconds (622 seconds) of the observed work. The limitation with the data set is the small sample size of analyzed data; 4 minutes and 23 seconds (263 seconds) for first worker and 5 minutes and 39 second (339 seconds) for the second worker. Some data is labeled as "out of view" because of the inability to capture both workers simultaneously in the video recording frame due to the distance between the workers. While the author is aware of the general tasks being performed, the classification was limited to the observed video data. For calculation purposes, the out of view portions for both workers were neglected from data sets to be consistent in our approach. While the sample is small, the purpose is not to develop a rigorous analysis of the production process, but to discuss test and compare the systems of time classification. The first worker was working at the ground level and performing sub-tasks of picking and cutting stone, checking placement of stone on wall, applying mortar to the stone, attaching the stone veneer to the wall and necessary movements in between. The second worker was working in a scissor lift at a raised elevation to prepare the mortar scratch coat for the future installation of stone. Each sub-task was decomposed into the lowest level of craft labor activity, with durations of movement down to a two-seconds duration for a partial activity of a worker to split apart their movement, cutting, and transportation sub-tasks for a given installation sequence.

All sub-tasks were categorized using both classification systems i.e., using VAEF for value-added assessment (VA - value adding tasks, C - contributory tasks and I - ineffective tasks), the seven types of waste and the type of action (lean assessment). The percentages of time spent by each worker for value added assessment tasks (value adding, contributory, and ineffective) and lean assessment of tasks (value adding, type one muda, and type two muda) were also calculated.

RESULTS

Data was time-coded from the videotape for both workers and decomposed into sub-tasks as shown in Table 2 and Table 3.

Table 2: Task Categorization and Assessment for Worker 1

Time (mm:ss)	Sub-tasks	Time (secs)	VAEF	Type of Waste	Muda
00:00 - 01:02	Out of view	62	-	-	-
01:02 - 01:07	Scrape off excess mortar from stone	5	VA	Over-production	One
01:07 - 01:14	Move for stone pickup	7	I	Transportation	One
01:14 - 01:26	Pick up stone & cut	12	C	VA	VA
01:26 - 01:38	Apply mortar to stone	12	VA	Over-processing	One
01:38 - 01:40	Move to wall to attach stone	2	C	Transportation	One
01:40 - 01:57	Attach stone to wall	17	VA	VA	VA
01:57 - 01:59	Pickup stone & move to mortar location	2	C	Transportation	One
01:59 - 02:08	Apply mortar to stone	9	VA	Over-processing	One
02:08 - 02:11	Move to wall to attach stone	3	C	Transportation	One
02:11 - 02:28	Attach stone to wall	17	VA	VA	VA
02:28 - 02:35	Scrape off excess mortar from stone	7	VA	Over production	One
02:35 - 02:50	Pick & check stone placement on wall	15	C	Over-processing	Two
02:50 - 03:04	Cut stone	14	C	VA	VA
03:04 - 03:10	Check stone placement on wall (rework)	6	I	Over-processing	Two
03:10 - 03:15	Cut stone (rework)	5	I	Over-processing	Two
03:15 - 03:20	Check stone placement on wall (rework)	5	I	Over-processing	Two
03:20 - 03:27	Cut stone (rework)	7	I	Over-processing	Two
03:27 - 03:34	Check stone placement on wall (rework)	7	I	Over-processing	Two
03:34 - 03:48	Cut stone (rework)	14	I	Over-processing	Two

03:48 - 03:52	Check stone placement on wall (rework)	4	I	Over-processing	Two
03:52 - 03:55	Cut stone (rework)	3	I	Over-processing	Two
03:55 - 04:02	Check stone placement on wall (rework)	7	I	Over-processing	Two
04:02 - 04:12	Cut stone (rework)	10	I	Over-processing	Two
04:12 - 05:58	Out of view	106	-	-	-
05:58 - 06:12	Check stone placement on wall	14	C	Over-processing	Two
06:12 - 07:04	Out of view	52	-	-	-
07:04 - 07:09	Check stone placement on wall	5	C	Over-processing	Two
07:09 - 07:13	Cut stone	4	C	VA	VA
07:13 - 07:21	Check stone placement on wall (rework)	8	I	Over-processing	Two
07:21 - 07:30	Cut stone (rework)	9	I	Over-processing	Two
07:30 - 07:38	Check stone placement on wall (rework)	8	I	Over-processing	Two
07:38 - 07:51	Cut stone (rework)	13	I	Over-processing	Two
07:51 - 07:54	Check stone placement on wall (rework)	3	I	Over-processing	Two
07:54 - 08:15	Out of view	21	-	-	-
08:15 - 08:24	Cut stone	9	C	VA	VA
08:24 - 10:22	Out of view	118	-	-	-

Note: Type One and Type Two are Muda; VA = Value Adding; C = Contributory; I = Ineffective.

The craft worker was working to install stone veneer, with their time spent cutting the stone to size, checking the fit into the desired location, then applying mortar and placing the stone. Using the VAEF classification, 67 seconds (25%) of the worker's time was considered value adding, 80 seconds (30%) were contributory, and the remaining 116 seconds (44%) were ineffective. However, when using the lean approach to identifying waste, 28% was value-adding; 18% of tasks were type one muda that was spent mostly in the application and removal of excess mortar, as well as some time in the transport task of the stones. Approximately 54% of tasks were type two muda with most of that time being over-processing or re-work for correcting the dimensional cutting of stone that did not fit in the first attempt.

The second worker was working on a scissor lift to prepare the surface material for the future installation of the stone veneer. Using the VAEF classification, 135 seconds (40%) of the workers time was considered value adding, 155 seconds (46%) were contributory, and the remaining 49 seconds (14%) were ineffective. Using the lean approach to identifying waste, none of the task was value-adding; 86% were type one muda – primarily when the working was performing the 'scratch coat' task of using a brush to scratch the mortar that was already applied at the workface. This is a necessary step in the process of applying the stone for this specific process and material, but the task of manually scratching the entire preparatory surface is not specifically value-adding for the final product; and 14% were type two muda when the worker appeared to be 'wandering around' the site for a period.

Table 3: Task Categorization and Assessment for Worker 2

Time (mm:ss)	Sub-tasks	Time (secs)	VAEF	Type of Waste	Muda
00:00 - 00:50	Apply mortar scratch coat	50	VA	Over-processing	One
00:50 - 02:17	Out of view	87	-	-	-
02:17 - 02:40	Apply mortar scratch coat	23	VA	Over-processing	One
02:40 - 02:52	Move scaffold up	12	C	Transportation	One
02:52 - 03:06	Apply mortar scratch coat	14	VA	Over-processing	One
03:06 -03:15	Move scaffold up	9	C	Transportation	One
03:15 - 03:54	Apply mortar scratch coat	39	VA	Over-processing	One
03:54 - 04:03	Move scaffold up	9	C	Transportation	One
04:03 - 04:12	Apply mortar scratch coat	9	VA	Over-processing	One
04:12 - 06:44	Out of view	152	-	-	-
06:44 -07:33	Unnecessary walk	49	I	Unnecessary Motion	Two
07:33 - 07:54	Out of view	21	-	-	-
07:54 - 08:04	Climb on scissor lift	10	C	Over-processing	One
08:04 - 08:27	Out of view	23	-	-	-
08:27 - 10:22	Move scissor lift and set up	115	C	Transportation	One

Note: Type One and Type Two are Muda; VA = Value Adding; C = Contributory; I = Ineffective

DISCUSSION

When comparing the tasks, categories were plotted, as shown in Figure 2, to highlight the differences in categorization between the two frameworks for assessing the craft worker time.

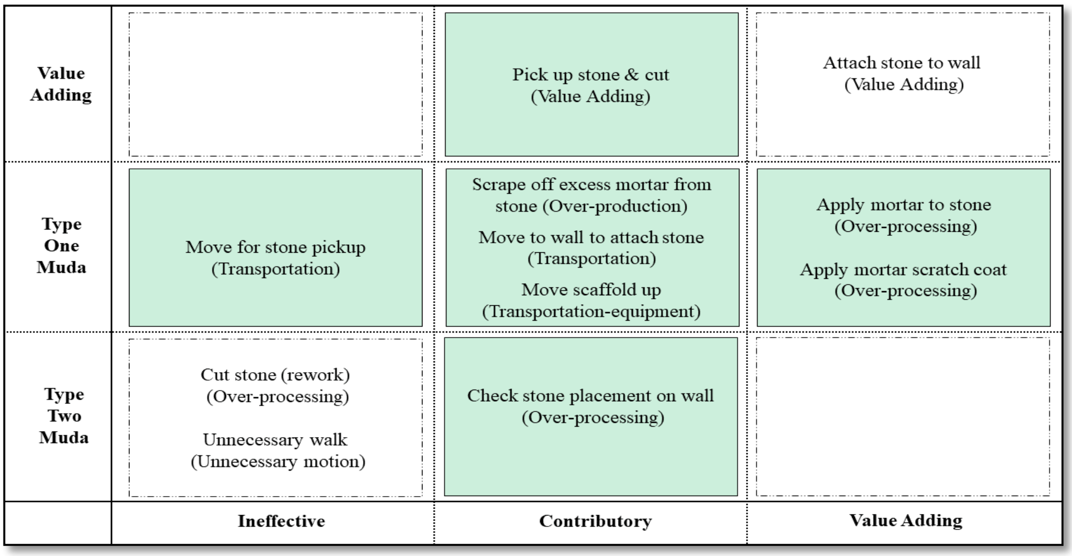

Figure 2: Matrix for comparing Task Categorization and Assessment

The horizontal axis is based upon Pregenzer et al. (1999), with ineffective tasks on the left and moving to the value-adding tasks on the right. The vertical axis is based upon the lean categories, starting with type two muda at the bottom, type one muda in the middle, and value adding at the top. When cross comparing, some of the tasks are closely aligned – ineffective tasks and type two muda generally match up quite consistently (bottom left): when the worker is walking without purpose, it is both ineffective and meets the type two waste classification. Similarly, but at the opposite end of the scale, the value-adding tasks related to the final placement of materials generally align (top right). The placement of work provides value in both classification systems. Further, there are two areas do not have any tasks. None of the Value adding tasks, per the lean categorization, matched the ineffective categorization in the VAEF framework (top left). Similarly, none of the type two muda matched the value adding category of the VAEF framework (bottom right).

However, when specifically focusing on tasks that may offer some discrepancy between the two classifications, the first areas to highlight are those noted in the VAEF framework as contributory tasks that address some of the necessary logistical tasks of supporting construction work that do not directly contribute to the value of the finished product. Within the lean framework, tasks add value or do not add value (waste). This middle column of tasks has elements that were categorized into each of the lean categories. For example. when the worker is checking stone placement on the wall prior to cutting and applying mortar it is considered type two muda as it is not creating any value and could arguably be eliminated if the stones were already pre-cut to correct sizes, but contributory because the worker needs to check the size of stone to assess how much stone cutting is required. It is also considered over-processing as per the type of waste.

Scraping off excess mortar falls in the category of type one muda and contributory. It is a required step arising out of the use of mortar as the binding material but does not creating value rather is considered over-production, but due to the nature of the use of mortar as a material is nearly impossible to remove in its entirety. Similarly, to perform work at a higher elevation, the worker needs to move the scissor lift to accommodate the location of the scratch mortar work at elevation, which is a required step but does not add value to the final product, so it is considered waste. Picking stone and cutting fits in the category of value adding as per lean assessment of tasks because it adds value to the final product but is contributory because it is a constructive action on a permanent object.

In addition to challenges in the cross-comparison, there were areas that were difficult to group properly as per classification – for example, the value-added assessment has explicit categorizations (per Figure 1) for tasks like cutting; but the scratch coat task is not an explicit example and appear to fall between their third and fourth decision nodes of the flowchart. It is not explicitly ‘finish work’ from a finished-product perspective, suggesting it is contributory, however it is part of the finished system – suggesting it may be value-adding by their criteria. This also poses a potential research limitation in the ability to consistently categorize tasks that may not match the definitions provided.

Within the lean analysis, there was similar difficulty in trying to determine how much movement was ‘value-adding’ vs wasteful when the worker was moving stone to its final location. Arguably, if the stockpile is closer to the workface, there is less wasted movement by the worker in selecting and placing the stone. However, there is value in having the stone moved to its final location for the ultimate customer. Similarly, when the worker moves to pick stone there is ‘some’ level of necessary movement to move to pick up a stone, but there is some unnecessary movement that ties back to where the stone is placed. This highlights one of the challenges of using the lean waste structure to the logistical aspects of task assessment in construction. In the ideal of single-piece flow, each stone would be placed immediately upon arrival at the site – however the logistics of delivering smaller materials in this manner could become cost-prohibitive and would introduce waste in the transport. Thus, construction’s distinction from manufacturing as site-specific must consider how to address the ‘contributory’ nature of the logistical tasks as necessary and value-adding in the importance of the location of the project to the client. However, this contributory value must be balanced with the potential waste introduced from excess inventory on site, as well as poorly located materials, that created added movement, over-processing, and potential damage to stored materials among many other potential areas of lost value defined by the seven types used.

Returning to the second reason for this analysis is the opportunity of how to reduce the inherent wastes through the consideration of automation and robotics. To analyze this aspect, we updated the matrix by plotting the time and percentage of all intersections for both workers as shown in Figure 3.

Value Adding	0	Worker 1 – 39 Secs (14.8%) Worker 2 – 0 Secs	Worker 1 – 34 Secs (14%) Worker 2 – 0 Secs
Type One Muda	Worker 1 – 7 Secs (2.6%) Worker 2 – 0 Secs	Worker 1 – 7 Secs (2.6%) Worker 2 – 155 Secs (46%)	Worker 1 – 33 Secs (12.5%) Worker 2 – 135 Secs (39.8%)
Type Two Muda	Worker 1 – 109 Secs (41%) Worker 2 – 49 Secs (14.5%)	Worker 1 – 34 Secs (13%) Worker 2 – 0 Secs	0
	Ineffective	**Contributory**	**Value Adding**

Figure 3: Task Categorization and Assessment for Worker 1 and Worker 2

First, the tasks that occur at the intersection of the ineffective and type two muda like unnecessary walking and rework for unprecise stone cutting should be removed which is the core emphasis of lean. Also, the high value tasks that address the unique attributes of construction projects at the intersection of the value-adding categorizations like attaching stone to wall should likely be prioritized for continued craft involvement.

Analyzing worker 1, we can see that the tasks at the intersection of contributory and type one muda totals 45%, which is a considerable amount of time when the worker is not performing value-adding tasks. Similarly analyzing worker 2, we find that tasks at the intersection of contributory and type one muda total about 85% which is a high amount of waste. This could also be helped using automation and robotics and benefit in savings in terms of labor costs. In the tradition of robotic adoption, transport of materials between workstations in manufacturing were one of the earliest uses. With the forecasted shortfall of skilled workers, finding a scheme for appropriate uses of robots on construction sites will become an urgent need to balance human-robot construction crews. Labor intensive and repetitive but low-value tasks, such as the step of performing the scratch coat, serves as example opportunity where the task is necessary for the specific system but offers limited value-add to the overall facility. Further, other opportunities for identifying tasks to de-prioritize for craft, such as methods that leads to repetitive stress injuries in workers, should also be considered.

The contributory tasks under the VAEF framework seem to offer a valuable lens for tasks that could reduce the logistical burden and repetitive tasks, such as material movement, that robots could support. However, there are several areas that were considered waste by use of the lean categorization that should be removed, rather than transferring to a robot to perform, there is a potential challenge of creating more waste if robots are added but not thoughtfully planned. Similarly, there were some tasks, such as the scratch coat tasks, that were arguably 'value adding' that might be better suited for application of robotics due to the lower value in the use of craft labor and potential negative impacts on the worker health – such as repetitive stress injuries. These tasks appear to offer increased effectiveness for the craft labor time, for example robots could be better positioned to provide 'just-in-time' material to workers that would reduce site congestion as well as excess transport and movement tasks by workers or congested inventory. There is potential waste in tasks at the intersection of contributory and type one muda (45% for worker 1 and 85% for worker 2) which is hard to remove due to the nature of the tasks but could potentially reduce the cost to projects or mitigate worker shortfalls through the implementation of automation and robotics.

CONCLUSIONS

In this paper an effort was undertaken to highlight the shortcomings of construction task assessment using value added assessment (VAEF), as well as the seven types of wastes for an observed stone veneer installation activity for consideration of construction robotics. The shortcomings are mostly due to the nature of construction industry with numerous contributory tasks that span the types of waste as per lean assessment of tasks. The correct identification and categorization of construction tasks as per the assessment systems is challenging with identified discrepancies between the two types of assessment primarily related to logistical tasks necessary at construction sites. Applying the core principle of lean to eliminate the type two muda and ineffective tasks shown in the bottom row of the matrix and letting the value adding tasks in the top row of the matrix being performed by the human craft, there still exists significant waste at the intersection of contributory and type one muda tasks. This waste demands removal too and potentially could be achieved by utilizing automation and robotics to tackle these tasks which are repetitive and add very little value

In this paper some inherent wastes lying at the intersection of contributory and type one muda tasks have been highlighted and one of the potential solutions to use automation and robotics suggested. Future work will focus on more details about how these contributory and type one muda tasks could be eliminated by analyzing multiple solutions like prefabrication, modularization and introducing robotics and automation.

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CBA AS A DIFFERENTIATOR TO WIN PROJECTS IN PURSUIT: A CASE STUDY

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ABSTRACT

This paper presents a case study where a Design and Construction project team, general contractor and architect were asked to use Choosing By Advantages (CBA) during the pursuit phase of the project. The paper describes how the design and construction project team implemented CBA throughout the project pursuit, including details surrounding the team's preparation and decisions developed during confidential conversations with the Owner. Ultimately the team implemented CBA when selecting the structural system, external facade, and the project programming. The researchers integrated the Owner's perspective to understand the motive(s) to utilize the CBA decision making method, why they chose the winning team, and the ways CBA methodologies were implemented beyond the project pursuit phase. This paper presents unique viewpoints, from both the project team and Owner's, on the benefits of using CBA during project pursuit and beyond. The aim of sharing this case study is to inspire more owners to request the use of the CBA method at the start of the project. Choosing By Advantages simplifies the internal decision-making process, which many team find as a challenge. CBA allows for project teams to approach owners with a decision-making process that allows for optimal owner feedback leading to productivity and clarity within the phases of the project.

KEYWORDS

Choosing by advantages, pursuit, collaboration, decision-making

INTRODUCTION

Owners appreciate a Design and Construction team that assists them with decision making. Traditionally teams struggle to make decisions together and projects are often delayed due to the lack of clarity on how to move forward (Arroyo & Long, 2018). This paper describes the UC Davis Project pursuit process that set a new standard, in terms of, how to choose a project team based on their capacity to lead collaborative decision-making efforts. The research is written from the perspective of the winning teams, DPR Construction and Smith Group and how they succeeded in demonstrating their ability to identify and drive decisions by implementing the Choosing By Advantages (CBA) method starting early on in pursuit. This research focuses on answering two questions from the design and construction team's perspective: How can CBA be implemented during the pursuit phase? What benefits and challenges did this approach present for the pursuing team?

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The Owner's perspective is also included in the research to compliment the findings and to provide clarity surrounding the Owner's motives for requesting CBA during pursuit. The research's primary focus here is to answer the question: What is the value (from the owner's perspective) of requesting the use of CBA during pursuit?

Few owners have publicly embraced the use of CBA and even fewer have published a case study or academic paper about the use of this decision-making method. UCSF has published the potential use of CBA for tender procedure (Schöttle and Arroyo, 2016; and Schöttle et al.2017). Schöttle et al. (2018) and Arroyo et al. (2019) also presented an example of the use of CBA by Highway England Projects, as another example of owners implementing CBA as part of their internal process. This paper contributes to the existing literature by providing a case study on how CBA was successfully implemented during pursuit by the winning team, what lessons were learned, the owner's viewpoint on the benefits of CBA and how the use of CBA aided in their selection of the winning team.

CBA Tabular Method

CBA is a multi-criterion decision-making method developed by Jim Suhr (1999). CBA allow teams to differentiate between alternatives based on the importance of the advantages among the alternatives evaluated. The CBA decision-making method provides a structured and transparent way to make decisions. CBA uses a defined vocabulary so that a group can formulate and discuss based on a share understanding (Schöttle & Arroyo, 2017; Schöttle, Christensen, & Arroyo, 2019). The common method is the CBA Tabular Method. According to Arroyo (2014), CBA is the best multi-criteria decision-making method compared to traditional Weighting Rating Calculating (WRC), AHP, and linear optimization methods, when it comes to 1) providing transparency by creating a shared rationale for the decision and differentiating 'value" from cost 2) building consensus, with focus on optimizing the whole and not just the pieces and avoiding unnecessary conflicts. 3) continuous learning, this method helps document decisions in a way that is transparent and can guide future iterations as more information is gathered.

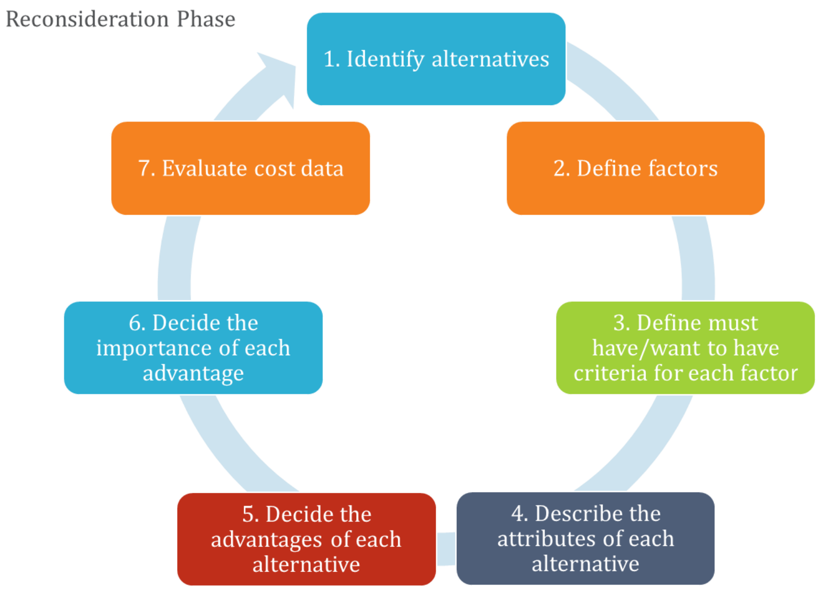

Figure 1: CBA Tabular method (Arroyo, 2014)

RESEARCH QUESTIONS AND METHODS

The research questions from the proposing team's perspective are:

1. How can CBA be implemented during pursuit?
2. What benefits and challenges did the pursuing team face when implementing the CBA approach?

From the Owner's perspective the research question is:

3. What is the value of requesting the use of CBA during pursuit?

To answer question (#1) "How" this paper uses a case study methodology (Yin 2019) to describe the process of winning a pursuit proposal based on a specific owner request (UC Davis) and is centred on showing how the team guides decision making with CBA. In addition, this study utilizes action research (Dikens and Watkins 1999). The first author taught the pursuing team CBA basics and provided feedback. The last author was of the pursuit team. The two additional authors were not directly involved in the project, but helped mitigate potential biases by the two authors involved in the case. The research describes the initial owner request and the process of developing the presentations that allied the team (DPR Construction and Smith Group) to win the project.

To answer question (#2) "What" from the proposing team's perspective, the researchers did a focus group with project participants and directly asked about benefits and challenges. The paper describes lessons learned and insights from the winning project team members. To answer question (#3) "What" from the Owner's perspective the authors reached out to the Owner via e-mail. Researchers asked about the owner's motivations to request CBA in the proposal, why they selected the winning team and how they plan to keep applying CBA to the project. Two owners responded to our questions via email. Finally, researchers talked to the project team to validate the accuracy of the project's story.

CASE STUDY

This section presents the project background, the design and construction team's approach to implement CBA, the design alternatives that were presented in the pursuit meetings with the owner, and the Owner's perspectives

THE OWNER'S REQUEST FOR PROPOSAL

The request for proposal was developed by the University of California Davis Health (UCDH)team and encompassed the design and construction of the Sacramento Ambulatory Surgery Center project. Part of the proposal's development was overcoming the challenge of identifying the scope and program of the building. The team was given little background information, including site location and size, to use in the development of the proposal's foundation.

In this case the owner decided to split the interview process into 2 confidential meetings and a final presentation. Confidential Meeting #1 (90 min) - Prepare a draft CBA presentation where your team outlines 3 key drivers that impact the SASC (Sacramento Ambulatory Surgery Center) project. Identify alternatives, define factors, describe attributes, and decide advantages and importance for each of the 3 drivers, along with the impact on schedule and cost. In addition, they requested a presentation of the team structure for the project and team dynamics to collaborate in the process. Confidential meeting #2 (60 min) - Present your final CBA presentation, be prepared to discuss your collaborative approach to the project with program validation and limited user engagement. Final Presentation (60 min)- Wow the selection committee. Show us what differentiates your progressive design-build team from others.

TEAM PREPARATION

The team consisted of Design and Construction experts. The challenge was to consolidate the huge amount of information and many of the questions the team had to get answered to develop a design and construction proposal.

The team had different levels of expertise and experience with CBA (some had previous training), so the team leadership decided to have an inclusive introduction to CBA for the Designers and Construction team together. After the team became familiar with CBA key words, definitions and process, main drivers for decision making emerged. The word "drivers" was confusing for the team because is not part of the standard CBA vocabulary. The team then decided to focus on 3 decisions (Figure 2):

- CBA #1 - What is the optimal Structural System?
- CBA #2 - What is the optimal primary Exterior Façade system?
- CBA #3 - What is the optimal program deployment?

The team decided to create a visual representation of CBA to present to the owners.

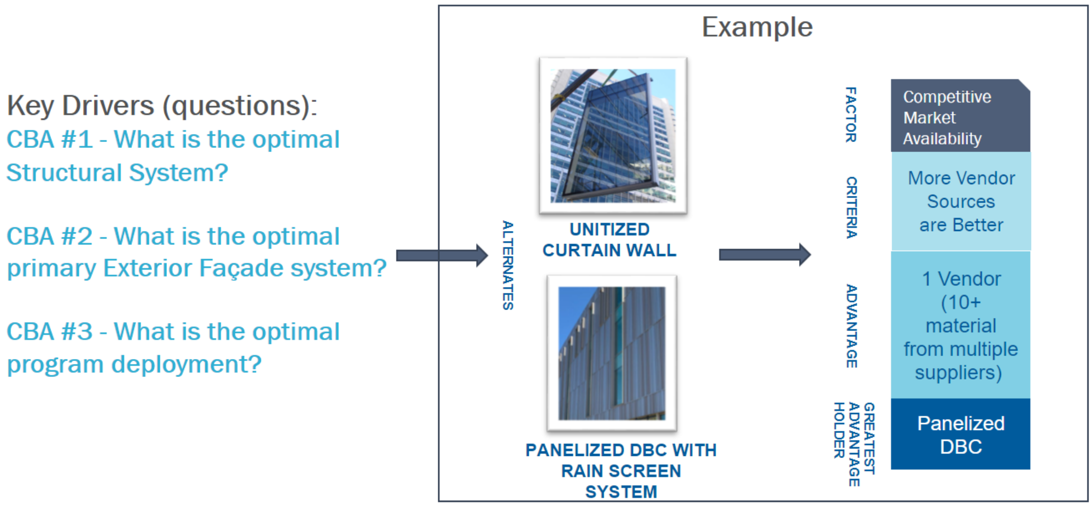

Figure 2: Decisions and example of CBA visualization.

The Owner's challenge making decisions forced the team to define these 3-pointed questions, requiring answers, to start the design process. Experts were assigned to collaboratively answer, develop initial factors, criteria, attributes and advantages to all 3 questions, which resulted in decisions being made. The team decided not to attempt to decide the Importance of Advantages (IofAs) since that would have required owner and user inputs. In addition to the team providing clarity on the decisions made and visual presentation, they also consistently practiced y how to communicate clearly.by defining the transitions between speakers for the owner meetings. This process also helped refine the decision, collect questions, and request for feedback from the owner's perspective. At the end the team wanted to develop a design attuned to the current owner's needs. The team also decided to present the decisions from simplest to hardest, mainly to avoid running out of time if discussions concerning more complex decisions extended over the allocated time.

STRUCTURAL SYSTEM DECISION

At the top of Figure 3 it shows the structural system alternatives and the main factors the team measured. Upon closer consideration, most of the factors did not differentiate the alternatives (i.e., no alternative had a big advantage), therefore the team was able to simplify the decision to only consider 4 differentiating factors and thus, focus on the relevant facts. The team knew that all structural systems being evaluated could achieve the desired building height, provide enough architectural flexibility and structural resiliency. They also have similar durability, requirements for on-site labor, permit risks, etc. The four factors that the team knew would really differentiate the structural alternatives were: 1. How the structure limits the initial plan layout. How much early the decision needs to be made. Availability of materials. 4. Future flexibility. Differentiating factors are shown with more contrast in Figure 3.

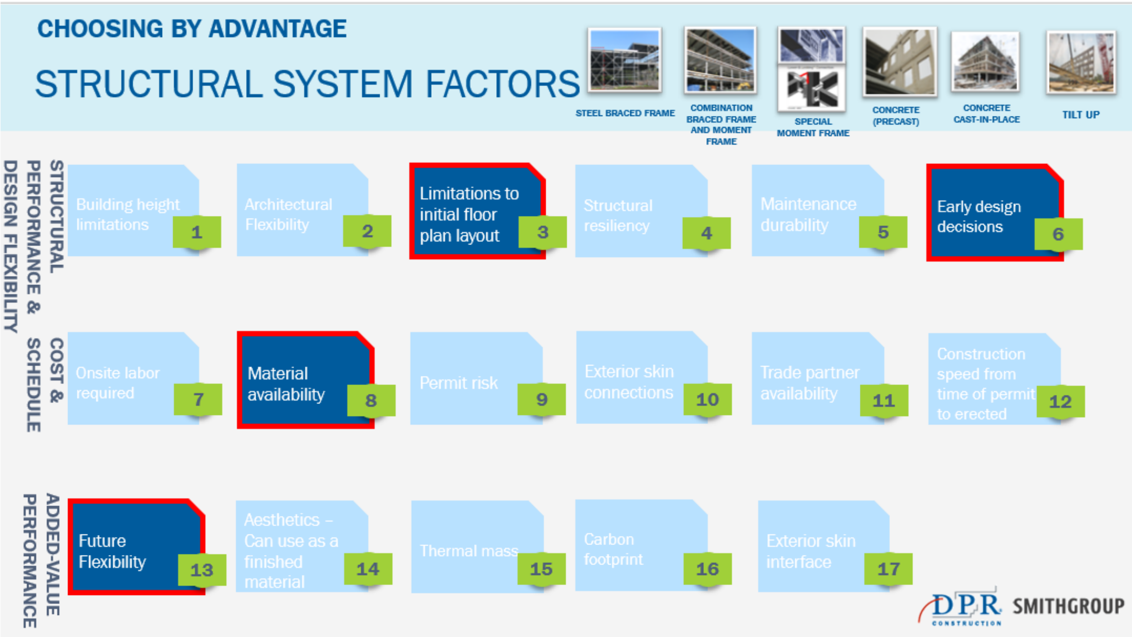

Figure 3: Structural Systems Factors.

Figure 4 shows how 2 of the 4 differentiating factors created a much greater advantage for the Special Moment Frame alternative. The team did not weigh the advantages since they were unaware of owner's preference at that point in time. Therefore they presented an initial visual assessment of the advantages.

This preliminary information was presented to the owner and the team requested further feedback:

- Is there an additional factor we should include in this decision that was not considered?
- Are there other structural system alternatives that the owner wishes to explore?
- Do our recommendations make sense?
- In addition to the advantages of a Special Moment Frame, the team also highlighted less installation time and the fact that this is probably the cheapest alternative.

As a result, it seemed that this could be an easy decision to make.

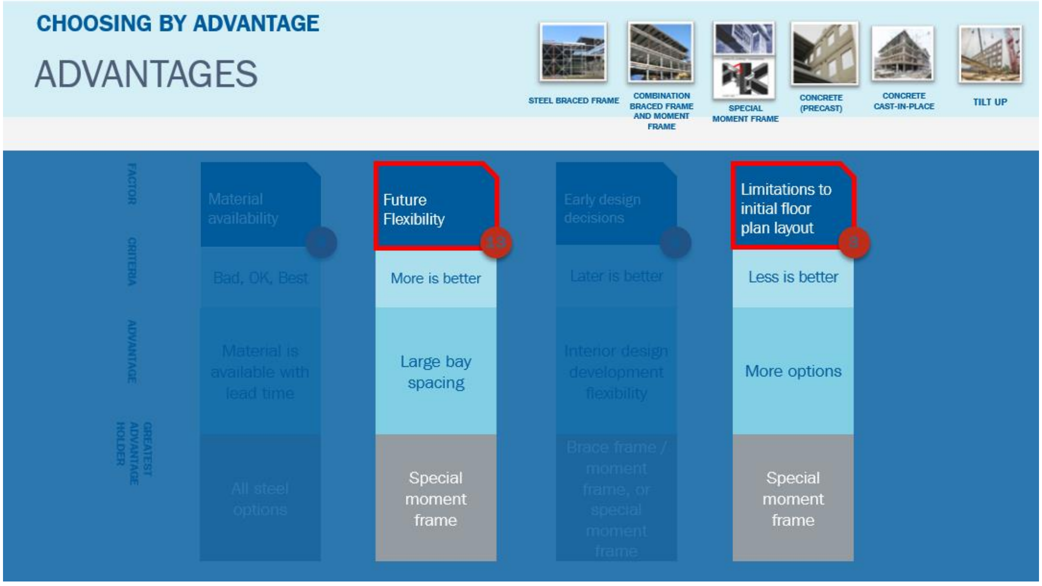

Figure 4: Special Moment Frame advantages.

EXTERIOR FAÇADE SYSTEM

The team followed the same structure for the exterior façade system decision. Figure 5 shows the final factors considered and a preliminary discussion on a recommended alternative.

Again, the team asked for feedback from the owner in efforts to understand what was important to them. During the interview the team learned that the advantage on campus continuity was very important for the owners. This helped the team identify an important advantage for the Pre-Cast C-CAP alternative, which is more consistent with the rest of the campus buildings. This alternative is the only alternative that allows for sharp angles that are valued by the owner. Therefore, the project team leaned towards this alternative even though it was more expensive than the other two alternatives.

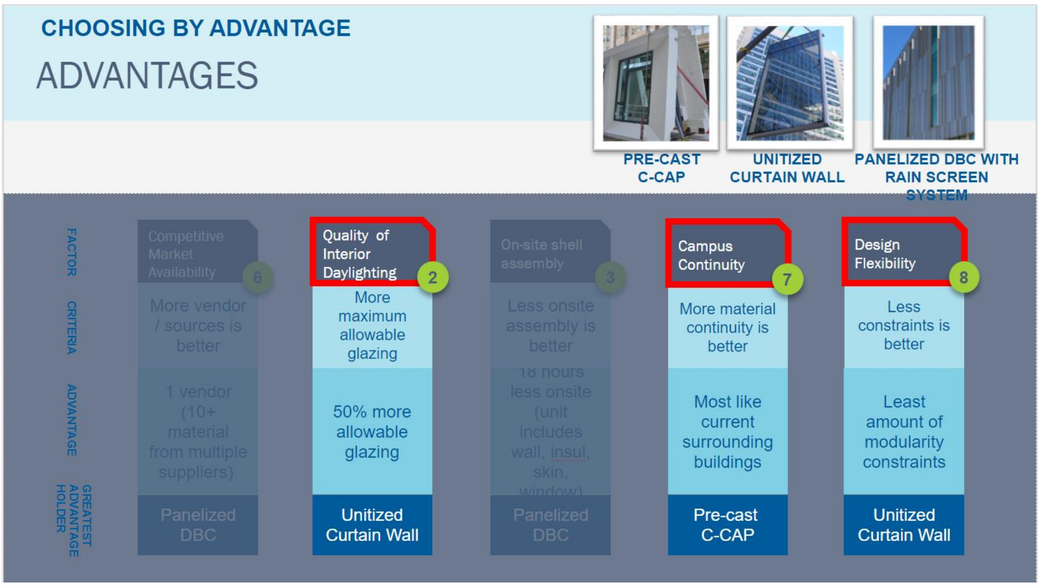

Figure 5: Exterior Façade systems advantages.

PROGRAM DEVELOPMENT ALTERNATIVES

Deciding on the program development alternatives was the most difficult decision to prepare, because there was much more uncertainty surrounding needs and preferences of owners and users. However, the team developed four high level design concepts that revealed important differences. This allowed the team to ask the owner for specific trade-offs that they needed to make. In this case, the design team decided to present factors and criteria first and then started asking for feedback (Figure 6). Finally, the designers developed 4 major concepts for the building footprint (Figure 7).

Figure 6: Program development factors.

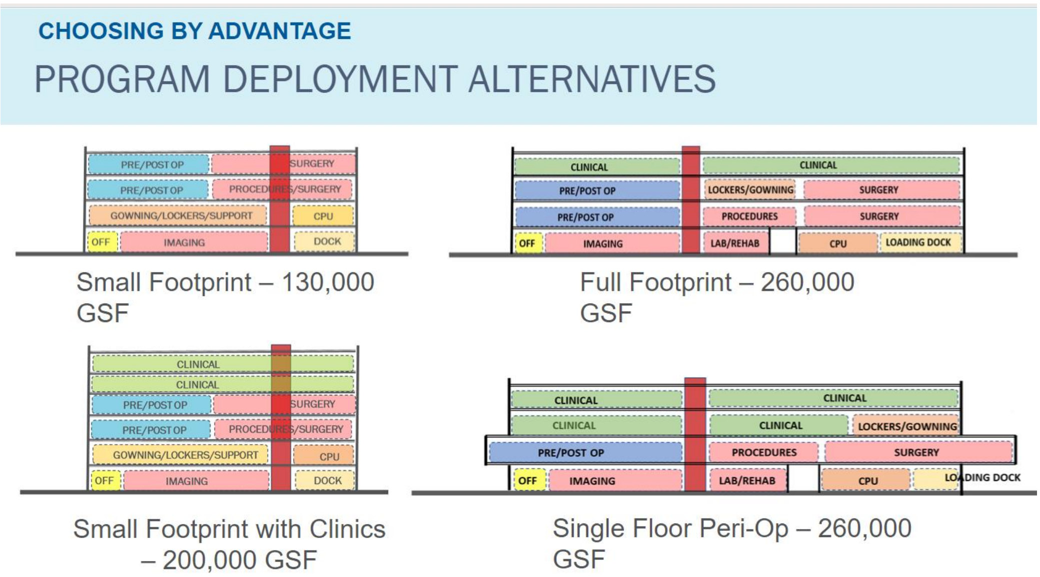

Figure 7: Program development alternatives.

Even though these designs were conceptual in nature they showed the know-how of the healthcare system since. All designs proposed to maximize separation of clinical space to increase clinical efficiency. The two designs on the left used smaller footprints and proposed the construction of a tower 4 to 6 floors depending on the owner's desire to provide clinical space. On the other hand, the two designs on the right used the full footprint available and achieved a higher GSF (260,000 SF / 24,155 m^2). However, the proposed distribution and building shape differed because the one shown on the bottom included more clinical space. After very quickly identifying the preliminary factors and creating 4 design alternatives the proposing team was able to have a rich conversation in both confidential meetings with the owner. This demonstrated the team's capacity to design, think innovatively, and be curious and relentless in testing assumptions.

OWNER'S PERSPECTIVE

The researchers posed 3 questions to the owners and received answers from two people - the Owner's Project Manager (UCDH Facilities Design and Construction) and the owner's representative (UCDH, California Tower Team). Their answers are presented in the text below:

- Why did you ask the teams to use the CBA method during the confidential meetings/interviews?

"On any complex project like the SASC, there are always many difficult decisions that need to be made in the course of planning and design to successfully optimize the project. CBA is a LEAN tool that not only assists with the decision-making process but also documents the process that leads to a particular decision. UCDH has had many successes in delivering projects with our design-build partners using LEAN methodologies including the use of CBAs. Because CBAs are so integral to the process, getting a glimpse into how each of the shortlisted teams for this project develop a CBA was deemed to be an important aspect in evaluating the prospective teams." - Owner's PM

"*Since the SASC is a complex, fast paced project that is being driven by tight logistics and a speed to market timeframe, the team wanted to challenge the proposers to use a tool that could assist in making smart decisions quickly. We wanted our failures to be fast and small! By asking the team to consider a CBA tool within the decision-making toolkit, we were looking to see how firms handled challenging questions and their thought process in (a) asking the right level of questions and (b) learning how the shortlisted firms came to the decision which appeared to have the greatest "advantage"*. - Owner's Rep.

- How did the other teams use the CBA method and did DPR – Smith Group's usage of these methods help them to be selected for the project?

"While many organizations use CBAs to help make and document decisions, methodologies can take on a range of flavors. The DPR/Smith Group team excelled at tailoring the level of detail to correspond with the planned time to discuss and to the audience. The DPR/Smith Group team prepared the work in advance, was able to synthesize and share that detailed work in a digestible way and was able to solicit feedback on the team assumptions without getting bogged down in all of the details. Other teams either struggled by either slogging through the details, not doing enough pre-work, or conversely, not demonstrating enough rigor in their approach." - Owner's PM

"Agree with (Owner's PM) on the summary regarding the other team approaches. As far as the DPR/SG methodology, it was very apparent that DPR/SG team prepared the work in advance, especially in their use of the Miro board. The ability of the team to highlight information needed from the client and use the client's assessment of the advantages along with their expertise is what set this team apart from the other participants."- Owner's Rep.

- How do you see the use of CBA influencing decision making within the UCDH organization?

"Perhaps the greatest value organizationally is assisting with various leadership teams with decisions that take into account priorities from a diverse group of stakeholders and competing interests, in prompting those conversations to take place, and to create transparency in the process." - Owner's PM

"*Use of facts, outside of opinions, to formulate a decision. CBAs don't just highlight the decision that is less costly, lesser impact and quicker on the schedule. They are a tool that*

can be utilized to look at all the options and to help the client make an informed decision."
- Owner's Rep.

DISCUSSION

The Request for Proposal requiring the team to explicitly use CBA was a first time for DPR Construction and Smith Group. This ask was both a challenge and a blessing. The owner requirement stating the need for CBA was something that the winning team celebrated and acknowledged as a great opportunity to work collaboratively with the owner and build a foundation of trust. According to the owner's responses, the DPR and Smith Group team was able to demonstrate the use of CBA in a visually appealing manner, presented relevant information and requested relevant feedback, which resulted in them winning the project. Per the Owners' responses, they were familiar with CBA before requesting the method. The DPR team was also familiar with CBA, as they have utilized CBA for a previous proposal with UCDH.

The project team is currently using CBA for design decisions. The information captured during the interview process helped them make decisions on the massing of the project. This has allowed them to move faster with the design, which is important due to the schedule constraints of the project. For the current decisions, the team has learned to reduce the number of factors typically from 15 to 3-4 factors by curating them, to make the decision making process more efficient. The team is learning to be more selective of the factors to be used depending on the type of alternatives and selecting the most applicable ones from a larger list of factors collected during project meetings with diverse stakeholders. In addition, keeping the project under cost is very important for the owner and that is considered when making decisions with CBA. However, the team doesn't always choose the cheapest alternative, as mentioned in the façade decision.

In addition, the team has learned to stop the process if a decision is obvious to maximize time. The CBA process has inspired the conversation with multiple stakeholders. The team has learned how to simplify the decisions, and the client's interest in the process has made applying CBA much easier. The team is also using a system for CBA and documenting the decision data with software. However, the software's generated A3 is not as comprehensive as the whole report. To maximize the visual effectiveness, the team needs to generate a clean overview in an A3 report, clearly depicting all advantages.

From the owners' responses we can state that they value the use of CBA based on their previous experiences dealing with complex decision making, as well as the current CBA use in this specific project. We can argue that the owners value a "smart and quick" decision process, the ability to separate cost and schedule from importance of advantages, and a transparent and inclusive decision-making process, which can be achieved using CBA. The owner also valued the proposing team's ability to ask questions requesting the right level of detail, at the right time. Owners wanted to see the thinking process of the team and their ability to synthesize complex ideas and show progress in an easily digestible way. Owners valued the proposing team asking for feedback and then used their expertise to facilitate the decision-making process.

CONCLUSION

This case demonstrates the value of having a clear expectation on how decisions will be made in the design and construction phases of a project. The winning team became more prepared to tackle the project after winning by having gathered feedback to allow them to make decisions. The project team has been able to make decisions transparently and collaboratively while maintaining the schedule and budget. The overall benefits of implementing the CBA approach will be clear by the end of the project. However, in early design the team has already learned how to implement CBA in a transparent way and made decisions together, beginning in the pursuit phase. The owner valued the decision-making process achieved with CBA, which allows them to make faster decisions, in a transparent manner, using the expertise of the whole team to understand the importance of advantages, and at the same time manage cost and schedule. Implementing CBA helped the owner and proposing team build a shared understanding beginning at pursuit.

ACKNOWLEDGMENTS

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BUILDING QUALITY BUILDERS: LESSONS LEARNED FROM SCALING A COMPANYWIDE TRAINING

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ABSTRACT

The fundamental purpose of this paper is to detail how a companywide educational training program has escalated in the USA and Europe in under 3 years' time. Details will include the many challenges faced throughout the process of developing the training structure and content, applying continuous improvement processes that are based off collaborative and integrated efforts, while simultaneously preparing new facilitators and maintaining program relevancy to the company culture and mission. The new virtual environment imposed by ever changing COVID-19 policies has created both challenges and innovative opportunities for the development of workplace training programs. The content of this paper builds on Arroyo and Gomez (2021) where the development of DPR Construction's Building Quality Builders (BQB) program was first explained and documented. The content of this document's focus will be aimed at voicing the escalating challenges, improved strategies, and trained facilitator perspectives that were utilized and shared to aid in the continued improvements of the Building Quality Builders training program. The depth of this research includes: the escalation process, communicating lessons learned within learning platforms, facilitator training, training impacts and ideas for improvement from the perspective of those who are performing the work.

KEYWORDS

Quality, Continuous Improvement.

INTRODUCTION & BACKGROUND

The struggle many organizations face with promoting change and building a culture of quality is no different. Developing training programs intended to provide employees with opportunities to learn new behaviors and new practices supporting a Quality Culture is important. However, the development is not enough to change the mindsets and actions if the training cannot be scaled throughout the organization. DPR Construction has more than 900 projects active at any given time, therefore making sure our employees understand the purpose and implementation of the DPR Quality approach is an ongoing challenge. This is true for DPR Construction and many other General Contractors,

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Architecture & Design Firms, and Trade Partner Organizations in the construction industry. This research focuses on documenting the escalation process that DPR Construction has followed with the hope that sharing our experiences will inspire new practices in other companies. DPR is a company that thrives from passion, innovation and continuous learning. By engaging outside of the organization, we can learn from other organization's experiences to inspire relevant research questions for academic partners and continuous development.

Building Quality Builders (BQB) is a four-week virtual workshop that was developed by DPR Construction between 2019 and 2020. It addresses the status quo understanding that Quality is a process that is done after the work in the field is complete to a mindset that project teams need to understand and align expectations throughout the project life cycle starting at the pursuit phase and continuing throughout closeout. By identifying Distinguishing Features of the work, aligning on Measurable Acceptance Criteria (MAC) and communicating effectively to everyone involved in planning and doing the work, rework will be avoided, which means the project can avoid recordable injuries, delays to the schedule and cost increases. *Arroyo and Gomez* (2021) describe in detail the development of the training content and the continuous improvement cycle to achieve the current version. The current version includes weekly pre-course homework and a one-hour instructor led conversation pertaining to the pre-work. The course is designed to intrinsically initiate DPR's quality culture approach by invoking passion and excitement within the course content. The primary intent of the workshop was to help participants create an action plan to implement DPR's Behavior-Based Quality approach (Spencley et al. 2018, Gomez et al. 2019, and Gomez et al. 2020) on their specific project jobsite. The workshop also initially intended to draw from the need for psychological safety in Quality conversations, training (Edmonson, 2012), and the need to improve communications using language action perspectives (Flores, 2012).

BQB continues to follow the Flipped Classroom Approach, where all learning material is available for participants prior to meeting with the facilitators. The course consists of short videos of DPR field teams presenting their project task implementation stories. These stories cover a variety of project types including small and large projects, different core markets, different regions and different perspectives based on a variety roles and responsibilities. The course provides a summary of key quality program tools including A3 templates for Distinguishing Features (DF), Quality Implementation Plan (QIP) templates, etc. Workshop participants are asked to dedicate 2 hours per week, totalling around 8 hours across 4 consecutive weeks. The commitment consists of 1 hour of pre-work (watching short videos, reading short documents, and answering 5 questions) and attending a 1-hour facilitator led team call where participants engage in a safe and productive conversation. In addition, participants are asked to attend a 1-hour follow-up facilitator led conversation held a month after the last session that allows everyone to share what they have been working on and what they have seen that needs to change.

<u>The BQB workshop current agenda includes:</u>

- **Session 1** -Why a Behavioural Approach to Quality?
- **Session 2** -Quality Language and Leadership
- **Session 3** -How to Apply the DPR Quality Approach? (Videos and materials include pursuit, pre-construction, construction, and post-construction examples)
- **Session 4** -Action Plan

- **Follow up** -4 weeks after session 4

The training started with 66 graduates in 2019, 169 graduates in 2020, 186 graduates in 2021, and 55 graduates in the first Quarter of 2022. The current escalation is evident; however, the continuing improvement process, challenges and overall benefits of corporate training are seldom documented in lean construction literature. Though there are a few exceptions such as Tsao et al. (2013), Hackler et al. (2018), Arroyo et al. (2019 and 2021) as well as some documented academic experiences in teaching lean construction, such as Nofera et al. (2015), Brioso (2015), Neeraj et al. (2016), and Cisterna et al. (2021). We found no published papers documenting the escalating of training in the Lean Construction literature, which directly ties to the DPR Construction Quality Culture. This paper aims to bring insight to the challenges and successes of scaling a companywide training, and to share the specific lessons learned at DPR Construction from a practitioner's point of view.

METHODOLOGY

The intent of this paper is to document a case study (Yin 2009) of the escalation of BQB, a corporate training program. The main research questions are as follows:

- How to use technological tools to discover and implement innovative corporate training opportunities when considering the challenges imposed by the COVID-19 Pandemic?
- How to prepare new BQB facilitators for the training content and commitment? How can we learn and grow from previous experiences? What are the risks?
- How is the escalation process affecting the efficiency and effectiveness of the training program?
- How new facilitators' perspectives provide value for continuous improvement of the BQB program?

This paper documents 1) the escalation process that DPR Quality Team followed based on direct experience from the authors; 2) the results in the number of graduates per year and region collected through our learning platform and be using Power BI, and 3) the program facilitator(s) feedback collected through a survey that was administered to all BQB facilitators. The surveys collected perceptions of the DPR learning platform, the facilitator's level of comfort in their role, and the BQB workshop impact on quality within the organization. The discussion includes a summary of challenges and potential next steps for the DPR Quality team.

ESCALATION PROCESS

Figure 1 shows the escalation process for BQB. The development, testing and early data collections about the workshop are documented in *Arroyo and Gomez* (2021). At the time of data collection, most of the BQB groups were located in the California Bay Area, with some groups focused on specific projects in the Southeast region and a few open enrolment groups in Europe.

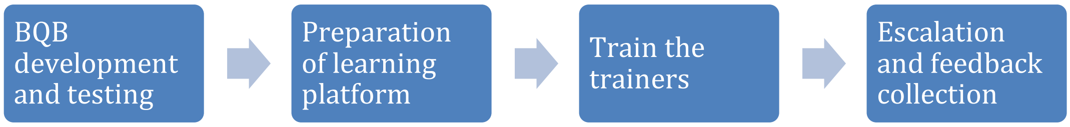

Figure 1: Escalation Process for BQB

The escalation seemed to peak during the second half of 2021. At this time the BQB workshop began offering the program 5 times per quarter, via 5 simultaneous groups, led by a team of trained facilitators. To complete the company rollout DPR relied on a new learning management software that provided timely pre-work (videos and questions), sent automatic reminders, and captured detailed participant answers. However, the learning platform presented its own set of challenges, such as invitations to webinar sessions not consistently being sent to all enrolled participants, and of course, the expected learning curve of understanding how to navigate a new online system. In addition to the new platform, facilitators and trainees used *Zoom* for the webinars, *Microsoft Teams* for sending workshop communication and *Microsoft OneNote* to organize and present the answers to pre work questions.

Each workshop group was led by 2 or 3 facilitators. The idea was to organize workshop groups so that at least one seasoned facilitator is present. The escalation and preparation efforts were supported by DPR's Learning and Development department. They provided feedback on previous escalation experiences for similar companywide training programs such as *Building Great Managers, Building Great Leaders, and Lean Leadership* (Hackler et al., 2018). The major finding, when examining lessons learned from previous training programs, was the need for facilitators to first be participants, then listeners, and finally take a more active role and facilitate the workshop.

To ensure success for the facilitators, DPR held a "train the trainer" session, where facilitators were asked, "What does it mean to be a BQB facilitator?". Additional discussions were held about the BQB training content, how to use DPR learning platform, experienced facilitators tips, coaching tools and additional virtual facilitation skills development. The top 3 facilitators tips discovered were the following:

1) Start with the big picture on every session.
2) Plan for who is speaking when (for participants answers)
3) Listen and defer judgment.

Defining and communicating the facilitator responsibilities was crucial for the success of the training implementation. The following facilitator roles & responsibilities were identified:

- Promote BQB peer group meetings +
- Create Teams Group and tags
- Get answers from DPR Learning
- Read and highlight answers and decide who is talking when
- Summarize key points per questions
- Track attendance
- Keep track of time
- Capture Plus/ Delta each session

- Manage *Zoom*, share screen, create breakout groups, pools (optional), record and post sessions (optional).
- Help people with getting into DPR learning or changing sessions
- Send notifications to remind people to do pre work (*Microsoft Teams* and DPR Learning platform)
- Communicate with people that missed session or pre work and ensure they understand the consequences for incompletes (i.e., no credits without pre work, listen to recordings, ask to join a future session, etc.)
- Validate students that did pre work and attended at least 2 sessions, (they will in turn receive credit and the post-evaluation survey).
- The participant workshop data is derived from the pluses and deltas communicated at the end of each of the 4 workshop sessions, the post-evaluation survey, the action items communicated in the one month follow up session, and the Power BI Tracking dashboard (which shows enrolments and graduate details per region). The combination of these feedback loops allows the company to improve communication across different regions and to adapt training delivery strategies. It also provides a means of healthy competition between business units and regions, which has proven to encourage more participation.

BQB GRADUATE RESULTS

Figure 2 presents a graphical representation of Building Quality Builder graduates per region; the larger the circle the more graduates there are in that region. The largest circle is in the San Francisco Bay Area, because during the year 2019 and 2020 there were many sessions offered only in that region (prior to the National escalation process).

Figure 2: BQB graduates by geography.

Figure 3 shows graduates per calendar year. A total of 467 graduates companywide. That number increased significatively from 66 (2019) to 169 (2020) and 186 (2021) amounting in an overall increase of 182% in just two years. During the first quarter of 2022 there were 55 graduates. Notice that the year 2022 only represents graduates through March 2022. The number of graduates is expected to quadruple by the end of the 2022 year!

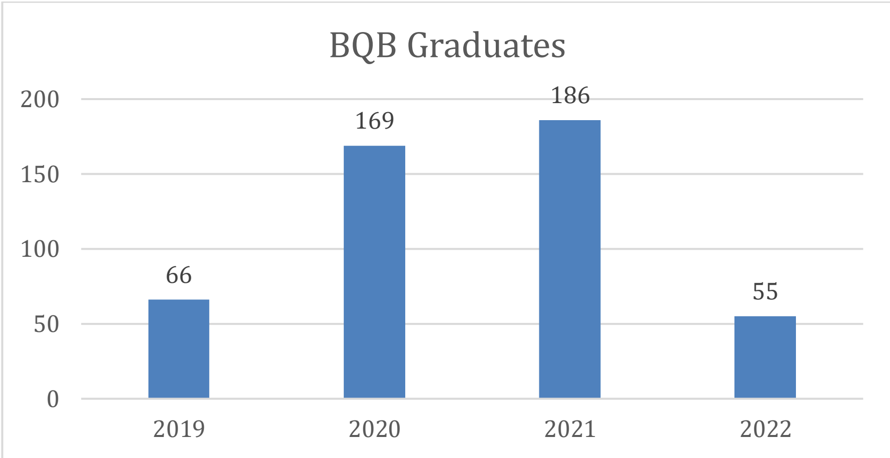

Figure 3: BQB graduates by year.

Figure 4 presents the number of graduates per year and region. The Northwest region led with number of graduates in the year 2020 and 2021. The Southeast region is leading so far in the year 2022.

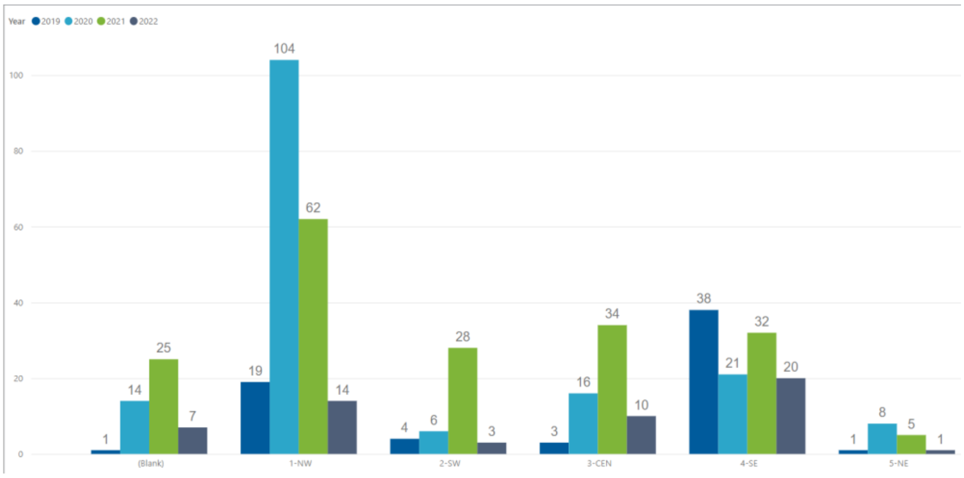

Figure 4: BQB Graduates per year and region (Blank represent Europe and affiliated self-performed work companies)

Figure 5 represents the graduates per job role. Most graduates are project engineers, project managers, and superintendents. Preconstruction managers and estimators have been participating in the workshop. Ideally, trainees from all phases of the construction process will take part in the Building Quality Builders workshop, as it covers quality concepts from project pursuit to closeout and turnover.

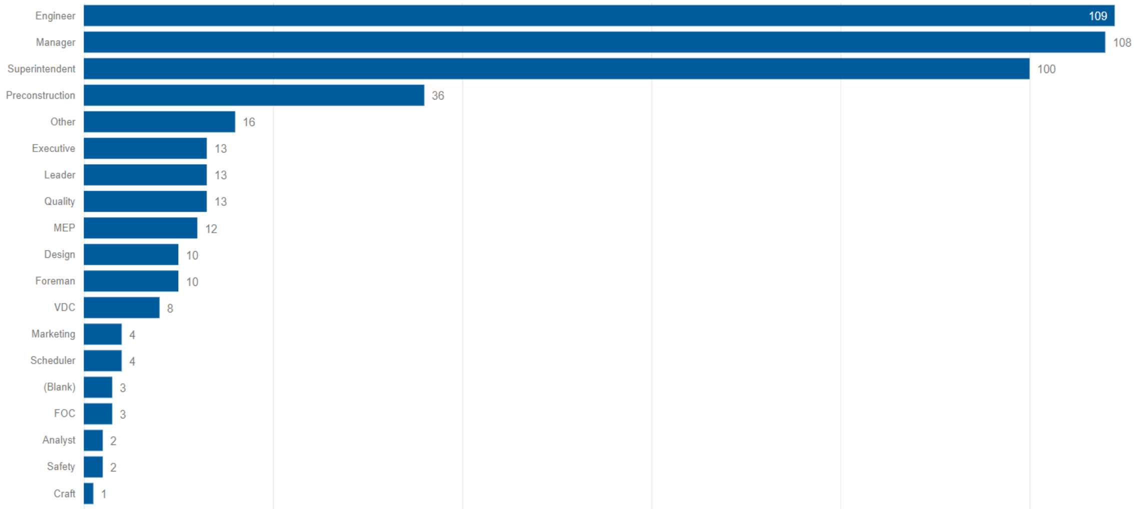

Figure 5: BQB Graduates per role

FACILITATOR FEEDBACK

According to DPR facilitators DPR survey learning platform pluses are:

- Pre work is easy to build
- Gives an overview of registered participants.
- Central location that people are becoming more comfortable using.
- Notifications for visibility to answers ready for review were useful.
- Response data is easy to export.
- Improvement over previous platform.

According to the BQB facilitator’s survey, the DPR Learning platform deltas are:

- Export format isn’t great, virtual sessions dates can’t be changed within the platform. Limited number of video sources allowed
- The platform is very clunky and not user friendly. Any normal user will get confused on how to extract data. Also, I wish there was a better way to extract the responses from the platform so that the facilitator can export the data in the format needed to facilitate the session. There is a lot of time wasted by the facilitator on cut/copy/pasting of all the answers into OneNote, etc.
- Transferring information from the Learning Center to the OneNote that's used during the training
- It is very easy for a participant to accidentally drop from a course: the button to drop is right above/below the button to continue the training assignments, and there is no popup verification. It would be useful for the system to send reminders 48 hours before the session (so that participants complete coursework 24+ hours before the session
- Having to manually transfer BQB responses manually over to OneNote. Having to score each response individually. Difficult to use unless you know what to click.

Not intuitive. Classroom link hard to spot in calendar invite. Having to use personal Zoom meeting link for classroom not ideal.

How can DPR learning and development resources ensure facilitators feel comfortable in their role? Facilitators mention what has helped them is:

- Time, experience of the material. Finding good co facilitator. Preparation for each session
- Experience
- Being on a team of facilitators where we can share the responsibilities for preparing for each session
- Built-in group discussions or talking points as part of the session OneNote

Facilitators need more support on (the facilitator comments are verbatim):

- I'd like more people to delegate to in Europe, will be looking for more co-facilitators
- I think I am all set except the comment on content I specified below.
- I think we do a good job of sharing successes between each group of facilitators, but it's typically after a full session has taken place. I think we can do a better job of sharing ideas as they're learned rather than waiting.
- Increase number of breakout group discussions, include more suggested talking points for each topic, better ways of gathering responses, better ways of getting participants to complete weekly coursework earlier

Making an impact! BQB facilitators think the most impactful workshop content has been:

- Teams developed mock-up rooms – Data Center Project in Europe
- Understanding DPR's approach to quality.
- We had a Project Manager in Houston who enjoyed the training so much, he has requested his new team be given an in-person BQB training session.
- Team members going through the example exercises and seeing immediate value in the DF discussions they were having
- It's rewarding to see past graduates encouraging other to participate but this is not common

Facilitators recommended areas of improvement to maximize workshop results:

- Add more practical tools and examples. Take some time to really concentrate on feedback for improvements in the business.
- The more we communicate the better. We have been doing a great job in making sure that people are aware of the sessions
- More application activities. People used to really like the DPR's "airplane activity" when we gave the Current Best Practices orientation, and it got the point across about asking the right questions from the right people.
- More example exercises and other ways for participants to practice skills related to the DF process

- Some participants have commented on the sound and production quality of the prework videos. Also, may be getting Business Units Leaders or Management Committee members to help create videos.

DISCUSSIONS

Based on the survey results, Pluses and Deltas meetings with BQB facilitators and company feedback, key findings and discussion points have been identified. Here the next steps are also discussed.

- **Company leaders have requested that the workshops are delivered just in time to project teams**. However, obtaining the resources to deliver this approach to hundreds of projects at the same time is very challenging. We have opted to offer 5 sessions per quarter and encourage teams to sign up in groups at a time that is appropriate for their project schedule. We are also exploring a self-paced version of the training where the project team can lead their own group.
- **Facilitators' tasks are very intensive, as described before.** In addition, many of the facilitators have a different role in the company, working on a project or another workgroup; the distribution of roles among facilitators is important.
- **Facilitation skills are hard to teach, what had helped facilitators was to work with a team and learn from each other.** Many of the facilitators also share personal stories and have a knowledge from current and past projects. In order to provide better support to facilitators, an internal adult learning specialist from the DPR Learning and Development department, will sit in (upon request) and observe a facilitator’s session and provide direct feedback and guidance for growth and development.
- **DPR learning infrastructure allows for a more consistent experience to give prework and videos.** However, the current platform has presented many navigation challenges and learning curves. The BQB facilitation team is constantly passing on feedback to the Learning and Development department. With an increase in the drive to integrate with the L&D department, as well as other training facilitation teams, we are finding ways to reduce friction by sharing experiences and facilitation methods The feedback is also passed to platform developers to ensure continuous improvement from a software standpoint.
- While the initial focus was delivering the training to project teams, we have seen **benefits of open enrolment** to our pursuit, preconstruction, VDC, marketing and self-performed work teams. The ability for a diverse group of DPR professionals to join a training program has proven to open the doors to integration, networking and relationship building creating synergy and beginning to build a common language amongst the whole company. The only region that does keep a separate training is Europe, due to the time difference and with the large size of the US network making it not feasible.
- When reviewing the BQB training pre-work answers **we have seen consistent mentions of quality challenges and stories across the regions**. The answers prove that the behaviors, skillset, and mindset needed to communicate clearly and efficiently are sorely lacking across the board. Note that job role and geographical region are not contributing trends currently.

- **Keeping a variety of job roles in each BQB workshop has shown value to the graduates.** Often, they mention the importance of hearing diverse perspectives around what constitutes a quality work environment and culture. In the future DPR plans to expand participation from job roles that are closer to the field such as foreman and laborers. Further explorations are being made about what training programs should be offered to craft team members. There has also been a great deal of consideration around the opportunity to train architects, design partners, trade partners and even owners.
- **Some facilitators have been requested for in-person training on job sites**. A self-paced training has been developed as an alternative. However, there is a potential opportunity to have a shorter in-person training for project teams that want a Quality Kick-off and do not have time for the four-week training module. This leads into our continued understanding that the level of success achieved from attending a training program is very much dependent on the exterior factors (phases of the project, workload, personal life, etc.) our trainees are faced with daily. Timing is key in achieving maximum success.
- **Pre-work content has been (and continues to be) improved over time.** Construction is constantly evolving, which means training content should reflect real time industry changes. For example, many of the videos describe DFOW (Distinguishing Features of Work) and the Quality leadership team has since decided to change the terminology to just DF (Distinguishing Features). These types of inconsistencies can lead to confusion and in some cases distrust in the processes.
- **The scale of the training program should match the scale needed by the organization.** The Building Quality Builders program has been able to reach a scale where training is deployed across most or all geographies in which DPR is located; however, the program must now evolve again to ensure that the number of attendees who desire or could utilize the training matches the capacity of the program. The scaling process must always be evaluated to ensure what is being offered aligns with the needs of the organization.

CONCLUSIONS

The escalation of BQB has been well worth writing about! The expected total graduates for the year 2022 are over 200. The impact of engaged facilitators has been essential to developing continuous program improvements and to communicate the relevance of the training. When a new facilitator joins a new region or business unit word of mouth about the program seems to multiply. The data captured on the graduate map is proof of a regional increase in participation. New facilitators bring fresh ideas for improvement and additional experiences that make the training better, which adds to the innovation and ever-changing updates to the program. The recruiting and educating facilitators is an ongoing task in the process of escalation. Planning and allocating resources to support them in their own learning is very important.

In terms of escalation results, the Northwest California Bay Area still leads in number of graduates, as it was the first location to offer regular BQB sessions. The Southeast region, Central region and Southwest region are rapidly increasing their total graduates. Europe has also been increasing the number of BQB graduates and represents a bigger overall percentage of graduates, given they have fewer total DPR employees.

Measuring the real live impact of a training program is hard. Over the last 3 years DPR has collected many data statistics, facilitator program implementation stories and experiences, outcomes, and details from the one month follow up sessions and an overall perception from those providing the trainings. However, measuring actual savings requires more research, which requires more time and continued innovative efforts.

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TAKT PLANNING: AN ENABLER FOR LEAN CONSTRUCTION

Iris D. Tommelein[1] and Samir Emdanat[2]

ABSTRACT

Takt planning is being lauded as a new tool for construction planning. It is described in the academic literature and successfully applied in practice. But is it just a tool for planning? This paper aims to show that takt planning can serve as the basis of a framework that supports the application of various lean tools and methods and, accordingly, is a tool to enable lean thinking in construction. Using this framework, the paper illustrates through examples how a project team benefited from using takt to identify where to apply lean tools and methods. It shows how takt informs when and where in the workflow it is appropriate to apply various lean tools and methods such as identification of bottlenecks, workflow reliability (process stability), underloading, process capability, mistakeproofing, standardization, continuous improvement, and cycle time reduction. The contribution of this paper is to highlight that a lean journey that starts with takt may proceed with implementing numerous lean tools and methods other than those directly pertaining to takt itself.

KEYWORDS

Lean construction, takt planning, continuous improvement, project production system design

INTRODUCTION

While takt planning is being lauded as a new tool for construction planning, the benefits of pacing work done by machines and people to a steady beat have been recognised for some time. The application of takt in the manufacturing industry dates to at least the early 1900s. Around that time in Germany, Hugo Junkers (1859-1935) used takt in airplane manufacturing (Baudin 2012), and in the UK, Frank George Woollard (1883-1957) used takt to create flow production at Morris Motors (Emiliani and Seymour 2011). The historical overview provided by Haghsheno et al. (2016) of the origins of takt that informed the use of takt in construction goes back even further in time. Fast forward to this millennium, and we are now seeing an increase in the number of construction projects around the world that are adopting takt planning and control and are reaping the benefits of doing so (e.g., Court 2009, Frandson et al. 2013, Frandson and Tommelein 2014, Linnik et al. 2013, Haghsheno et al. 2016,

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Binninger et al. 2017, Gardarsson et al. 2019, Tommelein 2017, 2020, Lehtovaara et al. 2020).

This paper situates takt planning at the basis of a framework that supports the application of various lean tools and methods. Besides being a planning method, takt planning is a tool to enable lean thinking in construction. The paper therefore starts by summarizing the conceptual foundations of takt planning and providing formulas with the rationale for computing a takt. It then illustrates the elements of that framework with examples obtained through direct involvement in a project, showing how lean tools and methods can be implemented so that the takt plan will be embraced to its fullest.

METHODOLOGY

A question for anyone wishing to get started with lean construction implementation is: Where to start? One option is to start with weekly work planning; another is to start with pull planning; both are specified in the Last Planner System® (LPS®) (Ballard and Tommelein 2021). While these options focus respectively on creating workflow reliability and defining handoffs between specialists, they do not indicate how the work is to be structured (Ballard and Tommelein 1999, Ballard et al. 2001). Takt planning provides a method for that (see pp. 26-28 in Ballard and Tommelein 2021). By providing a work structure, takt planning offers a means to “lower the water to reveal the rocks,” i.e., to put strain on the system in order to identify the next opportunity for improvement (Ballard 2009).

Our development of a framework for lean implementation based on the concept of takt started when the opportunity presented itself on a project where the second author was implementing takt planning. The second author and a UC Berkeley graduate student were embedded in the project. They were able to make first-hand observations while also having the opportunity to make interventions affecting the project’s unfolding (i.e., action research). Examples from this project are presented in the second half of this paper. They highlight how the takt plan served as the target condition—the strain put on the system—and achieving it would require the use of lean tools and methods to (1) manage negotiations needed upfront to streamline the work and (2) address logistics challenges (e.g., materials, laydown space, lifting) during execution.

The 2016 Benchmark of the Last Planner System® (LPS) (Ballard and Tommelein 2016) barely mentioned takt planning. Since then, takt planning has evolved in the construction industry. The 2020 Benchmark (Ballard and Tommelein 2021) now includes a significant description of takt planning as a work structuring method in the LPS. In this paper, we further expand on the use of takt as a tool to enable lean thinking, i.e., to necessitate the systematic use of many interrelated lean tools and methods. The paper first presents the framework for takt analysis including the takt calculation and planning methodology, and then presents examples from the project to illustrate the use of the framework.

MATHEMATICAL UNDERPINNING OF TAKT PLANNING

This section summarizes the mathematical underpinnings of takt planning and the levers it provides to balance workloads and create workflow.

Takt Calculation

Takt (or takt time) is 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) (Hopp and Spearman 2011). In manufacturing settings, takt is calculated as follows:

Takt = (Available production time) / (Customer demand) (Equation 1)

Takt applies to high-volume manufacturing, where it may be measured in seconds or minutes, or to low-volume high-variety (LVHV) manufacturing, measured perhaps more typically in hours or days (Ricondo Iriondo et al. 2016). Takt likewise applies to construction. Construction is a kind of LVHV manufacturing specifically structured based on fixed-layout assembly (as some manufacturing systems are, too), which means that workers, equipment, and materials "flow" to complete work in fixed locations, supported by information flows based on decisions made during design and pertaining to the supply chain.

While takt used in construction planning is evolving through on-site experimentation, theory, and support-tool development, it is worthwhile to recognize its mathematical underpinnings. Takt requires a calculation that sets the rate at which a production system should produce to meet customer demand. Demand can be external (the overall customer demand) or internal to the system where each assembly line (in manufacturing) or phase of work (in a construction project) must be paced per the production rate of the previous and the next line or phase so that in combination they will meet overall customer demand.

In construction, demand refers to the project as a single product completed within a given duration. Workers complete work in phases defined with clear handoffs and standard steps for each phase at specific locations (so-called zones). These zones are inherently 2- or 3-dimensional in nature and can be decided on using one of several approaches.

Approaches for Zoning

When takting a construction project, the project work space must be divided into zones to allow for concurrency of work and improve crew management at the job site. However, the underlying assumptions for how to define zones and how to determine the takt are not well articulated (Singh et al. 2020). Several approaches for zoning a project appear to be in use.

One planning approach is to start top-down by defining a location breakdown structure (LBS) for a project phase or the entire project, assessing work in each location, and then choosing means and methods while sizing crews. This is the approach taken in location-based methods such as the Line of Balance, Repetitive Scheduling Method (RSM) (Harris and Ioannou 1998), or Location-Based Management System (LBMS) (Kenley and Seppänen 2009), in which case the objectives are to work in sequence, eliminate crew overlaps, and keep the crew size constant while striving for high resource utilization and buffering with time. When an a-priori defined LBS is used to produce a takt plan, the crew size must be adjusted to synchronize better with the work of successive trades. A shortcoming of this approach is that changing the crew size is only one of several levers available to meet takt planning objective (e.g., keeping the time any crew spends in any location constant while striving to complete all work to meet demand and buffering with capacity to ensure reliable workflow). By revisiting the LBS and iterating, the Line of Balance approach can then possibly result in a satisfactory takt plan, but this raises the questions: Is starting from a-priori defined LBS the best way to create a satisfactory takt plan? What other approaches exist?

A second approach is to start by identifying Standard Space Units (SSU), such as a hotel room, bathroom, or office, then identify the work contents by trade for each one, multiply it with production rates to find the time each trade needs by SSU, and then adjusting resources to find an acceptable upper-bound on the duration each trade will be allowed to complete their work in each SSU (Dlouhy et al. 2016).

A third approach may be labeled “block planning.” It starts by choosing a certain duration between handoffs (e.g., a takt ‘wagon’ that is 5 workdays long) and dividing the site into zones, thus creating time-space blocks. Then comes deciding what work can be done by which trades by zone in the chosen duration, possibly resulting in multiple trades ending up in the same wagon. The Pentagon Renovation project followed this approach (Horman et al. 2003). Court (2009 p. 54) specifically choose a 5-day block (takt) and called it week-beat scheduling. In this approach, the scope of work and crewing is tailored to the time-space block that is locked in for all. Trades therefore may have to crew up and down to stay on schedule. The penalty for changing crew sizes is offset presumably by benefits of the discipline imposed on everyone following the week-beat and can be acceptable especially on fast-paced projects.

A fourth approach uses the Work Density Method (WDM) (Tommelein 2017). This method is based on identifying the work steps trades must complete in a phase (or process) and on mapping the time each crew needs to a relatively fine grid of cells superimposed over the work space. This identification may also be done by means of color-ups, e.g., a single-day color-up would identify the amount of work the minimum crew can produce in a single day. These cells of so-called work density are then combined to zone the work space. Using mathematical optimization for so-called Workload Leveling and Zoning to find the lowest workload possible (Jabbari et al. 2020) and manual adjustment (Singh et al. 2020), the zones can be right-sized to match crew capabilities, means, and methods.

These four methods differ in what they consider to be given at the outset, what objectives are pursued, and how changes are made while iterating to optimize the plan. For example, the WDM and the single-day color-ups differ from the other methods in the sense that they do not start with a LBS or a-priori assumed zones. We next expand on the takt calculation.

Takt Calculation for a Construction Phase

Construction takt is the fixed amount of time a trade gets to complete their work for a given step (a certain scope of their work) in a given zone, with several steps making up a process so that all the process steps in all applicable zones are completed within the required phase- or project duration. In practice, and due to the considerable variation between work phases, construction takt is the result of the analysis done at the phase level. It is rarely calculated at the project level. Each phase may be paced to a different takt. A phase identifies groupings of construction activities of similar nature, such as underground work, structure, overhead systems, in-wall systems, finishes, or testing. Clear handoffs (e.g., third-party inspections) separate one phase from the next.

For a given phase duration and number of phase steps, the takt can be calculated:

Construction Phase Takt = (Phase Duration) / (Total Number of Phase Steps) (Equation 2)

where,

Total Number of Phase Steps =
*Process Steps + (Number of Floors * Number of Zones) – 1* (Equation 3)

The following example illustrates this calculation. Assume that a phase of work for a two-story building must be completed in 50 days. Takt plan development starts by mapping the number of steps that must be performed in succession to complete all work in the phase (i.e., the "Total Number of Phase Steps" in Equation 2). The subsequent analysis is context-dependent. It starts by identifying which work steps must be performed in succession and which can be done in parallel. This reveals the critical handoffs between the steps. During analysis, some steps may be combined while others are split. Figure 1 illustrates the takt calculation where work comprising process steps 1 through 7 is done on two floors, each divided into two zones.

		50 Days									
		Phase Steps									
Floors	Zones	1	2	3	4	5	6	7	8	9	10
Floor 1	Zone 1	1	2	3	4	5	6	7			
	Zone 2		1	2	3	4	5	6	7		
Floor 2	Zone 1			1	2	3	4	5	6	7	
	Zone 2				1	2	3	4	5	6	7
Floors = 2, Zones =2, Process Steps =7											
Total Phase Steps = Process Steps + (Floors * Zones) -1 = 10											

Figure 1: Total Phase Steps Calculation Assuming two Floors each with two Zones

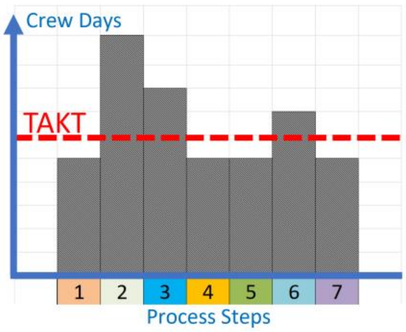

Figure 2: Charting the Process Steps and Cycle Time (expressed in Crew Days) per Floor with the Takt Target (shown by Dashed Line)

The analysis is iterative and produces several takt targets based on the assumed number of zones, for example:

Option 1: 2 Zones: Takt = 50 / (7 + (2*2) – 1) = 5 days / step
Option 2: 3 Zones: Takt = 50 / (7 + (2*3) – 1) = 4.16 days / step

Takt Analysis

The takt calculation sets the production target for each step in the production system, but it does nothing to align the work in each step with the target, and it does not define the location or the size of the zones. The next step is to collect data to determine the amount of time it takes for a crew to perform the work for each process step which is needed to define the crew size, location, and size of the zones so that each trade can perform the work in each step in roughly the same amount of time. The data needs to be collected in a way that keeps options open for further analysis, and thus the Work Density Method is preferred.

Input Data Collection

Color-ups (Linnik et al. 2013) and crew production rates are two related methods to collect data without pre-determining the zones. These can be used to identify the area a single crew can complete in a small unit of time (e.g., one day). In this context, a single crew is the minimum number of resources required to perform a work step in a process.

This systematic data collection approach provides two insights for the takt analysis. The first is the maximum duration to perform the work for each step in a work area (e.g., on the floor). The second is how the work is distributed in a work area: e.g., is it distributed evenly, or is it concentrated in specific locations? When the work is distributed evenly, zone definition is straightforward. However, if the work is not distributed evenly, additional approaches may be considered prior to deciding on zones, such as decoupling the process steps to create new work phases for such locations.

Cycle Time

Once data is collected, the takt analysis continues. The objective of the analysis is to define the location and size of the zones and to determine the appropriate number of crews so that the cycle time for the step when performed in a specific zone is less than the calculated takt.

Cycle time is the projected time it takes to complete the work in a step from start to finish based on the production rate of the crew and the quantity of the work. The crew production rate can be observed or obtained from experience when performing similar work. That is, during production, inventories would accumulate when the cycle time is significantly shorter than the takt, and bottlenecks would emerge when the cycle time exceeds the takt.

Continuing with the example, selecting option 2 and rounding it down to 4 days / step as a stretch goal, the calculated takt is 4 days so three zones need to be defined. Rounding down of the computed value helps to shorten the process duration if indeed the stretch goal can be met, which in turn frees up a time buffer that can be use elsewhere in the phase.

FRAMEWORK FOR CONTINUOUS IMPROVEMENT BASED ON TAKT AND USING LEAN PRINCIPLES

Balancing and finetuning the production system is the process by which cycle time is aligned with takt in such a way that allows the crews to have some excess capacity to accommodate variation and to be able to implement process improvements. To this end, many lean tools and methods can be used.

Underloading Principle: Cycle time < Takt Time

When the cycle time significantly exceeds the takt, a clear choice when balancing the production system is to add crews. However, this may not be the most effective choice. Improvements to the internals of a step should always be considered. Especially when the cycle time only slightly exceeds the takt, internal improvement could bring it down below the takt. Alternatively, improvements to the overall sequence may be considered.

The disciplined data collection and analysis process outlined above exposes opportunities to implement targeted improvements to streamline operations through lean thinking. The following sections explore some of those opportunities.

Step Analysis: Step analysis is the detailed study of the internals of a step in the overall process sequence. The analysis should identify value-adding and non-value-adding work. Additionally, step analysis provides context for evaluating alternative ways of performing the work, such as installing sub-assemblies instead of building on-site. Step analysis can further refine the process sequence itself, especially when considering the internals of the preceding and succeeding steps.

Step analysis is performed prior to production to finetune the means and methods used, and to reduce non-valuing adding work. It continues during production to spot further improvements. Before production starts, step analysis is based on experience and the study of the systems being installed. It can also be based on data collected through direct observation using a mock-up or a first-run study. During production, it is performed based on direct observation of the work and can reveal further opportunities for improvement. Lean tools and methods like 5-S analysis, 5-Whys analysis, and time studies can be used to study and improve the internals of a step.

Design Caused Bottlenecks: If step analysis is done early enough in the process, it could identify certain bottlenecks (design bottlenecks) within the sequence that can be resolved only through a design change to simplify or improve the assembly, e.g., through standardization. Such bottlenecks could otherwise choke the plan.

Mistakeproofing: The detailed analysis of the handoffs between the steps identifies steps that can benefit from related built-in-quality measures to (1) reduce variability in the time it takes to perform the step, thereby making the work product of the step more predictable, and (2) reduce the likelihood of making mistakes and passing defects from one step in the production sequence to the next. For example, during modelling, space claim objects (aka. block-outs) are inserted into the models, during coordination, designers agree on assumptions before working in parallel, or during construction, visual management is used to eliminate the chances of making installation errors.

Decision-making: The clarity regarding process flow steps, the handoffs, and the associated zones that takt planning offers lead to improved overall decision-making. Each step in the process flow is supported by a supply-chain flow starting from design to material delivery. Decisions must be made to release each step in that workflow (e.g., Tetik et al. 2019). Takt analysis makes it possible to group related decisions in smaller batches by zone, and batches can be spread over a period of time according to the takt plan. That is, decisions must be made at the rate of the takt. Small batches create an opportunity to learn and improve the decision when initiating similar phases later.

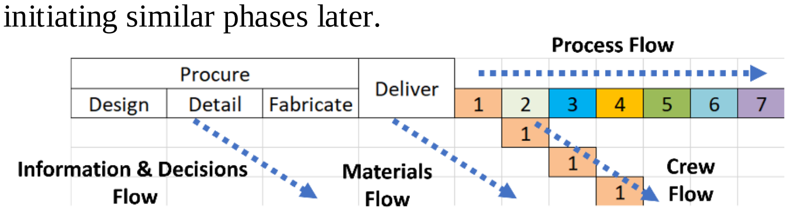

Figure 3: Takt Planning and the Supply Chain

Buffer Management: Buffer management protects the workflow from variability (Dlouhy et al. 2019). Capacity buffers are included in the takt sequence when setting the cycle time for each step to be less than takt. Such underloading gives the crews time to react to variation and complete the work for their step in a specific zone, so they will not delay succeeding crews. Location buffers can be used when steps in the sequence exhibit uncertainty or when the work requires additional space on the floor for materials and equipment. Location buffers can also emerge naturally when a phase of work has a slower or faster takt target than a subsequent phase.

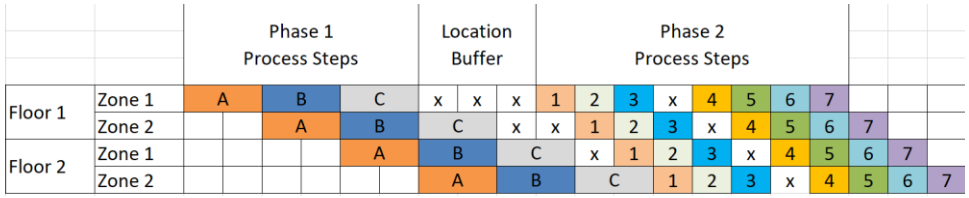

Figure 4: Location Buffers (marked ‘x’)

Logistics Planning: Takt analysis informs logistics planning. During the analysis and while zones are being identified, teams consider the laydown space required to temporarily house the materials required to install the systems within that zone. Since adjacent zones will be occupied by other work, each zone needs to be defined with enough space to organize the delivery for ease of installation. Kitting strategies should be considered so that deliveries are sequenced to enable just-in-time installation and first-delivered first-installed.

Furthermore, when planning vertical construction, the takt plan makes it possible to identify which steps will start at the same time vertically through the building along with their material delivery requirements. This allows the team to calculate lifting capacity and resolve any bottlenecks ahead of time.

Standard Work: The execution of takt plans allocates resources to perform similar work across all applicable zones. This makes the installation of future work more predictable, and the crews will become more efficient over time as they move from one area to the next. Crews can spot variation and implement countermeasures to control it.

Make Ready Improvements: Make ready planning is the process of identifying and removing any constraints on the work that should be done, so that it can be “done done” (Ballard and Tommelein 2021). Takt planning gives structure to the make ready process and enables teams to look ahead further in the future more reliably. Make ready planning can be done in smaller batches per zone, and as constraints, especially those related to information flow and decisions, are removed when installing the first few zones, they are also removed from later zones for similar work. This reduces variation as more work is put in place and allows the team to look ahead further with more reliability.

The following section provides examples of how the framework was implemented on an actual project to develop execution strategies and how takt helped the project team identify where to implement lean principles to streamline the workflow.

EXAMPLES FROM PRACTICE

Some of the concepts presented earlier were applied to implement targeted lean improvements on a recently completed project, a multi-story Medical Office Building (MOB). Takt planning was introduced at the start of the interiors phase after a late design change switched the interior wall construction from the standard drywall system to a high-end modular factory-fabricated system that included framing, in-wall systems, and finishes. The rough-in phase of the wall construction produced pre-assembled panels of the framing and any in-wall systems such as plumbing, electrical systems, backing, and low voltage systems. The finishes phase of the wall construction produced the final finish panels installed after rough-in was installed, connected, and tested. All the system parts were packed and delivered as a kit of parts for on-site assembly.

The takt analysis was driven by the owner's and the team's desire to improve crew flow during construction, reduce rework, improve decision making, and predict a reliable completion date. The interiors construction scope was divided into several work phases, including high overhead, low overhead, wall construction, finishes, and commissioning.

The takt analysis helped improve the understanding of the requirements for installing the new system and assess the feasibility of implementing the necessary design changes to accommodate the requirements of the new system. Further, the interiors construction team (one GC) was monitoring the process of the exterior construction (work performed by another GC). They were concerned about slipping milestones in the exterior construction schedule impacting the interiors team's ability to complete their work. The goal was to explore execution strategies that would make it possible to identify the last responsible moment for resolving key constraints that could affect releases for fabrication.

During process analysis, the team identified phase steps to be done in succession or in parallel. Parallel steps that required fewer crew members were combined. The trades collaborated to decide which resource-intensive steps should be done in succession. The analysis of the overhead systems suggested that the installation sequence could be simplified if certain systems were split into what the team identified as the pre-overhead phase, to include cores, penetrations, and vertical work that was localized near the shafts and electrical rooms. Data was collected using single-day color-ups.

The takt analysis produced execution strategies that were then discussed for feasibility. These strategies identified the takt targets per phase, the number of zones per phase, the crew requirements, and the known constraints, both external from the core and shell team to release the on-site work and internal to release the detailed design to start fabrication. The team analyzed the tradeoffs between speeding up fabrication to reduce resources at the site vs. speeding up installation to allow for more time to make decisions that would later impact operations in the MOB.

During analysis, several bottlenecks were identified. These were resolved prior to installation by applying lean thinking.

Kitting Strategies Bottleneck: The takt analysis divided the interior floor into six zones sized so that the crews could install the panels in each zone within four days (4-day takt). As the trades studied their sequence of work in detail to confirm the cycle time and validated their thinking through a first run study on a mock-up, they reported needing more time and more laydown space than what had been assumed in the analysis. A root cause analysis revealed that the kitting strategy from the factory to the site required the on-site crews to open all the delivery boxes for the zone and sort the panels to identify which panels are installed in which rooms, that is: supply was not matched with demand. The factory production lines were optimized to group the fabrication of similar panels regardless of their location, and the panels were packaged to maximize the number of panels on the truck. This was most efficient for fabrication and delivery but ended up being out-of-sequence for the site, making it cumbersome for the installation trades to stay within the takt.

The trades and the factory were then challenged to revise the process by improving the alignment between the deliveries and the installation sequence. The factory identified the smallest batch size they could fabricate without losing efficiency, which turned out to be about one fourth of the zone of the takt plan. The trades took that information and sub-divided each takt zone into four work areas. The sequence of installing the work areas within a takt zone was communicated to the factory to match. The modified kitting strategy enabled the trades to realign their installation time to the takt target without increasing fabrication and delivery costs and solved a bottleneck that would have gone undetected otherwise.

Lifting Capacity Bottleneck: All material deliveries made use of a single hoist. The use of a single hoist had been decided at the start of construction and before the takt analysis. When the team considered the number of deliveries for all process steps on a given day across all the zones, they realized that the hoist lifting capacity presented another bottleneck. The trades negotiated hoist time, and some deliveries had to be scheduled at night to match the required speed of installation. Additionally, the GC produced a detailed site logistics plan for truck movements to maximize the utilization of an alleyway which was the only access point for deliveries, which was another bottleneck.

Model Coordination Bottlenecks: Looking further upstream, 3D model coordination was another bottleneck. Initially, the GC had planned for a single model sign-off per floor to release model data to fabrication and planned their resources accordingly. However, the takt analysis required the release of overhead systems for fabrication at different times and in smaller batches than the in-wall systems. Vertical penetrations had to be finalized so that the in-wall panel fabrication could proceed. Process maps for releasing the various systems to fabrication were developed and discussed with the detailers and the design team on a zone-by-zone basis. The analysis revealed code issues to be resolved before starting detailed coordination. The team added modeling resources, increased the frequency of coordination check-ins, and adjusted their model sign-off process so that sign-offs aligned with the zones rather than with the entire floor.

Owner's Decisions Bottlenecks: The takt analysis revealed the last responsible moment for key decisions that the owner stakeholders had to make to release detailed design and coordination to start fabrication in time to maintain the takt target. The advantage when using takt is that decisions can be spread over time and batched at the rate of production. Batching the decisions enabled the owner's stakeholders to prioritize their resources and improve the quality of their decisions.

Bottlenecks During Installation: The project team implemented the LPS make ready planning and commitment management to manage work execution. As the finishes phase deliveries began to arrive at the job site, the team noticed a new, anticipatedbottleneck. The finished panels were delivered by work area similar in size to the work areas previously identified for the panels (one fourth of the zone for the takt). However, the number of finish panels to install was much larger than the number of wall rough-in panels. Each wall panel housed four or five finish panels which resulted in longer sorting times at the job site to identify where the finish panels should go and in which sequence. This on-site sorting required a large, conditioned space. The team used an underground parking level and conducted time studies to improve the sorting task to mitigate the impact on the cycle time.

These are just a few examples of how takt analysis can enable lean thinking on projects. The analysis identified several bottlenecks before the work started and enabled the team to resolve them early through lean thinking. Similarly, during execution, additional bottlenecks were discovered and mitigated through lean thinking as they presented unplanned variation.

CONCLUSIONS

In summary, takt may be viewed as foundational to a framework that supports continuous improvement efforts. Thanks to the clarity a takt plan provides, teams can identify and resolve bottlenecks before starting work, spot and react to variation in the workflow during plan execution, and implement countermeasures. When takt is implemented as a method integral to the LPS, it streamlines the implementation of the LPS. We recommend that 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. Takt must be considered at the strategic level (takt to inform design and supply chain alignment) as well as at the operational level. Takt planning cannot be done as an afterthought.

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SO MANY FLOWS!

Iris D. Tommelein[1], Vishesh V. Singh[2], Rafael V. Coelho[3], and Joonas Lehtovaara[4]

ABSTRACT

Flow is one of three perspectives in the Transformation-Flow-Value (TFV) conceptualization of project production systems. Accordingly, many papers published in the IGLC proceedings and elsewhere have addressed flow on a theoretical or practical basis. This notwithstanding, quite a few of these papers describe various flows only loosely without defining them formally. For example, a term such as workflow is widely used in the Lean Construction literature, but what exactly does it refer to? This paper poses the question: What kinds of flow can be distinguished? In response, different kinds of flow are listed, some already well-described and others (e.g., assembly flow) seemingly overlooked in the Lean Construction literature. The contribution of this paper is distinguishing and defining a certain number of flows in construction, using a vocabulary that is internally consistent. Flows need comprehensive attention in the design and execution of Lean Construction systems, so it is important to be clear on terminology. The goal of providing definitions regarding flows in Lean Construction is to facilitate research and communication of ideas with scholars and practitioners around the world.

KEYWORDS

Flow, assembly flow, equipment flow, location flow, material flow, operation flow, process flow, product flow, resource flow, service flow, tool flow, trade flow, value flow, worker flow, workflow

INTRODUCTION

Koskela (1992, 2000) presented flow as one of three perspectives in the Transformation-Flow-Value (TFV) conceptualization of project production systems. Whereas the traditional view on construction is focused predominantly on transformation and correspondingly the efficiency of conversion processes, the flow view sheds light on the management of handoffs between and within conversions (Ballard and Howell 1994).

Focusing on the point of handoff between supply and demand, namely the start of an activity, Koskela (1999) identified seven flows as the preconditions for work. So, are there only seven flows in construction? Koskela (2000 p. 187) hints at more. "[O]ne may

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argue that [the concept of seven flows] is not based on a structured analysis of the nature of the process and its flows" (Bertelsen et al. 2006 p. 35); these "are just put forward as an example of the impact of a relatively small uncertainty in each of the flows on the soundness of the whole process" (Bertelsen et al. 2006 footnote 6). This raises the question: What shape and form do various flows take on before they reach a handoff?

Terms such as workflow are not new (e.g., Birrell 1980) and have been used widely in the Lean Construction literature. However, taking a closer look at that literature reveals that, for example, the term workflow appears to mean different things to different people (as Tommelein et al. (1999 p. 304), Kenley (2004), Kalsaas and Bølviken (2010), Sacks (2016), and others noted) and the term does not appear to have a generally accepted definition. The same can be said of several other construction flows. Even among the members of our P2SL research group, achieving agreement and consistency in use of terminology is an ongoing challenge. We therefore set out to identify flows in construction and define them to the best of our ability, not only for conceptual clarity to facilitate our own research work but also to be able to share ideas clearly with others. It is unrealistic to expect that this terminology will be universally adopted, however it seems reasonable to highlight that there is a need for everyone to strive for consistency in their own word use and to define the terminology they use as clearly as possible.

The methodology followed to arrive at the terms in this paper stemmed, first, from our long-standing attempt to use words consistently while teaching Lean Construction concepts and methods. Clear definitions are necessary to make sense of the literature (e.g., what one calls lead time, another calls cycle time, and vice versa) and crucial when communicating ideas. For that reason, over the last 20-some years we have been developing and continue to incrementally improve an online glossary of Lean Construction terms (P2SL Glossary n.d.). Second, it stemmed from the authors' familiarity with the literature (especially in Lean Construction and Lean Production in general) and our joint effort to iron out workable definitions. Readers may not agree on the exact wording of the definitions provided in this paper, but they may find it worthwhile to map these terms to their own (in English or other languages) and find value in understanding the distinctions that are made.

This paper has a simple structure. The following section defines flow. The section thereafter presents a set of cogent and internally consistent definitions of different types of flow that can be discerned in construction production systems. We hope this will provoke discussion to further sharpen the here-provided list with definitions of various flows as well as to further augment the list.

DEFINITION OF FLOW

Kalsaas and Bølviken (2010 p. 54) cited the Oxford Advanced Learner's Dictionary definition of flow: "to flow" means to "*move freely and continuously* (verb)" and "flow" is "*the flowing movement / continuous stream of something* (noun)." This definition is adopted here and that "something" is the focus of this paper.

In construction, that "something" frequently appears in discrete parts (e.g., a trade crew, an assignment, a pallet of materials) and less frequently as a continuous medium (e.g., concrete flows when it is being pumped, paint flows when sprayed onto a surface, dirt flows when it is transported using a conveyor belt). The extent to which continuous flow is achieved in construction is a matter of degree.

DEFINITION OF TYPES OF FLOW

WORKFLOW

In the context of Lean Construction, early use of the term workflow appeared in the Last Planner® System (LPS): Ballard conceived the LPS as a means to counteract low workflow reliability (Ballard 1994, Ballard and Howell 1994).

In the LPS, workflow refers to a stream of chunks of work that have been planned and must be assigned to production units and executed in a timely fashion. Using Percent Plan Complete (PPC)—the most well-known metric in the LPS—Last Planners (front-line supervisors) can gauge workflow reliability by assessing whether WILL matches DID (see Ballard and Tommelein (2021) for an explanation of these LPS terms that are printed in caps). When the time comes to add an assignment to a weekly workplan, the Last Planner must assess the degree to which that assignment satisfies five quality criteria (being defined, sound, sequenced, sized, and allowing for learning)—a process that is called SHIELDING—and, if all are met, can make a reliable promise when committing to performing the work. The objective is to ascertain that the Last Planner's production unit will reap the benefit of planning and have sufficient, ongoing work of the right kind, achieved by having a reliable workflow coming towards them. This is to enable them to work close to or at their capacity, that is: have a high utilization. In turn, high utilization results in high productivity if the work is "done well," i.e., if it is both efficient and effective. The Last Planner achieves this by stabilizing the work environment by (1) reducing inflow variation (using SCREENING, making work ready, conducting first-run studies, SHIELDING, etc.) and (2) improving performance behind the shield, to include learning by doing and relentlessly improving how work is done (see Figure 1 in Ballard and Howell 1994).

While an assignment tends to be a relatively small chunk of work so that a production unit can start and complete it within the commitment period (e.g., spanning a day or a week), the LPS has been silent about the relationships between those chunks, that is: it has been agnostic about work structuring (Ballard 1999, Ballard et al. 2001, Tsao et al. 2004). It is only in the most recent benchmark (Ballard and Tommelein 2021) that a method is presented for work structuring, namely takt planning. While the higher-level schedules in the LPS (master- and phase schedule) typically show sequential dependencies, activities can be broken down and detailed in numerous ways and at many different levels until they become chunks. Chunks can have various dependencies or other relationships between them, even if none are shown.

Relationships between chunks at the assignment level may exist but not be shown explicitly. In fact, several of the following characterizations of flows, other than workflow, will reflect them.

WORKER FLOW

Worker flow (or people flow, more generally) captures the path a worker travels in the course of their workday. People come to work and go home each day, attend team meetings, go to the workface (the location where they install materials and products in their final position) or other location to perform work, take breaks, etc.

Alves and Formoso (2000) refer to a related flow, the flow of production units (which could be an individual worker or several, e.g., a trade crew or design squad), comprising people (with individual expertise, know-how, motivation, etc.), tools, and equipment, which they studied together with material flow. They offered guidelines to make such flows more transparent and thereby amenable to more explicit and systematic management.

MATERIAL FLOW

Material flow refers to the physical movement of products, arriving from off-site (here leaving out the details of supply flows to the site) and being relocated on-site, some of which will be consumed or put in place (e.g., Tommelein 1998), and others will be wasted or removed from site after use. Figure 1 depicts flows of materials between off- and on-site locations, with the thickness of the arrows reflecting the author's assessment of the degree of desirability of the flow, assuming one tries to minimize overall flow. Dashed arrows and loops are the least preferred of all as they indicate a kind of rehandling. Each circle describes a function fulfilled in a certain location for a certain duration, where a location can fulfill several functions. These functions are explained in greater detail in Tommelein (1994).

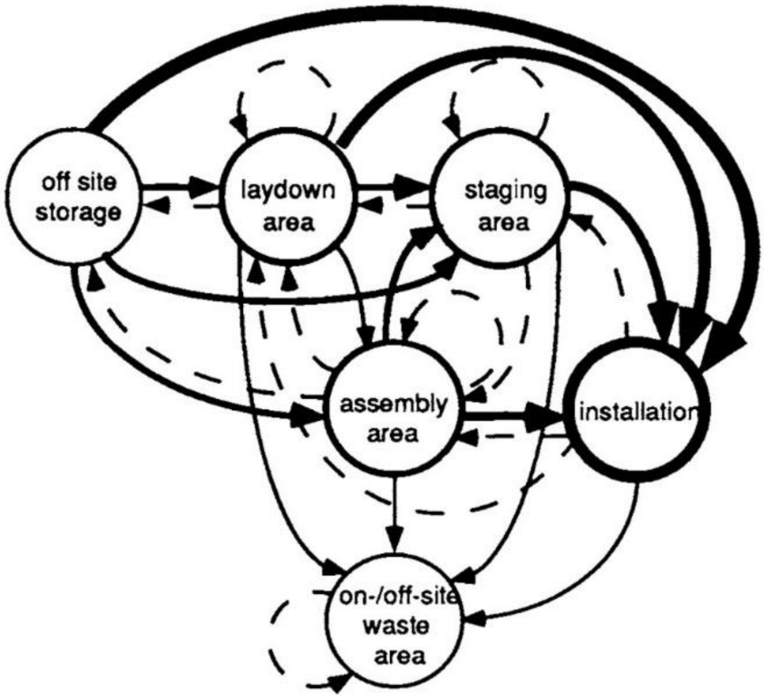

Figure 1. Preferred Materials Flow
(Figure 1 in Tommelein 1994 reprinted with permission from Elsevier)

EQUIPMENT FLOW AND TOOL FLOW

Equipment flow is related to worker flow and material flow. Equipment (e.g., bulldozers) and operators are separate resources, each with their own flows, but combined make up production units that will be engaged in unison for certain amounts of time to move or hold materials (e.g., when robotic equipment is involved, the production unit may be called a co-bot).

Tool flow is similar. Some tools (e.g., table saws) are stationary with workers coming and going to use them. Other tools (e.g., hammers) can be carried along by workers as they move about from one location to another.

TRADE FLOW AND TRADE LOCATION FLOW

The distinction we are making between trade flow (defined in this section) and process flow (defined later) is explained by drawing an analogy between manufacturing and construction. In assembly-line manufacturing, the product moves along a line from one workstation to the next according to the process flow, and production units (workers with their tools etc.) at each station—and thus more-or-less stationary—perform certain value-adding steps and thereby transform the product. In contrast, in fixed-position manufacturing as in construction, the production unit moves from one work area to another, more-or-less repeating the same kind of work.

It may be possible to structure the production system so that production units (of the same or different trades) can follow one another from one location to the next. This is not necessarily the case, but along this line Birrell (1980 p. 399) describes location flow as follows: “the construction work is made up of many flow lines, each of which contains a mobile work squad [crew or production unit] which moves through a set of work locations (which are the same set of work locations for all work squads).”

Birrell’s location flow refers to trade specialists moving from one location to another and performing work in each location; we define this as the trade location flow. In construction, the trade or their company must provide the requisite resources to meet the requirements of the project schedule. Often-times it is desirable to keep resource continuity. In the case of crew continuity, this means the same number of people and the same people. In practice the crew composition can change over time with people joining and leaving for various reasons (e.g., an apprentice joining the crew, a crew leader being called to help on another job, or work varying from one location to another). Therefore, trade location flow is synonymous with trade flow; it could be, but it is not necessarily synonymous with worker- or production unit flow. Figure 2 illustrates the direction of a trade flowing from Floor 1 Zone 1, to Floor 1 Zone 2, all the way to Floor 2 Zone 3, i.e., changing work locations over time, according to a takt plan.

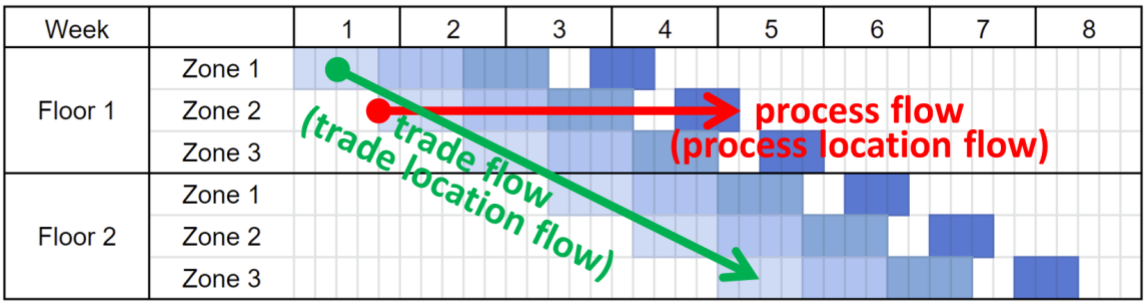

Figure 2: Trade flow and process flow

ASSEMBLY FLOW, ASSEMBLY SEQUENCE

Assembly flow is related to materials flow, but it focuses on materials with different characteristics coming together by performing a sequence of steps for the purpose of making a “final” product (i.e., the assembly). The term may suggest that discrete parts will be put together to make the whole but, in its general sense, assembly may also involve non-discrete materials of which a quantity more-or-less certain is needed (e.g., placing concrete, applying glue) to make the whole.

Assembly flow is mentioned in the Lean Construction literature (e.g., Koskela 1999 p. 246) but it is rare in construction project management to begin with simple parts and spell out all the steps from start-to-end that are needed to put them together. At the highest level of planning the master schedule depicts assembly flow in some very abstract way, but even when details are elaborated on in production-level plans, at the time of execution many aspects of the assembly flow still are not depicted. Might this be because people doing the work presumably will know what to do, and do they? Would more comprehensive assembly instructions be of value, e.g., for training, to measure process capability, and to establish standard work?

In any case, creating assembly instructions is a subject of formal study (e.g., Agrawala et al. 2003). It is also an art. Consider for example IKEA's practices (e.g., Pavlus 2015) and what can be learned from them for use in construction (e.g., Li et al. 2008). Danzico (2017) states "While many of us have at least one frustrating IKEA assembly story, what the process does accomplish merits astonishment. Each tool and part is enumerated. Each step is isolated and requires a kind of mindfulness to do one thing at a time. Right and wrong are charmingly illustrated with line-drawn figures. And all of this—whether for a 4- or a 400-part piece—is done without a single letter of type. In this way, good and affordable design is easily accessible to speakers of any language, any level, any skill. The instructions serve all equally."

To illustrate, Figure 3 depicts that more-or-less 14 steps are needed to assemble a BILLY bookcase (IKEA 2021). "More-or-less" is used here because defining these steps, what is included in a step vs. what separates one from the other, is an act of work structuring. The rationale for the characterization and depiction of each step has to do with presentation (e.g., graphical conventions, clarity, and comprehensibility in making the drawing) and the means and methods for doing the work (parts needed, changeovers, use of tools, number of times some work is repeated, etc.).

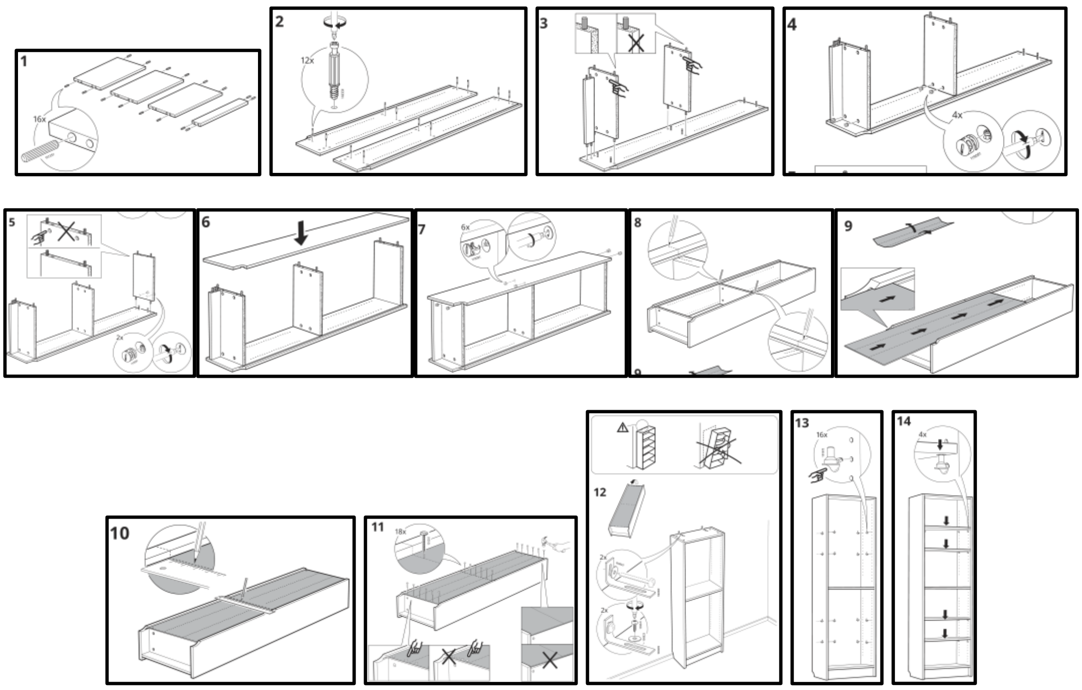

Figure 3: Assembly sequence for BILLY bookcase (IKEA 2021)

Of note is that steps are numbered, thereby implying a linear sequence although some could be re-sequenced without ado (e.g., steps 1 and 2). Furthermore, the numbering of discrete steps appears to imply a finish-to-start relationship although no such relationship arrows are shown or exist necessarily (e.g., a combination is possible by doing some work of step 2 followed by some work of step 3, then reverting to doing more work of step 2 followed by more work of step 3).

Also of note is that assembly instructions are non-specific about the actual, physical place or context where work may take place although these are of course relevant (e.g., if you assemble the bookcase while it is lying on the ground, will you be able to tilt it upright without hitting the ceiling?). The assembly sequence can be broken up to perform certain steps in one place and other steps elsewhere (e.g., steps 1 to 11 could be done in a place distant from the final installation location of the bookcase, but step 12 to secure the bookcase to the wall to prevent it from falling over, a safety concern, must be done in situ).

Because of the desired simplicity and worldwide use of IKEA instructions, not everything is or can be shown. For example, when securing a bookshelf to a wall made of studs and drywall, in seismic zones it is important to use screws long enough so they will be secured well into the studs, not in drywall alone; the sequence does not indicate the amount of time needed to perform each step; and a worker must have some skills (e.g., be competent in using a hammer or screwdriver). Furthermore, not everyone wishes to follow the assembly instructions. Creative minds may hack them to customize their assembly or invent new products (e.g., Rosner and Bean 2009).

OPERATION FLOW

When reading Lean Construction papers, a significant amount of confusion appears to stem from the distinction between operation flow and process flow. Many authors refer to Shingo's (1986) schema of production shown along two axes. One is along the flow of materials being worked on, the so-called process from raw materials to finished goods, and the other along the flow of steps a production unit (e.g., worker(s) with tools and equipment) performs on those materials. Of note is that this schema does not tie any steps to specific locations.

In this paper, we adhere to Shingo's definitions of operation flow and process flow. Operation flow refers to a sequence of steps to complete a certain scope of work, all done by "agents of production: the people in charge of making products, as well as the machines, tools, and other equipment that assist them" (Shingo 1986 p. 3). An agent could be a worker, production unit, or crew of a certain trade. At this level of definition of what an operation is, steps tend to not be location specific. Operation steps typically are a subset of steps in an assembly sequence. That is, operations are sequences of work chunks that must be performed more-or-less one after another, e.g., to make an assembly or a part thereof, to complete a part of an installation or all of it, or to deliver a certain service (e.g., steps 1 to 11 to assemble a BILLY bookcase make up the trade's "assemble bookcase" operation).

Operations comprise multiple chunks of work, to become an assignment to be performed by workers of a certain trade and typically of one company. Operations may span across multiple commitment plan periods. When a Last Planner commits to taking on an assignment, with assignments getting to them ideally in a reliable one-piece workflow (otherwise more work structuring might have been in order), they commit to completing the operation. The operation flow relates to people-and-machines utilization and productivity (point speed) (e.g., Rooke et al. 2007).

PROCESS FLOW AND PROCESS LOCATION FLOW

Process flow, with materials worked on (or services provided) stepwise by different trades, determines how long it will take to get the “object of production: the product” (Shingo 1986 p. 3) to the customer. This time is called the process cycle time and relates to the system’s speed (aka. throughput rate). A product may have to flow through several processes before it is ready for the customer, that is, multiple process flows make up the product flow (defined next). Figure 2 illustrates a process flow by showing the different trades’ work in different colors, with each instance of the process being performed in a certain location (e.g., on Floor 1 in Zone 2). Accordingly, we define process location flow to be synonymous with process flow. The more general term location flow is sometimes given this meaning (see the Discussion section) but differentiation between trade location flow, process location flow, and location flow in general is in order. Locations may or may not be occupied over the course of the duration of a project by trades performing steps belonging to one or multiple processes or operations.

A process flow comprises steps for each of the trades involved. These steps are part of the trade’s operations. So, process flows and operations flows are interwoven with one another. In figure 2, for example, the step in the darkest color may be the step for the final installation of a bookcase (i.e., steps 12, 13, and 14 of the assembly sequence for the BILLY bookcase make up the trade’s “install bookcase” operation).

VALUE FLOW, PRODUCT FLOW, SERVICE FLOW

Product or service flow like assembly flow is related to materials flow, but it specifically captures not only steps but also the time and resources needed to create something that is of value to the customer. Often left out are the specifics of space requirements and the location where steps take place. The product can be one of many things, physical or abstract. Product flow may be illustrated by means of a value stream map, showing cycle time as well as value-added time and non-value-added time (e.g., Cano and Rubiano 2020). So, as defined here, product flow aligns with value flow (e.g., Luoma and Junnila 2011).

OTHER FLOWS

It is possible to identify other flows, e.g., communication and information flows (e.g., Fisher and Yin 1992, Titus and Bröchner 2005), knowledge and understanding (which Pasquire (2012) and Pasquire and Court (2013) identified as the eighth flow, augmenting Koskela’s (1999) aforementioned seven flows that are the preconditions for work), monetary flows, flows related to managing multiple projects (what Sacks (2016) calls portfolio flow). The list provided in this paper is not exhaustive. Further work is in order to augment the set of terms provided here with refinements and additional definitions of flows.

DISCUSSION

The definitions of terms provided in this paper are internally consistent; they build on one another. Some readers may use a different spelling or definition for a term, e.g., work flow, work-flow, and workflow are all in use. There is no general agreement on spelling of this noun.

The terms location flow and trade flow vary in meaning when reading the literature. Among others, Binninger et al. (2019) appear to equate location flow with process flow (process location flow) as defined in this paper. Lehtovaara et al. (2021 Figure 1) appear to equate operations flow with trade flow as defined in this paper. Sacks (2016 Figure 6) appears to equate location flow with process flow as defined in this paper, and trade flow with operations flow as defined in this paper. The ambiguity may stem from Shingo's schematic of the structure of production (Figure 1-2 in Shingo 1986 p. 6), showing the relationship between process flow vs. operation flow. We stress that Shingo's figure is indeed a schematic (i.e., a map of something, not the real thing) depicting the various steps relative to each other on different axes, and the depiction should not be interpreted as indicating the actual location where these steps take place.

The term workflow used by different authors also refers to different flows. For example, Kenley (2004 p. 1) uses 'work-flow' and 'work flow' to refer to "the flow of resources through locations" so that "work completed in multiple locations will be treated as part of a continuous process" Kenley (2004 p. 5). His resource flow corresponds to trade flow (trade location flow) as defined in this paper.

It is hard to reach an agreement on terms when definitions are spelled out in a single language. It is even harder when terms get translated to different languages (e.g., try translating "lean").

FUTURE RESEARCH

Bertelsen et al. (2006) suggested that theoretical concepts pertaining to flows in construction should be developed. In addition to defining additional types of flow and studying interdependencies between flows (a topic broached by Howell et al. 1993 and Tommelein and Ballard 1997 among others), more research should be done to define metrics that gauge their quality (Kalsaas and Bolviken 2010 p. 52, Bølviken and Kalsaas 2011, Kalsaas 2012). This paper did not say much about metrics, but of course different flows will have different metrics, e.g., the PPC metric applies to workflow, and several flow metrics may be defined specifically related takt plans (Binninger et al. 2019).

Assessing the quality of combinations of flows is not an easy task. Sacks et al. (2017) attempted to define a composite metric for flow in production of repetitive construction projects but admit that "The meaning of a composite index value to a user is dependent on that individual's understanding of the notion of flow and it may obscure the relative importance of its components." One would expect any optimization of multiple flows simultaneously to require tradeoffs. "Various perspectives of flow must be considered and harmonized" (Binninger et al. 2019 p. 1279).

CONCLUSIONS

Many flows can be identified in construction. A first step towards managing them is to recognize they exist and to define them by name and by their characteristics. The purpose of this paper was to shed light on a certain number of flows namely workflow, worker flow, material flow, equipment flow, tool flow, trade flow and trade location flow, assembly flow (assembly sequence), operation flow, process flow and process location flow, and value flow (product- or service flow). We know all too well that this list of flows is not exhaustive, and that follow-on research is needed in this regard.

This paper contributes to the IGLC scholarly community's and the Lean Construction practitioners' body of knowledge by offering a cogent set of definitions for different types of flows encountered in construction production systems. The contribution of this paper is not so much addressing a gap in knowledge, but rather clarifying terms that are ambiguous in use by different authors.

Flows will invariably encounter turbulence if not subjected to work structuring. The distinctions made between flows and their metrics will help people make performance tradeoffs when designing production systems.

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THE IMPACTS OF LEAN IMPLEMENTATION REVEALED IN THE COURSE OF BUILDING A DIGITAL TWIN OF A CONSTRUCTION MANUFACTURING FACILITY

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ABSTRACT

Successful implementation of lean philosophy in various sectors has inspired many construction manufacturing companies to foster a lean culture and embark on open-ended lean transformation initiatives. This study presents the case of a panelized construction company that has embraced the lean philosophy over the past decade. Experiments undertaken during the process of building a digital twin of the company's production facility to verify the logic underlying the developed model reveal an increase in productivity. Using the same productivity regression models to model framing operations in two different years, the simulation of combined productive and delay times results in an underestimation compared to actual production data from 2013 but an overestimation compared to actual production data from 2017. Moreover, prominent lean changes implemented over the years that are positively correlated with productivity improvement are identified. These include standardizing the design and manufacturing processes, minimizing waste (including Mura, Muda, and material waste), ensuring a continuous flow, balancing the production line, following a just-in-time approach for the delivery of materials and implementing the 5S program. The findings underscore the long-term benefits of adopting lean thinking in construction manufacturing.

KEYWORDS

Lean thinking, construction manufacturing, benefits realization, productivity improvement, continuous improvement.

INTRODUCTION

The pressing need to fulfill diverse customer needs in a timely, efficient, and cost-effective manner continues to drive the adoption of lean production principles and

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methods. Although lean production is derived from the Toyota Production System, the philosophy has been translated to production models outside the automotive industry, with the construction manufacturing industry being a notable example. Despite the significant differences between the automotive industry and the homebuilding industry, there are also many similarities that have provided the rationale for the implementation of lean in construction manufacturing (Yu, 2010).

Many case studies can be found on the implementation of various lean principles in construction manufacturing and their associated benefits. For instance, a case study carried out at a modular construction facility by Moghadam & Al-Hussein (2013) found that, as a result of waste minimization—a fundamental lean principle—the duration needed to fabricate the modules for a two-storey building and the probability of a timely project completion could be improved from 36 days and 97%, respectively, under the current state, to 30 days and 98.5%, respectively, under the proposed future state. A similar study carried out at a precast factory projected that an estimated 50% reduction in production lead time could be achieved as a result of reducing batch and inventory sizes and applying the 5S program across the plant (El Sakka et al., 2016). A recent study at a modular construction manufacturer, meanwhile, estimated that lead time could be improved by 20%, along with a 15% reduction in man-hours, upon the implementation of various lean principles, including minimizing different forms of waste, balancing the workload, and balancing the workforce density on production lines (Zhang, 2017). In another case study, a cloud-based production planning and tracking system that comprised lean processes and building information modelling was applied on a construction manufacturing project (McHugh et al., 2019). Among the benefits realized by the system was reducing working at height, defects, and labor requirement by 75%, 60%, and 45%, respectively. Moreover, a comprehensive analysis of bottlenecks and the effect of incremental productivity improvement measures on the overall (i.e., global) operations (versus examining only the local effect on a particular altered process) at a modular construction facility found that a 22% increase in the weekly production rate could be achieved (Alsakka et al., 2020).

While the added value of implementing lean principles is evident in these case studies and similar ones that can be found in the literature, most of these studies evaluate the effect of lean based on abstract representations of the actual operations (i.e., virtual models of reality) at the time of the study and do not evaluate the long-term effects of implementation. When we build virtual models of reality, we filter out details that we deem unnecessary in order to reduce the complexity of the model. Nevertheless, the real world constantly changes, and this makes it challenging to anticipate the long-term effect of changes made in the present based on static virtual models. Hence, it is of value to observe the long-term effect of implementing lean practices. In this context, this study examines the productivity improvements achieved by a case company that has been actively implementing lean principles for more than a decade. These productivity improvements having been identified in the process of building a digital twin for the case company, as detailed in the methodology section. The case company specializes in panelized construction manufacturing and operates production lines in which walls, floors, and roofs are manufactured (to be shipped to construction sites for installation). The company's current operations are semi-automated and comprise a combination of manual, semi-automated, and fully automated activities. The company’s management team participated in lean training more than a decade ago and then sought support from researchers at the University of Alberta to devise and implement a lean transformation plan. Since then, many lean practices have been implemented and sustained throughout its supply chain. The company has been fostering a lean culture as these lean practices have become habitual and an inherent part of the company's operations. The study focuses particularly on the wall production line in showcasing the benefits obtained over time as a result of lean implementation.

METHODOLOGY

MODEL DEVELOPMENT

The work presented in this paper is a by-product of an ongoing research project in which a digital twin of the case company's manufacturing plant is being built using Simio software. (The architecture of the digital twin under development is outside the scope of this paper.) The digital twin mirrors the manufacturing operations as they proceed at the plant. After modeling the actual workflow at the plant as shown in Figure 1, experiments were needed in order to verify the logic underlying the model prior to further development.

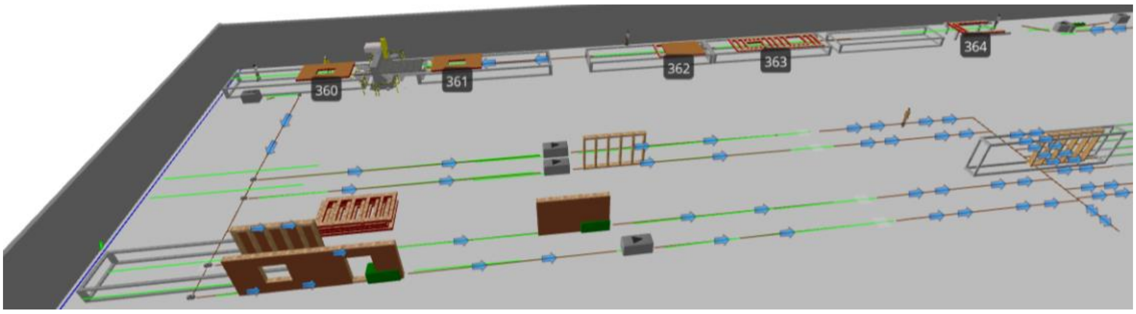
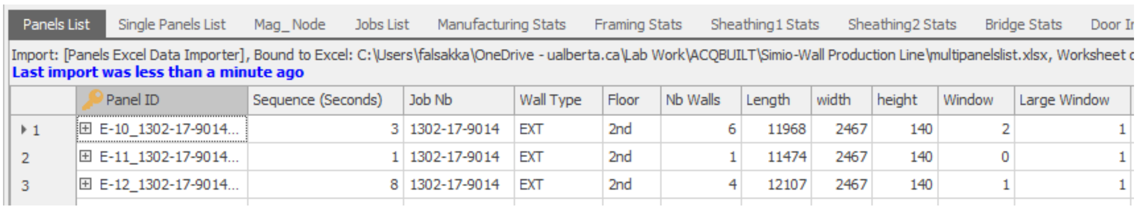


Figure 1: Digital Twin Under Development

To conduct these experiments, task time regression models, trained in a prior study by Shafai (2012) for the same wall production line, were deployed to model the durations of tasks performed at different workstations. The regression models were used to estimate the time required to complete a task (e.g., framing, installing sheathing, nailing sheathing) as a function of the design attributes of each panel (i.e., the number of studs, windows, doors, nails etc.). As such, the wall panel data fed into the model included both the design attributes and the manufacturing sequence, as shown in Figure 2. It should be noted that, although these regression models were trained based on time studies conducted in 2012 and were only used on a provisional basis to verify the logic of the model, using these regression models was key to discovering the benefits of the lean changes made by the company, as described in the "Value Gained from Having a Lean Culture" section of this paper.



Panels List | Single Panels List | Mag_Node | Jobs List | Manufacturing Stats | Framing Stats | Sheathing1 Stats | Sheathing2 Stats | Bridge Stats | Door I

Import: [Panels Excel Data Importer], Bound to Excel: C:\Users\falsakka\OneDrive - ualberta.ca\Lab Work\ACQBUILT\Simio-Wall Production Line\multipanelslist.xlsx, Worksheet

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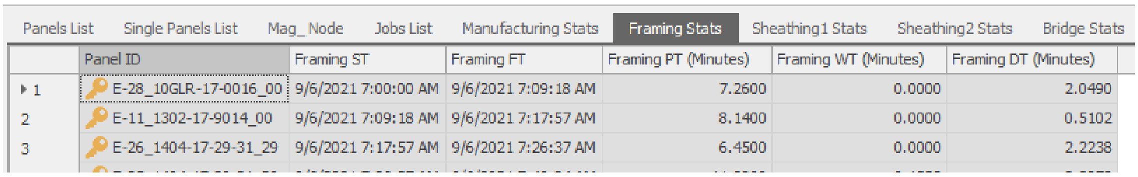
	Panel ID	Sequence (Seconds)	Job Nb	Wall Type	Floor	Nb Walls	Length	width	height	Window	Large Window
1	E-10_1302-17-9014...	3	1302-17-9014	EXT	2nd	6	11968	2467	140	2	1
2	E-11_1302-17-9014...	1	1302-17-9014	EXT	2nd	1	11474	2467	140	0	1
3	E-12_1302-17-9014...	8	1302-17-9014	EXT	2nd	4	12107	2467	140	1	1

Figure 2: Sample Model Input

The model simulates the manufacturing operations of the panels and calculates (1) the processing time of each panel at each workstation, (2) the time the panel waits to be transferred from one station to another (i.e., from when the manufacturing tasks are completed at a given station to when the downstream station becomes available), and (3) the delay time at each workstation, attributable to different sources of delay such as machine breakdown, material shortage, and rework, to name a few examples. It should be stressed that these delays are based on time studies conducted in 2012, and they have been reduced through various process improvement interventions over the years. A sample output of the model is presented in Figure 3.


Panels List | Single Panels List | Mag_Node | Jobs List | Manufacturing Stats | Framing Stats | Sheathing1 Stats | Sheathing2 Stats | Bridge Stats

	Panel ID	Framing ST	Framing FT	Framing PT (Minutes)	Framing WT (Minutes)	Framing DT (Minutes)
1	E-28_10GLR-17-0016_00	9/6/2021 7:00:00 AM	9/6/2021 7:09:18 AM	7.2600	0.0000	2.0490
2	E-11_1302-17-9014_00	9/6/2021 7:09:18 AM	9/6/2021 7:17:57 AM	8.1400	0.0000	0.5102
3	E-26_1404-17-29-31_29	9/6/2021 7:17:57 AM	9/6/2021 7:26:37 AM	6.4500	0.0000	2.2238

Figure 3: Sample Model Output

MODEL DEPLOYMENT

Productive, waiting, and delay times were computed and analyzed for the framing workstation using actual production data, and the model was deployed to simulate one day of operations (39 wall panels) in 2017. The model was fed data encompassing both the design attributes and the manufacturing sequence for the wall panels manufactured on that day. The results were compared to actual data on the time and location of each panel as it flowed throughout the wall production line (tracked using a radio-frequency identification system). At the case company, the timestamps when a panel enters a workstation on the wall production line as well as when it leaves the workstation are recorded. Based on these timestamps, the time elapsing while a panel is at a given workstation can be calculated. These time values include the processing time at each workstation, any delay time, as well as the time the panel waits before being transferred to the downstream station. It should be noted that the simulated day (in 2017) was a normal working day for which the radio frequency identification data did not include any outlier values unrepresentative of reality.

In previous R&D carried out by the case company, a simulation model was built based on the same task time regression models used in this study to simulate days of operation dating back to 2013. Similar patterns were observed for all these days, although, in the interest of brevity, only the results corresponding to a single day in 2013 (35 wall panels) are presented in this paper.

LEAN EVALUATION

An increase in productivity having been observed in comparing the 2017 data to the 2013 data, Q&A sessions were held with the case company's R&D department in order to gather more information about the lean practices adopted by the company. Moreover, lean-related research studies undertaken at the plant were reviewed. The most prominent lean practices adopted by the company were identified accordingly and are described in the "Lean Changes Implemented by the Case Company" section of this paper. Although the direct impact of the lean changes identified is difficult to evaluate, clear correlations between lean implementation and actual productivity improvement were identified, as discussed below.

VALUE GAINED FROM HAVING A LEAN CULTURE

The cumulative "*simulated productive + delay times*" and cumulative "*simulated productive + delay + waiting times*" at the framing station were computed for every iteration of a panel being framed. The purpose of these calculations was to determine the difference between simulated and actual values as the day progressed. The results for the 2013 and 2017 data are plotted in Figure 4 and Figure 5, respectively.

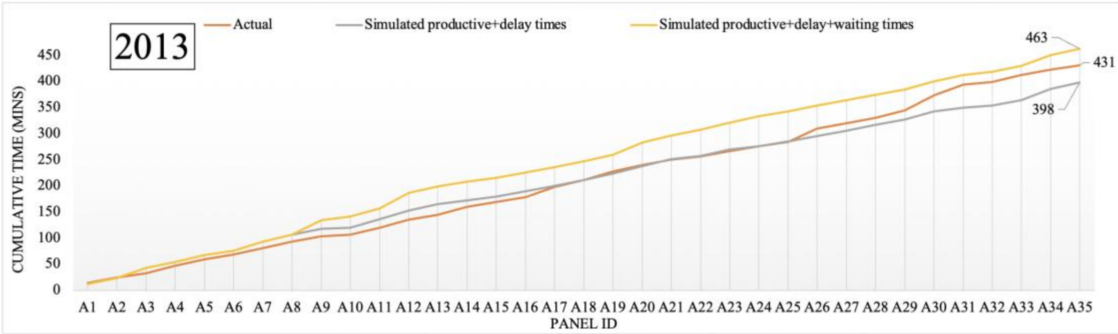


Figure 4: Actual Versus Simulation (2013 Data)

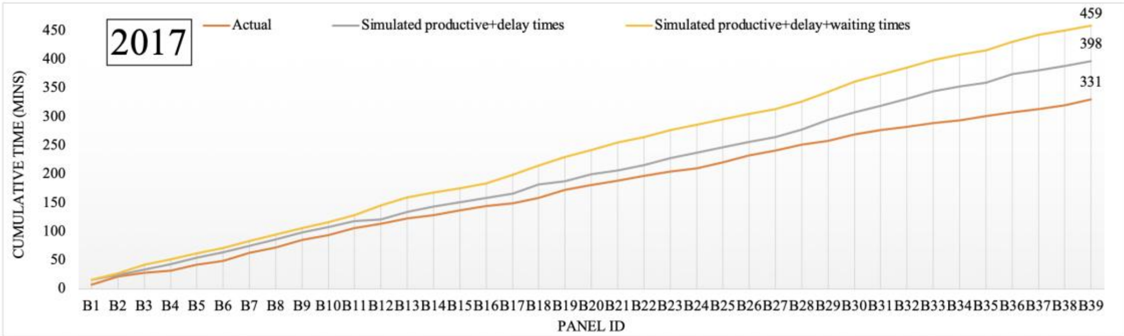


Figure 5: Actual Versus Simulation (2017 Data)

The simulation models generally overestimated the durations of tasks, with the simulated "*productive* + *delay* + *waiting times*" being higher than the actual times. However, it should be emphasized that the purpose of presenting these results is not to assess the accuracy of the task time models (which are outdated), but rather to determine whether any discernible improvements have been realized as a result of the lean transformation implemented at the case company in recent years. Among the most noticeable differences between the two charts is the position of the actual time curve (refer to the orange line) relative to the simulated time curve "*productive* + *delay times*" (refer to the gray line). The total actual time needed to frame all the panels on a specific day was found to be higher than the total simulated "*productive* + *delay times*" in 2013, but lower than the total simulated "*productive* + *delay times*" in 2017. Moreover, the difference between the actual time and total simulated "*productive* + *delay* + *waiting times*" increased from about 7% for the day in 2013 to about 38% for the day in 2017. Since the same task time regression models were used for both years, the resulting differences indicate that the actual framing times decreased. Based on the limitations of the available data, it is not possible to determine whether this decrease was the result of a reduction only in delay times and waiting times or also in productive times. Either way, the results show productivity improvements accompanying the lean transformation implemented at the case company over the past decade.

LEAN CHANGES IMPLEMENTED BY THE CASE COMPANY

While the case company seeks to continuously improve its overall operations, the main wall production line has been the focal point of its lean-related R&D over the years. As such, it is currently deemed the "most lean" production line at the factory. This section describes some of the most prominent lean applications implemented on the wall production line (i.e., the lean applications most clearly correlated with productivity improvements).

STANDARDIZATION

In the context of lean manufacturing, it is not possible to improve a process that is not standardized (Liker, 2004). Indeed, the effect of an improvement made to a variable process will vary depending on the state of the process, and may become counterproductive. Let us consider the example in which an extra worker is permanently assigned to reduce workload at a workstation where the cycle time highly fluctuates. When cycle time drops at this workstation, the extra resource becomes waste.

One prominent example of the case company's efforts to standardize its operations has been the establishment of standard operating procedures (SOPs) for each workstation. A well-defined set of activities and fixed resources (workers, tools, and machinery) is assigned to each workstation. The workers assist in the formulation of these SOPs, and as such they have a thorough understanding of all the information they contain. Each worker also carries a copy of the SOP for the workstation to which they are assigned so they can retrieve information about the tasks they are responsible for in a timely manner as needed.

The company seeks not only standardized processes but also standardized products. For instance, they adopted the concept of the "multi-wall panel" as proposed by Liu et al. (2017). In this system, a set of wall panels of the same height and dimensional lumber type are grouped and produced together as a single multi-wall panel. The multi-wall panel is then cut into single panels towards the end of the production process. The multi-wall panel system helps to reduce variability in production by reducing design variability in this manner. The adoption of this system has helped to mitigate variations in cycle times, thereby reducing idle and waiting times and supporting a more balanced production line.

CONTINUOUS FLOW

In a process that is founded on continuous flow, work in progress flows between workstations as they get pulled from downstream workstations when they are needed instead of getting pushed by the upstream stations once they are processed (Liker, 2004). Continuous flow has the benefit of eliminating multiple forms of waste when implemented on a production line, as the work in progress flows with minimal stoppages (i.e., waste in the form of waiting time in queue) between stations (Bulhões et al., 2006). This approach also exposes inefficiencies, which can then be minimized, thereby reducing cost and saving time (Liker, 2004). One-piece flow is the ideal version of continuous flow. In this approach, components and materials are processed one piece at a time and proceed directly from one workstation to the next (Liker, 2004). Nevertheless, it is not efficient to establish one-piece flow on production lines where variability cannot be controlled, since doing so will result in frequent disruptions to the flow (i.e., stopping the production line). As such, for settings in which cycle times tend to fluctuate (as is the case in construction manufacturing), the concept of FIFO (first-in, first-out) lanes has been introduced to control inventory between workstations. A FIFO lane is a production lane that has a limited capacity for work in progress (Rother & Shook, 2009). The first unit that enters the lane is the first one to get out, and, when the lane reaches full capacity, the upstream process must be stopped (Rother & Shook, 2009).

At the company under study, there is continuous flow between the first four workstations on the production line where most of the work is completed (as shown in Figure 6). The maximum panel length that can be accommodated on these workstations is 40 ft, so multi-wall panels can be up to 40 ft in length. This means that there is a one-piece flow when 40 ft long multi-wall panels are manufactured. On the other hand, when panels are shorter than 40 ft, a conveyor that is part of the framing station serves as a FIFO lane, as it can accommodate multiple panels waiting to be pulled to the sheathing workstation. The use of this conveyor as a FIFO lane is justified by the fluctuations in cycle times at the sheathing workstation. In particular, the cycle times at the sheathing workstation vary significantly depending on whether the wall is an exterior or an interior panel. An interior panel does not require sheathing and therefore can be passed directly through the sheathing workstation, whereas an exterior panel may spend even more time at the sheathing station than at the framing workstation. Hence, depending on the panel type, the sheathing workstation may be faster or slower than the framing workstation, and the use of a FIFO lane helps to reduce idle time at the framing workstation or starvation time at the sheathing workstation.

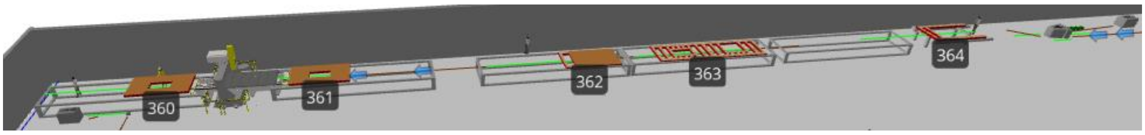


Figure 6: Continuous Flow

MINIMIZATION OF DIFFERENT TYPES OF WASTE

The key objective of any lean system is to eliminate waste in all its forms. Any inefficiencies that lead to use of equipment, materials, labor, or capital beyond what is deemed necessary for production are characterized as waste (Anearo & Deshmukh, 2016). The following subsections describe the case company's efforts to reduce waste in various forms.

Balancing the Workload: Minimization of Shop Floor-Mura

"Mura" is a type of waste in which imbalance in production results in overloading of human resources and machines at times but underutilization at other times (Liker, 2004). This can result from fluctuations in demand and/or inefficiencies in the design of operations. Leveling out production allows for the efficient use of available resources by evenly distributing the workload across all workstations and ensuring that no workstations are idle while other stations are overloaded (Binninger et al., 2016).

The case company has devoted a significant effort to balancing its wall production line. Major improvements have been realized by implementing strategies to alleviate bottlenecks and even the workload. This has resulted in reducing the waiting times at workstations that were originally faster than the other workstations on the same line. Examples of these strategies included the following:

- Some tasks that were performed at slower workstations on the production line (e.g., backing and blocking installation for interior walls) were not predecessors for the tasks assigned to the immediate subsequent stations and could be completed at later stages in the manufacturing process. Such tasks were accordingly moved to workstations later in the production line.

- Production scheduling was altered so that material preparation activities (e.g., cutting sheathing, cutting studs) are completed one shift or half a shift before the material is needed at workstations. This limits the waiting times resulting from delayed internal material supplies to workstations.
- The company regularly conducts analyses to determine whether, based on the current state of operations, various activities should be carried out at the plant or subcontracted. As part of this analysis, they actually perform the activities under investigation to evaluate whether completing them in-house is having an adverse effect on overall efficiency. For instance, they have performed this analysis for insulation, drywall, and siding installation activities, and in the latter case they in fact opted to discontinue their practice of installing siding as a result of this analysis, which had revealed that demand had declined to the point that they were not able to maintain a continuous workflow for this activity.
- The team lead responsible for the wall production line has the authority to allocate additional workers to a specific workstation based on demand in order to expedite production. For example, when there is a large number of exterior wall panels scheduled for a given day, the team lead may add an extra worker to the sheathing workstation in order to prevent a bottleneck.

Material Waste Reduction

Material waste (in which additional costs are incurred without adding any value to the final product) is among the most frequently targeted forms of waste in construction (Viana et al., 2012a; Anearo & Deshmukh, 2016). In this regard, automated approaches have been devised and applied at the case company for material waste reduction. Manrique et al. (2011) developed a combinatorial analysis algorithm to optimize the process of cutting lumber and sheathing materials for walls in order to reduce material waste. In addition to this optimization method, the company's implementation of the multi-wall panel system, previously explained, contributes to waste reduction, as a group of wall panels are framed together, which reduces the need for material cutting (and resulting material waste).

Additional Muda Minimization

The practices of leveling out the production line and reducing material waste have been adopted by the case company, as explained in the previous sections, to reduce waiting times and overprocessing of materials. Waiting and overprocessing of materials are categorized as Muda, which refers to any activity that does not add value to the final product (Liker, 2004). The company also takes measures to reduce other types of Muda, such as unnecessary transport of materials or movement of workers. Excessive transportation waste in particular, it should be noted, can lead to other adverse outcomes, including material damage, ergonomic problems, and unsafe working conditions (Pérez & Costa, 2018).

The case company has redesigned its factory layout to minimize unnecessary transport of material and excessive movement of workers. Material preparation mills as well as material inventories have been relocated to within close proximity to the workstations at which they are needed (refer to Figure 6 and Figure 7). One example was moving the mill for cutting sheathing to a location closer to the sheathing station. This has significantly reduced the time wasted on delivering pre-cut sheathing from the mill to the workstation.

Another example is the setup of the framing workstation. An automated feeding machine transfers pre-cut studs to a location from which the worker can directly pull them without needing to move from one location to another. Moreover, a workstation at which subassemblies for window and door openings are separately framed (before being directly nailed to the wall panel frame at the framing station) is located directly next to the framing workstation. Once the subassemblies for openings have been framed, they are placed on a table located between the two workstations in the same order in which they will be required by the framer. Such practices have contributed significantly to minimizing Muda.

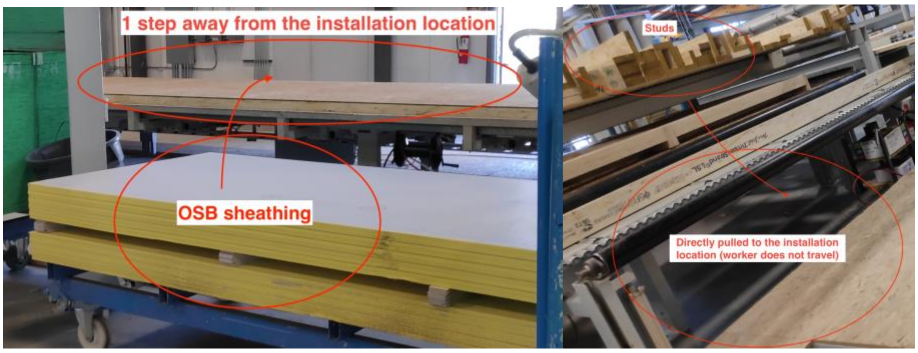


Figure 7: Material Inventories and Installation Locations

JUST-IN-TIME DELIVERY

The just-in-time (JIT) philosophy aims to deliver exactly what is needed when it is needed (Liker, 2004). The importance of such a philosophy is manifest in terms of reducing inventory and its corresponding drawbacks (e.g., storage requirement, material damage, material waste, double-handling, overproduction). The most notable example of JIT at the case company is its practice of procuring material and parts from the suppliers who pose the least risk in terms of delayed deliveries. For example, the company procures doors and windows from a local supplier who regularly delivers the ordered parts one day before installation. Moreover, the workers do not transport the delivered parts to the door and window installation workstation until the morning of the scheduled day of installation.

5S PROGRAM

The "5S" (*sort, straiten, shine, standardize, and sustain*) program is an important lean concept that helps to mitigate the risk factors that can result in errors, defects, and injuries in the workplace (Liker, 2004). A dirty and disorderly work environment is associated with inefficiencies, defective production, and safety hazards (Patra et al., 2005). As such, the implementation of the 5S program to address these issues has been proven to improve the performance of manufacturing systems (Omogbai & Salonitis, 2017).

The 5 Ss are clearly manifest in the case company's daily operations. For instance, only the tools and materials that are needed for a given activity are on hand (Sort). Moreover, every tool or material has a place, tagged with its corresponding label, and can be found in its place when not in use (Straighten). These practices are easily observable at the plant, as is the commitment to keeping the workplace clean (Shine). Although working with wood generates a considerable amount of sawdust and wood scrap, the floor is kept clean at all times. In addition to this, the mills are equipped with sawdust collection systems that workers must check and empty as needed on a daily basis. All cleaning instructions are clearly outlined in the company's SOPs and are part of the workers' daily routine (Standardize) as shown in Figure 8. Maintaining the S standards is critical to ensuring their ongoing beneficial effect (Sustain). As such, the practices of "Sort", "Straighten", and "Shine" are continually reinforced at the case company. For instance, it is well-established at the company that an employee should be confident at any given time to eat a slice of pizza that has been dropped. The president actually did this, reinforcing in a memorable and tangible way the importance of maintaining a clean and orderly workplace.

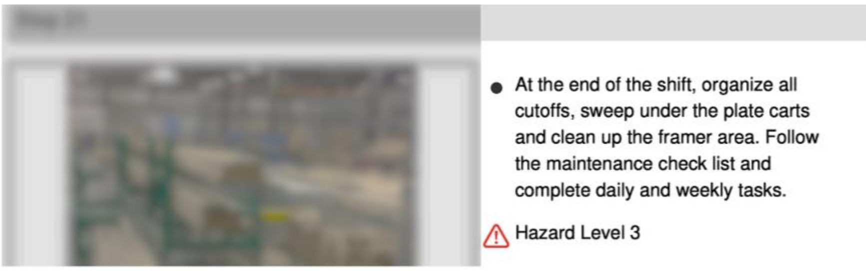


Figure 8: Snapshot from a Standard Operating Procedure

CONCLUSIONS

This paper highlighted the value gained from adopting lean practices at a construction manufacturing company. An analysis of actual and estimated productive, waiting, and delay times recorded and simulated, respectively, for the framing operations undertaken in two different years revealed significant changes in productivity corresponding to increasing implementation of lean principles. In particular, the same productivity models were used to estimate productivity-related measures for production days in two different years.

The results show that the simulated combined productive and delay times at the framing workstation represented an underestimate of actual times with respect to the 2013 data but an overestimate of actual times with respect to the 2017 data. In other words, the case company's actual productivity performance has generally improved over the years corresponding to its adoption of lean thinking and a culture of continuous improvement. Accordingly, some of the most prominent lean changes made to the case company's wall production line over the years, which contributed to the overall productivity improvements that the company has realized, were identified and described. These include standardizing the design and manufacturing processes, minimizing different types of waste, including Mura, Muda, and material waste, ensuring a continuous flow, balancing the production line, following a JIT approach for the delivery of parts, and implementing the 5S program.

It should be noted that the direct effect of implementing lean principles is difficult to measure, as numerous factors could alter the results. Specifically, if a very well-defined change is made to operations, corresponding variations are not necessarily solely attributable to this particular change, given the various sources of variability encountered in such working environments. Nevertheless, we observed general trends of productivity improvement accompanying the implementation of the operational changes.

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TEACHING UNIVERSITY STUDENTS THE LAST PLANNER SYSTEM THROUGH LEARNING-BY-DOING

Frode Drevland[1]

ABSTRACT

Using games and simulation have long been a staple in teaching lean construction. While such games work well for teaching narrow concepts and ideas, they struggle when it comes to teaching all of the complex interactions found in the Last Planner System (LPS)

This paper describes the development and implementation of a new approach to teaching university students LPS. Rather than using games or simulations, the students were tasked with using LPS to plan and manage their work on the course assignments.

The developed approach led to a superior understanding of LPS than what was previously seen in the course where it was implemented.

KEYWORDS

Lean construction, last planner system, teaching

INTRODUCTION

Construction education has increasingly focused on active learning over the past decade (Aliu & Aigbavboa, 2021). However, related to lean construction, this is not a new trend. For example, using serious games and simulations in the classroom has long been a staple in teaching lean construction (see e.g. Tsao et al., 2013).

According to Rybkowski et al. (2021), lean games and simulations provide *"the type of controlled laboratory conditions that are usually found in the physical and biological sciences where the impact of a single variable is tested and measured between rounds of play."* While the benefits of lean games and simulations are many, I would argue that the previous statement hints at a limitation of the typical games we employ in our community – the focus on a single or few variables at a time. In my experience, these games and simulations excel in teaching limited concepts and theories – for example, batching, variability and buffers, or push and pull – but can fall short in teaching more complex interactions—case in point – the last planner system (LPS).

LPS is a methodological framework for project planning and control (Ballard & Tommelein, 2021). It has several primary components: project execution planning, master planning, phase planning, lookahead planning, weekly work planning, and learning. Several games and simulations exist for teaching LPS. However, in my experience, teaching the interplay between all the LPS parts using a game or simulation is challenging.

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I have used Villego as an aid in teaching LPS for several years. Villego is an LPS simulation based on teams of 6-14 participants constructing Lego buildings (Warcup & Reeve, 2014). The simulation has two rounds. The first round relies on a traditional planning and control approach, and the second round uses LPS methodology. As far as lean simulations go, Villego is one of the most time-consuming ones, requiring at least four hours of class time.

While Villego is an extensive and comprehensive simulation, it has been my experience that it fails to teach LPS thoroughly. It covers certain LPS aspects well – such as pull planning and weekly coordination meetings. However, I have found it lacking in teaching other aspects. In particular, the students do not learn much about the different plan levels, constraints, or constraint removal through the lookahead process. In Villego, one plan functions as a mashup of a phase schedule, lookahead schedule, and weekly work plan. And while the student, to some extent, will discuss constraints during the game execution, there are no elements of formal constraint analysis.

As part of a comprehensive redesign of the assignment and assessment scheme in a course where I taught LPS, I decided to rectify this shortcoming in my teaching approach. One approach would have been to expand on the base Villego game. However, this would have led to significant logistical issues. Expanding the game would have led to splitting the game over several class sessions or having longer sessions. Considering I already had difficulties getting assigned room for these sessions, doing so was not an option.

Another option was to consider other games and simulations that purportedly better cover the missing pieces. (e.g. González et al., 2014). However, I chose to go in another direction. Instead of simulating using the last planner system in a serious game, I would have them learn LPS by using it throughout the semester to plan and manage their course assignments.

This paper aims to describe the approach I took in the course and its experiences. First, the paper describes the methodology – the teaching approach and how it was developed, and how I gathered data to document the experiences. After that, the paper presents results and experiences using the described LPS teaching approach, including the significant challenges and issues identified during the semester. Finally, the paper concludes that the approach is a sound concept, but there is much room for improvement in the implementation.

METHODOLOGY

This section describes how the new teaching approach was developed and summarizes the approach. The teaching approach was developed and introduced as an integral part of a new assignment and assessment scheme 7.5 ECTS credits elective course taught in the spring of the third year of a five-year integrated master's program. The LPS assignment was tightly interwoven with the rest of the assignment scheme. Therefore, to properly discuss the approach to teaching LPS, this section will first present some background about the course and the reasons for changing the existing assignment and assessment scheme.

CREATING A NEW ASSIGNMENT AND ASSESSMENT SCHEME

To help develop the new assignment and assessment scheme, I hired one of the students who had just taken the course as a teaching assistant. She did most of the work developing the new assignments based on my overall ideas and guidance.

The overall idea of the assignment scheme was to move from traditional assignments and school exam to portfolio assessment. At the end of the semester, the students would turn in a portfolio consisting of group assignments and individual reflection memos on the students' experiences participating in the lean games and simulation. I introduced the reflection memos to incentivize the students to participate in the lean games. However, as these did not have any relationship with the LPS teaching approach, the paper will not discuss these any further.

At the outset, the idea was that the course would have a group assignment for each of the topics taught in class. However, it occurred to us early that having all of these assignments be mandatory would result in a too high workload for the semester. Therefore, the teaching assistant and I decided to have three mandatory group assignments and a pool of elective assignments, of which the student would have to choose two. The idea behind the elective assignments was that for the students to choose which assignment they wanted to do, they would have first to attain some notion of the subject matter.

The assignments were mostly independent of each other. The only exception was two of the mandatory assignments. In one assignment, the student groups had to map out what value factors would be important for each group member when buying a home. In another assignment, each member first had to find and nominate a home currently on the market, and then the group had to use Choosing by Advantages (CBA) to select an identical home for all of them. It was encouraged – but not required – that the groups used the value factors mapped out in the first assignment as factors in the CBA analysis.

Most of the assignments had the groups using A3 reports. Sometimes with additional documentation. For example, the groups had to turn in an A3 report, a complete CBA form, and a two-page memo of the groups' experience with the process for the CBA exercise.

DEADLINES

With regards to deadlines, we took a novel approach. There were no fixed deadlines for the assignments. Instead, each group would decide when to hand in their assignments – with some restrictions. The groups could only submit one assignment per week for comments and approval. If an assignment had failed to receive prior approval, it would only count for 50% of normal if a student included it in their portfolio. We chose this approach partially to force the student to work more evenly throughout the semester and partially to put them in an environment where they need and benefit from using a planning method such as LPS.

LPS AS AN ASSIGNMENT AND AN ASSIGNMENT FRAMEWORK

We incorporated LPS both as an assignment in and of itself and as a framework for the other assignments. The students would use LPS to plan and follow up on the group assignments. At the end of each week throughout the semester, the groups would submit a report of their LPS usage. This LPS report consisted of their weekly work plan for the following week, their weekly work plan for the current week – with PPU and reasons for non-completion, their lookahead schedule for the following three weeks, and their phase schedule – if they had updated it. To enable the student's LPS use, we created a simple Excel spreadsheet that they could use.

As an aid for the groups' continuous improvement work, we had them do a team evaluation twice during the semester. The evaluation was based on Lencioni's (2002) five team dysfunctions: Absence of trust, 2) Fear of conflict, 3) Lack of commitment, 4) avoidance of accountability, and 5) Inattention to results. The dysfunctions take the form of a pyramid where lower-level dysfunctions are a cause of the higher levels ones. For example, lack of trust leads to fear of conflict.

In addition to group work on LPS, as part of the portfolio, the students also had to include an individual two-page reflection memo on how they had experienced the LPS process.

LIMITATIONS OF LPS IMPLEMENTATION.

While the idea was to give the students a more complete experience of working with LPS than what can be achieved through simulations like Villego, we did elect to have a somewhat simplified LPS implementation. We included no aspect of project execution planning, as this is taught in other courses in the master's program. In addition, we did not let the students do any milestone planning themselves; instead, we handed them a predefined milestone schedule at the beginning of the semester.

Of the five metrics now typically used in LPS implementations (Ballard & Tommelein, 2021), we only included Percent-Plan-Complete (PPC) and Frequency of Plan Failures.

LECTURES AND LECTURE SCHEDULE

While the assignments and assessment scheme were wholly revised, I left the lectures and lecture schedules mostly unchanged, including the lean games. The only notable exception was the addition of a startup workshop In the first week of the semester. Here, the students were organized into groups, given a cut-down lecture on LPS, and tasked with creating the group's phase plan for the semester.

SUMMARY OF LPS TEACHING APPROACH

- LPS used as a framework for managing group assignments throughout the semester
- Each group had 4-5 members
- The groups had to hand in an LPS report each week consisting of:
    - Revised phase schedule
    - Weekly work plan for the current week with PPC and reasons for non-completion.
    - Weekly work plan for the coming week
    - 3-week lookahead-schedule with constraint analysis
- Teaching assistants checked and gave feedback on LPS reports
- Student groups carried out two team evaluations during the semester
- Each student had to write a two-page reflection memo as part of the final course folder.

DATA GATHERING AND ANALYSIS

Gathering data on how well the teaching approach worked was done in two steps. First through observation throughout the semester by myself and two teaching assistants. This observation was *ad hoc*. We had no observation guides or tools typically applied in more formal observations. In addition to the observational data gathered throughout the semester, I analyzed the final folders that the students handed in. In particular, the groups' LPS spreadsheets and the individual LPS reflection memos. I imported all of the 39 LPS reflection notes into the computer software Nvivo for thematic analysis.

Since the folder assessment differed widely from the school exam used in previous course iterations, making rigid benchmarks like comparing grade outcomes would be difficult. Therefore, assessing how well this teaching approach had achieved the desired learning outcomes relied on subjective expert opinion. Using qualified experts' opinions has been shown to provide very accurate assessments when statistical data is not available (Vanston & Vanston, 2004). While it is preferable to rely on a panel of experts, this was unfortunately not possible in this case – myself being the only person having sufficient knowledge about the students' previous performance in the course.

RESEARCH LIMITATIONS

I did not plan from the beginning to carry out research on the new LPS teaching approach. Doing so was more of an afterthought. The data I gathered during the semester was for continuous improvement of the course, not for research and publication. Thus, I did not do any structured data gathering about the student – for example, their educational background and previous knowledge – beyond what I gathered during a normal course execution. Nor did I make any attempt to benchmark the students' LPS knowledge gained through the course related to the previous, more traditional version of the course.

The evaluation of the teaching approach's efficacy in teaching the students LPS rests solely on my expert judgment. I have tried to be as honest and objective in my assessment; However, there is always a possibility of unconscious bias – especially since I am evaluating something I myself created. Thus, while I later in the paper argue that the teaching approach worked well, the evidence for this is somewhat tenuous. A more stringent test protocol would need to be devised to properly assess how well this teaching approach works versus more traditional approaches. However, I would argue that this research still provides adequate proof of concept of the feasibility of this teaching approach.

RESULT AND DISCUSSION

This section presents results and experiences using the described LPS teaching approach, including the significant challenges and issues identified during the semester.

OVERALL RESULTS

The students reported varied experiences using LPS to manage the work on the course assignments. While most of them reported gaining an understanding of how LPS works and is beneficial in construction projects, they were diverse in their opinion on how they had experienced it using it themselves. Some were very enthusiastic, expressing that they would continue using LPS for group assignments in other classes. However, others expressed that they had experienced LPS as complete overkill for managing the coursework – the effort they needed to use LPS vastly outstripped the benefit they had from it.

This divide seemed to stem from personal preferences mostly. The students who liked using LPS typically voiced a strong preference for having highly structured work, while those who found LPS to be overkill preferred more ad-hoc approaches. However, most of them who found using LPS overkill still acknowledged that it would be beneficial to use LPS on construction projects.

The students' comments suggest that I should have communicated to them more clearly the intent of using LPS in the course. It was not primarily to make it easier for them to plan and control their work but instead to learn LPS.

Based on the semester's observations and the reflection memos' analysis, the teaching approach worked reasonably well for teaching them LPS. The students gained a better and more in-depth understanding of LPS than seen in previous incarnations of the course. However, still not as good as desired. As pointed out later in this section, there is significant room for improvement, discussing issues and challenges identified during the semester.

OPEN-ENDED ASSIGNMENTS AND ASSIGNMENT SCHEME

One issue I had not considered when designing the assignment scheme was the students' ability to handle its open-endedness. The first two years of our master's program courses contain primarily engineering fundamentals such as math and physic. That is, courses where they get clearly defined problems on a silver platter, which they employ "cookbook" recipes to solve, with one absolutely correct answer, with a specified deadline. Therefore, it was challenging for the students to define their own problems with no clear solution path, no objectively correct solution, and no set deadline. The students were mentally unprepared to tackle many of the assignments they saw in this course.

Many of the students reported feeling overwhelmed at the beginning of the semester. They had no clue how to tackle not having fixed deadlines for the assignments. However, most of them noted that they had managed fine when they got over the initial shock and started planning out the work to be done.

While I believe that the students should be taught to handle open-ended problems from the beginning of their studies, my influence on the overall study program is limited. However, introducing the concept of open-ended problems at the begging of the semester – through lectures, discussions, and games – should remedy the worst of the mental shock that some students experienced.

PHASE SCHEDULING

Phase scheduling within LPS is typically done with pull planning. However, since pull planning was not on the lecture schedule until a few weeks into the semester, I elected to have the groups create the first phase scheduled through more traditional means. I based this choice on the assumption that they already had some rudimentary knowledge of project scheduling. Unfortunately, this assumption proved to be wrong. The students had not encountered any form of formalized planning in previous courses. Nevertheless, through some guidance, they could still create passable phase schedules. In hindsight, it would have been better to rearrange the lecture schedule and teach them pull/planning from the get-go.

LECTURE SCHEDULE

The previous issue shows that it was a mistake not to rework the lecture schedule and lectures. My original thinking was that the students would learn LPS by using it as they went along throughout the semester. However, as previously pointed out, this thinking assumed they had more previous project planning knowledge. In hindsight, I should have given them a thorough introduction to the subject matter before throwing them in at the deep end. Thus, I will include more project planning and control material in future iterations at the beginning of the semester, including moving up the LPS lectures and the Villego simulation.

Another issue with the lecture schedule was that it was too crowded. There needed to be more room to have class discussions and make clarification on the last planner use. The student groups got weekly feedback on their LPS reports from teaching assistants.

However, these were insufficient in clearing up some common mistakes and misconceptions – for example, misunderstandings about constraint types as described later in this paper.

LOOKAHEAD PLANNING AND CONSTRAINT ANALYSIS

One of my primary reasons for using this approach to teaching LPS was better to teach the students about constraints and the lookahead process. This approach did give the students a better understanding of these topics; however, not as good as I had hoped.

The students themselves expressed differing opinions about the lookahead planning and constraint analysis. While most found it helpful to enable them to identify and remove constraints in advance, some expressed that it had been more or less a useless chore as they had no real constraints.

Most of the students expressed that they found identifying constraints difficult. This problem was also evident in their weekly LPS reports. I identified two main underlying issues as to why constraint identification was difficult for them. First, the work to be done was inherently too unconstrained. The different mandatory and elective group assignments were, for the most part, unrelated. That is, they were free-standing exercises with no constraints between the tasks. Also, few of the tasks were of a sufficient size that would yield many internally constrained sub-tasks

Second, the students were unable to identify constraints that were there. An industry practitioner in a construction project will identify constraints based on their experience doing the same or very similar tasks. Students can and will do the same to a certain extent. However, they are limited constraints related to their generic experiences with group tasks - such as booking a meeting room for the group to do a task or their availability to do a task. They lack the domain knowledge to detect issues with the task itself without starting to do it.

I had naively hoped that this is what they would do just so – to start doing preliminary work on the task, way before the date they had planned for the assignment to be finished, to sufficiently understand what they would need to complete the task. However, unfortunately, the students did no such thing. Instead, they would block out a day or two for doing the assignment on the plan and not look at it until this date.

For example, one group assignment entailed creating a takt plan based on a case description. This case description had – unintentionally – ambiguous and missing information. None of the groups flagged this as a constraint in the LPS process. Indeed, very few groups even raised questions about the insufficient information during the task execution – most of the groups relied on making-do and made assumptions rather than pausing the task to get clarification.

The takt planning example also relates to another issue of task identification – the groups focused too narrowly on their own work. They were mostly blind concerning external issues, like problems with the assignments. Another example: for some of the possible weekly assignment submissions, I had forgotten to create the submission in advance in the learning management system (LMS). No group ever identified this as a constraint in advance, but many would contact me right before the deadline to get me to do so.

In addition to having problems identifying constraints, many students struggled to classify correctly the constraints they did identify. For example, most groups reported constraints and reasons for non-completion related to assignments in other courses. I would argue they should have classified these occurrences as labor constraints. The groups could not do the work because their laborers – the students – were tied up elsewhere. However, many groups did not categorize this as labor constraints but external condition constraints.

The student's inability to classify constraints correctly is not due to any weakness of the LPS teaching approach. Instead, the teaching approach here exposed a failure to give the students a sufficiently good understanding of the topic from the related lecture and the course literature. Applying LPS to their own work illuminates their understanding of the topic in a matter that the more traditional school exam never could.

For future iterations of the course using this teaching approach, introducing more constraints into the assignment work is of primary concern. One possibility would be to build upon the accidental constraints that were introduced; the missing and erroneous information in the assignment texts and the late posting of submission links on the LMS.

To incentivize the students in identifying these constraints, their ability to do so could be considered in the grading. However, doing so could be a tricky balancing act. Since the students have limited prior knowledge of the tasks they are embarking on, they will often not be able to identify constraints such as missing information until the task is well underway. Therefore, grading their ability to identify constraints could lead to them making shadow plans and completing the task before the tasks go onto the official plan, enabling them to identify constraints after the fact.

Another option for introducing more constraints would be to create more interlinked assignments and possibly interlink the groups. For example, there was a weak link between the assignments on value and CBA. The groups were encouraged – but not required – to use the output of the value assignment as the input to the CBA assignment. Making doing so mandatory would create a hard constraint between the assignments. Furthermore, instead of having the groups use their own work, they could be tasked with using the results from another group.

WEEKLY WORK PLANNING WAS TOO EASY

It became evident early on that that weekly work/planning was too easy – within the parameters we had given the students. I told them to plan within standard LPS guidelines. That is, no activity should span across weeks. The problem was that the students would allocate three days to a task that might take two hours, and there was no issue for them getting it done during this time frame. This problem occurred partially due to unclear instructions; however, a significant underlying challenge is that the total assignment workload was too low to make planning the execution of it a challenge at the week level. I partially remedied this issue by specifying that no assignments should span more than a day.

Another reason – for the work planning being too easy – is that most of our students have a high degree of flexibility in their lives. For example, they might have programmed lectures, but we do not require that they attend them. Moreover, they often have few other obligations. For example, they seldom have family obligations and have no qualms about using nights and weekends to get work done.

In addition to students individually having a flexible schedule, the groups had too much internal flexibility. That is, there was a lack of skill diversity in the groups. All the students have the same skill set and could perform all the tasks. Thus, if one of a group's members could not do any work – e.g., due to becoming sick – any of the other group members could easily pick up the slack. This situation is very different from what one will encounter in a construction project, where different trades have specific skills needed for specific tasks. The task of wiring a circuit cannot be shifted over from an electrician to a plumber.

It could be possible to design group assignments where the different group members are assigned specific roles and tasks – similar to what we often do in Lean simulations like Villego. However, I fear that the roles would be difficult to enforce without the active oversight from a facilitator – not possible in this teaching approach. Thus, I would argue that a better option is to have different groups have different roles. That is, having the groups be dependent on each other, as previously discussed.

TEAM DYNAMICS

In general, the groups worked well together. Some groups had initial issues with working together but could identify and handle them as part of the team evaluation process. For example, several groups reported having issues due to different ambition levels among members – for example, group members who were content with just passing the course would skip group meetings. The group evaluation processes gave them an avenue for bringing the matter to light.

In hindsight, I should have had the groups create conditions of satisfaction for themselves at the beginning of the semester. Doing so would have brought up issues like different ambition levels at a much earlier stage

FACILITATION

As all lean educators know, good facilitation is a key to success when running lean games and simulations. However, in this case, the groups did receive facilitation in the traditional sense of having a facilitator lead them stepwise through the process.

After the initial startup workshop, the groups were left more or less to their own devices to start using LPS and hand in their first LPS report. They then received comments on their weekly reports from the teaching assistants through the LMS. In addition, the student assistants and I held weekly supervision sessions where we were available to help the groups might with any of their assignments, including the LPS reports.

The described efforts worked reasonably well in steering the groups in the right direction; however, a key component was missing. In addition to providing feedback and help to each group individually, it would have been beneficial to have plenary discussions at several points throughout the semester – i.e., to facilitate the kind of guided reflections that are typically part of lean games and simulations. However, as previously mentioned, the existing lecture schedule did leave room for them.

LEARNING BY DOING VERSUS VILLEGO

I would argue there are two main benefits of using the learning-by-doing approach described in this paper versus Villego: 1) the time horizon and 2) the fidelity of the LPS implementation.

While Villego is one of the most time-consuming lean simulation games, it is still run over a very short time horizon – typically one 4-5 hour session. In the learning-by-doing approach, the students use LPS throughout an entire semester. The benefit of doing so is that they can absorb and mature the knowledge piecemeal over time. LPS is a complicated system with many moving parts. Absorbing it all at once is hard, especially for university students with little to no practical experience to serve as anchor points for the knowledge.

Regarding the fidelity of the LPS implementation, Villego uses a very simplified version of the LPS. There is only one plan. This plan functions as a mashup of a phase schedule, lookahead schedule, and weekly work-plan. Thus, Villego gives a limited feeling of LPS as a concrete tool. This simplification is necessary due to the time horizon Villego is run within. While the learning-by-doing implementation this paper reports on also made several simplifications – for example, PPC was the only metric used – running a semester-long exercise allows for a full-on LPS implementation. The limiting factor here would be software. While the Excel workbook I made worked well enough for the current implementation, a full implementation would likely require moving from Excel onto more dedicated software.

While I would argue that the two described benefits are significant, that is not to say that Villego and similar simulations do not have a function in teaching LPS. They can work well for introducing the fundamental concepts embedded in the system. In real world practice, Villego might be used to teach LPS to practitioners immediately before they will start with actual use on a project. From the learning-by-doing in real life, they attain tool skills and cement the concept they have been introduced to with Villego. For university students, the situation is very different. There might be years from when they learn LPS at the university until they encounter it in practice and can start to learn the tool skills. Hence, it is beneficial for them to practice something very close to actual LPS use. However, LPS simulation games can also function here as an excellent first introduction to the concepts and ideas behind LPS.

CONCLUSION

This paper has described and discussed a new approach for teaching LPS to university students. I would conclude that the approach works at the conceptual level; that is, it is beneficial to have students use LPS over an extended period to plan and control some work. However, the practical implementation could have been better. Some of the issues were minor and easily corrected in the future. For example, to tweak the lecture schedule and add conditions of satisfaction for the groups. However, other issues require a more fundamental redesign of the implementation. The most significant issue is that the work done for the students was too unconstrained for various reasons. This issue will likely require something more than minor tweaks.

In described course implementation, the students used LPS to plan and manage their course assignments. Another option could be to go back towards simulation but have it as a semester-long affair instead of just a single class session. Doing so will likely require the simulation to be performed on a digital platform. It is unlikely that the university would allocate me room to run a semester-long lego-building exercise. I am currently exploring using the game Minecraft as a platform for this purpose.

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DEVELOPING PROJECT VALUE ATTRIBUTES: A PROPOSED PROCESS FOR VALUE DELIVERY ON CONSTRUCTION PROJECTS

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ABSTRACT

Increasing efforts are being made by lean researchers and practitioners to improve value delivery in the built environment. However, the preliminary process to identify a substantiated list constituting the interests, desires, requirements, and design essentials of different stakeholders on projects is still vague and unorganized. Establishing the Value Attributes List (VAL) is considered fundamental for delivering value. Thus, to answer the question of how to develop the VAL, a set of guidelines and steps are provided. The process was constructed by performing action research and engaging two case studies depicting two Canadian public projects. This paper also provides a generic list of value attributes to be the starting point for the project team. The list included the major categories to be considered on projects. Findings suggested that developing a customized team-led list is particularly important and pursuing a clear direction on the subsequent steps for monitoring is required. The research concludes that an in-house advocate is needed to (1) promote the process and move it onward, and (2) to make sure the whole team and project stakeholders understand the importance of these value discussions.

KEYWORDS

Design management, benefits realization, collaboration, value delivery, value creation.

INTRODUCTION

At the onset of projects, owners or developers typically go for consultation to determine important decisions including the decision to launch their projects. Project initiation is an important phase authorizing a new project (Project Management Institute, 2004). Business cases and feasibility studies are thus prepared based on the general vision offered by owners and sponsors. With the project's goals in mind, the owner's team would identify a set of general requirements and limitations called Owner's requirements. Here the owner value proposition is equivalent to the business case and the reasoning behind

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the project initiation (Hjelmbrekke et al., 2017). Then, Project Objectives are developed which embrace the funding requirements, Base program, Added Value incentives Items, Base target Cost, Final Target Cost, Milestone Schedule, and any other objectives agreed to by the parties (CCDC 30 Integrated Project Delivery, 2018). Therefore, with complex projects and in a fast-changing environment, the vision and project goals need to consider the wider perspective of different teams and stakeholders (Laursen & Svejvig, 2016). The general requirements and the needs of different stakeholders are thus harder to compile on the onset of projects. To this end, the recognition and creation of value on construction projects is directly dependent on clear strategic thinking (Normann & Ramirez, 1993) including the engagement with diverse stakeholders and meeting their needs.

The briefing exercise has been a major process performed to identify the needs, desires, and aspirations which are translated into design criteria and design concepts (Ballard & Zabelle, 2000). The exercise includes a meeting that encompasses the key stakeholders. The result of such exercise is a brief, which is a formal document that records the needs of the involved parties. However, concerns about end-users' needs being generally overlooked are reported, leading to end-user dissatisfaction (Pemsel et al., 2009). Other concerns are discussed in the literature including the impact of project brief clarity on project performance (Vahabi et al., 2020). Additionally, Pegoraro and Paula (2017) identified the critical factors affecting the requirements' identification process, including: the lack of open and effective communication, lack of clarity of the objectives, lack of precision in defining client's requirements, client's inexperience, difficulties in accommodating requirements of all involved stakeholders, among other problems. The study also provided some guidelines for overcoming such problems within design, focusing on information clearness to define objectives. Nonetheless, the study suggests future research to investigate more the requirement engineering and requirement management practices. Moreover, additional research was called for to maximize value creation for stakeholders with theoretical and empirical antecedents (Rojas & Liu, 2015). In short, requirements identification and value generation are interconnected concepts; thus, there is a need to revisit their approaches to identify them in a coherent manner.

While identifying owners' requirements might be thought of a basic and clear process, practitioners expressed their concerns about owners avoiding the detailed identification of their requirements to prevent future change orders, as they are proved to be the major cause for change orders due to changes in their requirements and scope (Khoso et al., 2019). Additionally, the problem lies in either the inability of the client in describing their needs, or the unconsciousness about the exact requirements and desires, with some needs surfacing late in the process (Wandahl, 2004). Moreover, the lack of a clear process to develop the value targets is also a prevailing issue. In this paper, we will be focusing on the phase where the owner had gone through the steps of establishing the preliminary vision and goals of the project, and now there is a need to develop a set of attributes representing the requirements and needs of the different stakeholders and what they value. Different stakeholders in building perceive projects' value differently and have diverse requirements (Haddadi, Johansen, et al., 2016). Though these value considerations depend on the involved parties and the nature of the project, identifying some general and basic concepts connected to the value of building projects as perceived by different stakeholders is needed. The literature calls for maximizing the environmental, social and economic value of projects as part of the sustainability trend and demand, however, it overlooks the other core value attributes justifying this that it is context dependent. The main problem is that value attributes impact one another and are correlated which mandates the need to explore them in a structured inclusive way, to avoid the challenges imposed by overlooking the diverse values of myriads stakeholders. A need to investigate who is interested in what, and who is responsible for attaining the value attributes is vital.

Consequently, the research herein is trying to answer the following questions: (1) What are the basic and main value considerations discussed in the literature and need to be considered on a project? And (2) How to identify a customized clear and inclusive value attributes list that reflects what is needed to have a successful project? The research contributes to the body-of-knowledge by proposing the essential early steps needed for preparing a solid and cohesive project value attributes list and advising on the topics that need to be considered for this list. The list is considered the foundation for delivering successful projects in terms of their intended value. The literature had focused on the subsequent steps in the value delivery framework, therefore, aiding the initial steps within the process was needed.

LITERATURE REVIEW

THE VALUE DELIVERY CONCEPT

The concept of maximizing value has been regularly called out to in the construction engineering and management literature. Specifically, maximizing economic, environmental, and societal value of the built environment is regarded as a trend and as a vision for the next 50 years (Levitt, 2007). Authors have then examined the numerous terms that were adapted in the construction literature in reference to value in the built environment. Thus, to resolve the discrepancies and the inconsistency, Barima (2010) conducted a study on the “best term which (if fulfilled) can be used to mean value in projects”. Results revealed three main terms: goals, standards, and needs as a representation of value on construction projects.

Benefits realization is another concept in relation to value generation, where the main challenge for generating value is understanding the project holistically and ‘generating benefits aligned with strategic intent’ (Tillmann et al., 2012). Mainly, value delivery includes: fulfilling goals, desirable, and standards, achieving end-users’ and teams’ satisfaction, meeting project purposes, and addressing hidden needs and intangible objectives (Barima, 2010; Haddadi, Temeljotov-Salaj, et al., 2016). Understanding the value concept and the value delivery context is the first step towards pushing for improved practices for achieving higher value on projects and from a life cycle perspective. Value delivery is not a straightforward process but offering guidelines and best practices would help in getting towards the goal. Value is dynamic by nature, so it tends to change throughout the project (Khalife & Hamzeh, 2019). Yet, the initial process of identifying the general value attributes during the early conceptualization of projects would help in avoiding changes downstream and increased costs (check “MacLeamy curve”).

CORE VALUES AND VALUE TRADE-OFFS

Core values is a common terminology used in companies or businesses offering services and/or products. On top of the core values come social responsibility and customer service. In construction, core values are discovered in different studies.

Emmitt et al. (2004) presented six key areas for value: Beauty, Functionality, Durability, Suitability (for the site and the community), Sustainability (respect for the environment), and Buildability. This value hierarchy is considered as the project’s objectives. Then through workshops, the team would specify the sub-objectives. A distinction between process and product values is highlighted in the literature, where market value and utility value are types of product value, and the process value is related to the ethical value (Wandahl, 2004). Another research project, called “Oscar – Value for User and Owner of buildings”, highlighted the means which contribute to value creation (economic incentives, knowledge, contract, and processes and assurance quality), and identified 4 characteristics contributing to value creation: economic value (investment cost, core business cost, etc.), social value (people and organizations), environmental, and physical (space and infrastructure) (Bjørberg et al., 2015). Zhang & El-Gohary (2016) developed a value hierarchy that is based on the trio environmental, social, and economic value, and 50 sub-values were assigned to these categories.

Hjelmbrekke et al. (2017) explained about the importance of governance on enhancing value. They suggested a governance framework model with the following key components: strategic need (why questions), strategic effect (what questions/business perspective), project success criteria (intended outcome: user effectiveness and project efficiency), suppliers project business model (how questions: design team plan to align outcome to owner’s needs), and project business model (how: metrics/ KPIs). Kheirandish et al. (2020) presented a comprehensive value framework for design and collected more than 500 responses on the Human Values Survey. Nine value groups were identified: carefulness, justice, ecology, respect for others, meaningfulness, status, pleasure, respect for oneself, and personal development. This value framework is meant for designers to widen their perspective on human values, so they address these in design.

Moreover, given the fact that requirements change during design development and the fact that conflicting needs exist on any project, a recent study by Serugga et al. (2020) suggested a design decision support model based on the utility theory to assess the changing requirements, compare competing alternatives, and predict emergent needs. In fact, conflicting needs on projects are pushing research to offer tools that help design teams in the trade-off exercise. Arroyo (2014) discussed in details different multiple-criteria decision making (MCDM) methods to help designers in their decisions to select sustainable alternatives and explained the advantage of the choosing-by-advantage (CBA) technique. CBA was recommended and tested on different studies; it proved effective in helping teams understand value vs. cost and that trade-offs between factors are not linear (Arroyo, 2014). Additionally, studies have been exploring models to measure value creation on projects and prevent value losses. Huovila et al. (1997) advised teams to (a) closely coordinate with owners about their requirements, (b) use systemized management tools for the requirements (for instance use quality function deployment (QFD), and (c) collaborate with all participants generating design and construction information (Huovila et al., 1997). These suggested practices, along with other improvement tools, such as interactive coordination, checklists before/after design, and value stream mapping, are expected to generate improvements in the design process and prevent loss of value on projects (Freire & Alarcón, 2002). Likewise, Giménez et al. (2020) proposed a value analysis model which helps in value loss identification through proposed indexes. The approach is important as it suggests a quantitative method for identifying value loss.

With these different studies and attempts to provide categories, value listings, and approaches for emergent needs and value loss identifications, this research builds upon these ideas and take one step forward as to identify the initial steps and guidelines to customize the list of value attributes. In this research, we define the value attributes list (VAL) to be the collection of project vision, guiding principles, and stakeholders’ needs by compiling both process and product value propositions to guide the design decisions.

METHODOLOGY

The objective of the present study is twofold; first, offering a generic list of value attributes as a template and starting point for discussion among the project team, and second, providing the recommended steps to develop the customized list of value parameters then follow up on the process of value alignment and attainment. To attain these objectives, the action research approach was adopted. Action research focuses on contributing solutions to a problematic situation by testing research and proposed methods in real life practice; it includes five phases: diagnosing, action planning, action taking, evaluating, and specifying learnings & reflections (Susman & Evered, 1978). The steps of the methodology are described in **Error! Reference source not found.**. By following the action research approach, the proposed list and steps were validated in the action taking process discussed in the two case studies.

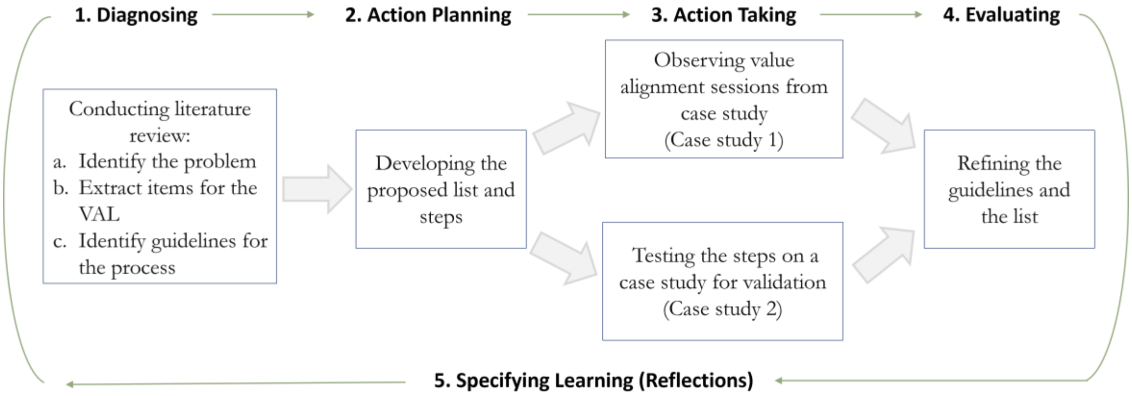

Figure 1. Action Research Methodology

The first step is diagnosing (1), it includes identifying the problem. As explained earlier in the introduction and literature, there is a need to advance this area specifically in relation to developing a substantiated team-led list and informing practitioners on the steps and best practices to do that. The problem lies in the unstructured methods usually performed in practice. After identifying the problem and the need for proposing solutions, the subsequent step was conducting an extensive literature review to extract the core values that are generic to any project. The construction management literature offered separate lists which we tried to consolidate to produce an extended collective list. Some guidelines and preferred practices were also extracted as part of the diagnosis and exploration. Then, the final list and the proposed steps are put together as part of the action planning step (2). Afterwards, for the action taking phase (3), two case studies were employed to (a) observe the value alignment sessions and assess them to extract best practices, and (b) implement and test the proposed process developed as part of the suggested action plan. Based on the results from the two case studies, the evaluation phase (4) was conducted. It involved assessing the outcome, thus far, from implementing the suggested process and then refining it as necessary. The final phase was specifying learning (5) by performing reflections on this implementation.

ACTION PLANNING: GUIDELINES AND THE PROPOSED PROCESS FOR IDENTIFYING VALUE ATTRIBUTES

In the attempt to investigate what are the major attributes to consider on a project in coordination with the team and extended list of stakeholders, and what are the attributes that guide the decisions while evaluating the different design alternatives, several rounds of literature review was conducted by two of the authors. Based on what is offered in the literature, more than 135 identified keywords and factors were considered as essential on projects. Some of these keywords were similar in nature and therefore, the related terminologies were gathered under 31 categories. Another round of revision concluded to 16 value families, as revealed in Figure 2. The authors acknowledge that this list is not necessarily comprehensive as it is not a result of a meta-analysis or scoping review aiming for exhaustive searching. However, the authors acknowledge the particularity of different projects and their considerations. Nevertheless, the completeness of this list is not the aim of this study, instead, the aim is to produce a list to help project managers or consultants in leading the discussions about value attributes on projects. Therefore, the need for this list is pertinent to checking the areas that need to be investigated among the project team.

Beyond this list, actions need to be conducted and steps need to be followed in order to develop the customized list of what is of value for a specific project from the perspective of different parties. The key for this process is coordination/collaboration. Whether in a traditional setting, or in an integrated project delivery setting, the list of value attributes shall be generated beyond the sole requirements of the owner. Additionally, another important aspect of this process is the realization that the list might keep updating during the development of the project, as per the nature of projects and the dynamic nature of value which is affected by perceptions, values, needs, and desires. However, the last responsible moment is a concept to be kept in mind for revisiting the core items in the VAL. Then comes the notion: if everything is important, then nothing is important. Keeping this in mind, negotiation is an important process in the value assessment. While we identified 16 different families for the value attributes, **consolidating** the list is an important step through tradeoffs and negotiations. The CBA method mentioned in the literature is a good practice for selecting among alternatives in value attributes.

The detailed steps in the proposed process are represented in Figure 3. As a start, two main prerequisites are needed to launch the value discussions. First, the owner and his team should draft the Owner's general needs, goals and vision for the project based on the business case. This would include the owner's perspective on what he values for project success. This step is the first in terms of value elicitation on a project. The second prerequisite is obtaining the agreement of the Owner's requirements and needs with the project steering committee, where the team check if there is other pertinent information to add. Acknowledging the fact that the Owner could not identify the complete list of requirements and needs at the beginning, and that some information would be unknown to them, the process of value formulation is extended over several phases.

The first phase of the process is identifying the teams or stakeholders and it is a preparation step where an advocate for value attributes should be assigned. The advocate could be in-house from any of the Owner's or consultant's team members. They need to be a knowledgeable individual who would lead the discussion and dig into the heart of the stakeholders' values and needs. Their first mission though, is the identification and then classification of stakeholders as: manage closely, keep satisfied, keep informed, and monitor. With the stakeholders list ready and the Owner's general needs obtained, phase 2 – Generating the preliminary list, could launch. The project steering committee and the advocate could discuss the preliminary list offered in this paper. For end-user involvement, representatives from different users should be identified and they would be identified as the user groups. They shall provide their opinion and feedback on the VAL. The evaluation criteria are as follows: indicating the obligatory (regulations, codes, standards), essential (important features), desired (good to have if the budget allows), neutral (indifferent about having it), resistance (against this value attribute or not desired) (Khalife & Hamzeh, 2022).

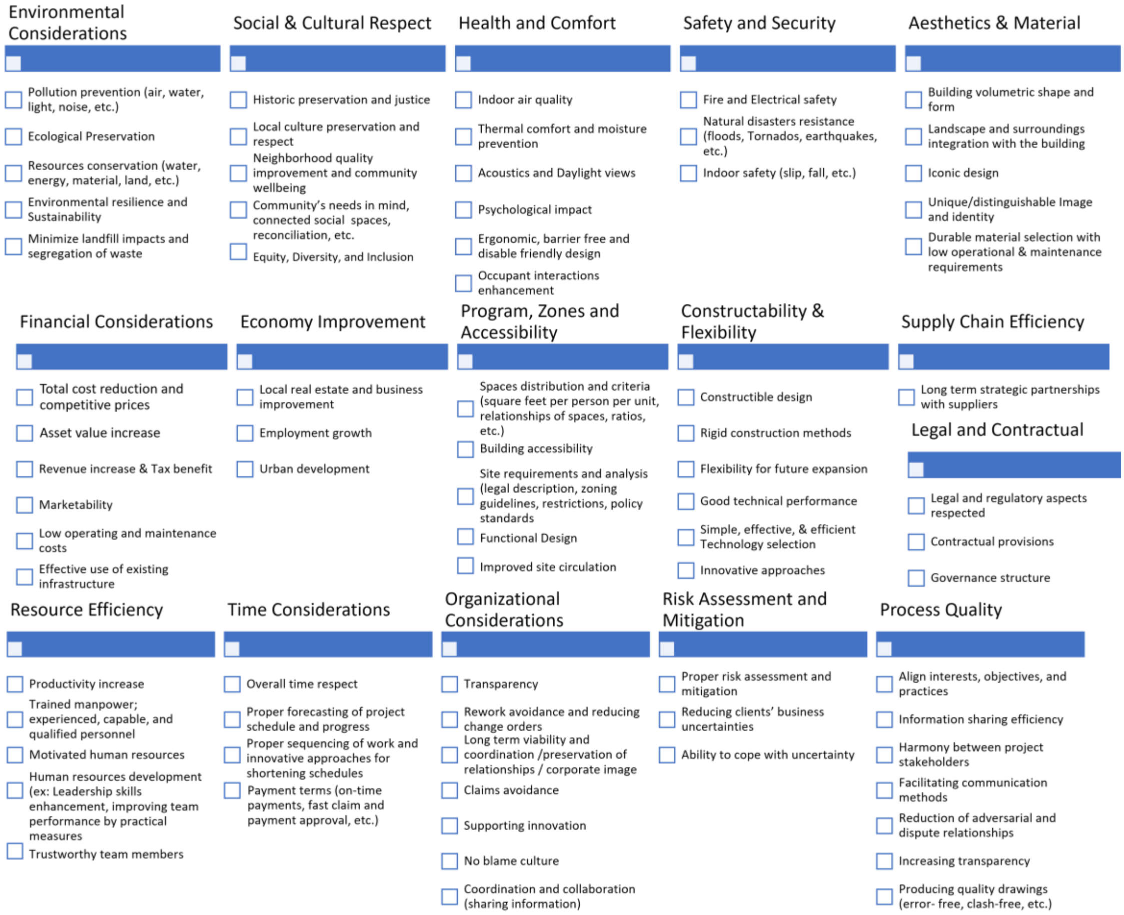

Figure 2. Value Categories

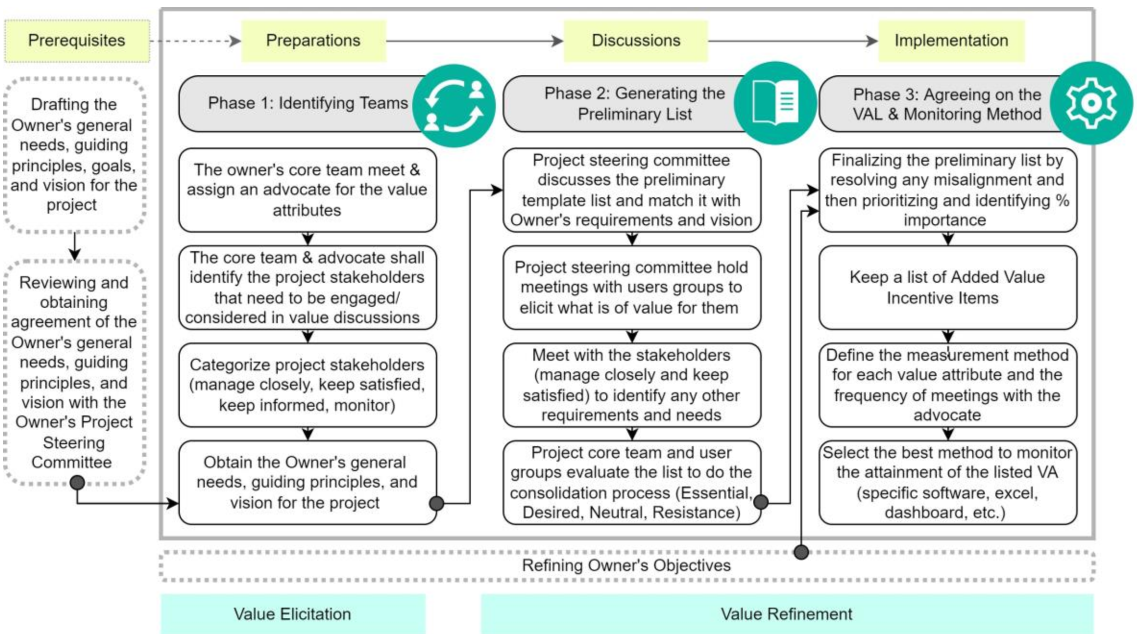

Figure 3. The process of developing Value Attributes List (VAL) and subsequent steps

After consolidating the list and soliciting stakeholders' views and input, phase 3 can commence. Note that during the different phases of this process, the Owner's objectives are being refined and revisited as more information from different parties are revealed. In phase 3, the preliminary list needs to be finalized by negotiating any identified resistance or misalignment between participants. Then, the team members should identify the % importance of the attributes. In addition, a list of Added Value Incentive Items should be shared with the team to include any item they deem good to include on the project if budget permits.

The last two steps in the implementation phase are (a) defining the measurement method and/or the evaluation criteria for each attribute (KPIs, leading and lagging indicators) plus the frequency of meetings to follow up on value attainment; and (b) selecting the best method to monitor it or the format for filling the evaluation, so specify a computer program or software that will be used (excel sheet, a dashboard, etc.).

ACTION TAKING, EVALUATING, & REFLECTIONS

PROJECT 1 - OBSERVING

Project 1 is the first of the two case studies employed for validating the proposed process. For this project, the authors used the observational research, where researchers observe participants in a natural situation. One of the authors started attending the Design Coordination & TVD weekly meetings, and the value alignment bi-weekly meetings. These meetings were hosted by one member of the Project Management team who is also one of the authors. The project is a public services facility and is performed under the Integrated Project Delivery contract. The Project steering committee met to develop the Owner's requirements and goals in 2019 and then the validation phase commenced in January 2020. The resulting validation report included the Basis of Design and indicated that the IPD team is committed to applying Lean principals and pushed for five key drivers: continue to generate value as seen from the Owner's perspective, focus on process and flow efficiency, look for and strive to remove waste, continuously improve as a team, and optimize the whole and not the parts. The contents of the report also included the regulatory requirements, Owner's requirements, goals and constraints, project values, and project cost (all under the Project Objectives).

Project values were described under 4 headings: General, Behaviour, KPIs, and Sustainability. The General category included operational excellence, resilient design, social responsibility, project satisfaction. 13 subheadings were described under the 4 headings apart from the items under sustainability. Every other week, the team would meet and evaluate one of the 13 listed value attributes. The values assessment includes pluses, deltas, and reflections pertaining to this specific value. *Mentimeter* is used, where each participant evaluates "how are we doing as a team in relation to this value attribute" and give a score out of 10. The team would be distributed into breakout rooms as meetings were held virtually during COVID. Each group discusses the plusses and deltas and write them down in the "Virtual Values Assessment Template" document. The team would come back to the main session, and one representative would summarize the discussions.

Observing these meetings and discussions had shown that it is important to keep track of how the team is doing on project values. These meetings reflect "*the IPD Team's 'commitment' to the project during regular intervals: are we doing what we said we would do?"*. One observation is that participants need to be reminded of why they are doing this, in order to keep them motivated to participate and express their opinion.

Additionally, one concern remains about the actions taken after reporting the results to the Senior Management Team (SMT) at the monthly SMT/PMT Report-out meetings. For this reason, the guidelines highlighted the need for a value advocate to keep track of the needed improvements and take the necessary actions to address any shortcomings.

Finally, the project manager on this project, and based on his experience and involvement on this IPD project, suggested another categorization for the value families. It included 5 basic categories: (1) behaviour values, (2) budgetary values, (3) experiential, (4) operational, and (5) sustainability values. He also highlighted the importance of outlining good practices and guidelines that would help owners in developing the Project objectives (the prerequisites for the process explained in this paper).

PROJECT 2 - TESTING

Project 2 acted as an application for the proposed process to validate its applicability and suggest adjustments based on this experimentation. The project is an educational facility within a university that is seeking to have this building serve as a 'crossroads for the university community'. A historic building is being renovated to accommodate new spaces and modern infrastructure, along with a newly constructed adjacent structure.

Two of the authors got on board with the project management office of the university. The topic of value delivery grabbed their attention. The research team and the project manager coordinated to produce the list of value attributes based on the: (1) key project drivers, (2) programming principles, and (3) Core & Shell (C&S) guiding principles. The participating research team delivered three presentations about the importance of value discussions and value delivery on projects, to the PM office, to the project steering committee, and to the Executive Oversight Committee EOC. This helped in getting buy-in from the whole team to support the process. The main incentive for this collaboration was seeking end-user satisfaction. The project management team is also looking for measurable ways for evaluating project success. While the project is not under the IPD contract, the team is striving for a collaborative approach and an IPD *spirit*.

The implementation process followed the same steps expressed in the process of Figure 3. Up until the drafting of this paper, phase 2 has been completed, while phase 3 is yet to be implemented. Figure 4 (a) shows that discussions around the generic list were performed to match the guiding principles and key project drivers. Figure 4 (b) shows the first evaluation of the value attributes related to "team behaviors" (scale out of 5).

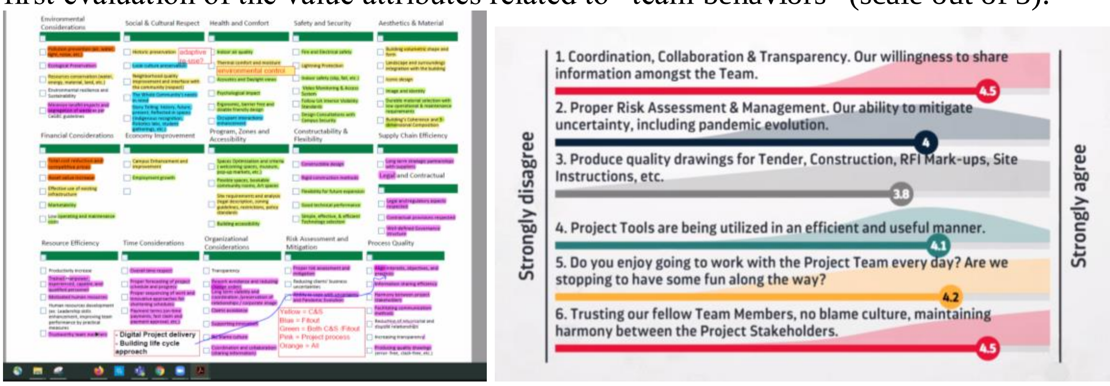

Figure 4. (a) Discussions with the PM based on the generic list and highlighting the attributes in connection with the educational facility; (b) first evaluation of the value attributes list under the team behaviour category (using *Mentimeter*)

The value discussions revealed some conflicting interests which reflected the need for further negotiations. Usually, when such cases surface, the team would be innovative in their approach, and creativity would be higher leading to thinking outside-the-box. The project manager expressed some concerns over participants' actual review of the list, and their approval that it reflected their needs rather than being a pre-prepared list that fell as a 'parachute' on them. Other concerns were recorded regarding how to avoid subjectivity during evaluation. As indicated earlier, and based on those concerns, the authors recommended an advocate that would keep reminding the team about the importance of this exercises, keep them engaged to feel they are committed to this list, and agree on how to translate subjective matters into more objective targets and measures.

REFLECTIONS

We present in this section the general reflections about the process and lessons learned from the case studies. These are presented in the form of a set of recommendations for practitioners. The following steps are thus necessary:

1- Specify the network of people that need to be engaged at each stage (ex: when discussing the evaluation of *process* value attributes – transparency , team coordination, etc. – these are more related to the core design team not user groups).
2- Agree on the general categories upfront, the subheadings under each category could keep changing due to the dynamic nature of project values.
3- Ask the right questions to determine the benchmark (propose a set of questions)
4- Describe value attributes in a clear language and maybe identify glossary.
5- Identify how to translate these value attributes into design elements.
6- Keep track of contradicting value attributes and apply trade-off techniques such as CBA. Keep also track of any value losses (refer to studies in literature section). Report lessons learned.
7- Keep the team fully engaged. The team should know that this is not an additional burden/exercise to the project, it is part of the process for achieving success on projects similar to risk management, for instance. The team should also feel the ownership of the value attribute list, as they shall be part of the development process, or at least they should be given the chance to provide feedback on the list.

CONCLUSIONS

The need for a well-defined foundation for developing the value attributes list has been regularly asked for whenever the topic on value is raised in front of practitioners and scholars. In this paper, we presented a preliminary list to be the starting point for discussions on projects. The list needs to be revisited when coming across different types of projects and should be customized to meet the stakeholders' focus. While the list is not comprehensive in its whole, the authors argue that the headings are sufficient to raise the dialog needed for detailed specific subheadings. One of the reasons for not having an exhaustive ready-to-go list is the nature of value attributes being subjective and context specific. Nonetheless, this list can help novice practitioners looking for a starting point to launch discussions and guide the negotiations on value. The paper also outlined practices and guidelines to help develop the customized extended list and keep track of its implementation along the project design development and construction phases. Two case studies were presented, and discussions were made to benefit from their experience in implementing these practices. Future studies will tackle in depth the prerequisites and steps for helping owners develop their needs on complex projects. This paper adds one layer to the body of knowledge pertaining to delivering value on projects by highlighting the steps for developing a vital list of what is important to stakeholders on a project.

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UNDERSTANDING THE RELATIONS BETWEEN BIM MATURITY MODELS AND LEAN PRINCIPLES

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ABSTRACT

The increasing adoption of BIM is requiring organizations to assess their BIM maturity level. For this assessment, several authors have proposed BIM maturity models to assess capabilities of organizations or projects. However, although previous researches have demonstrated positive synergies between Lean philosophy and BIM, it is not clear the role that Lean principles currently have in the assessment of BIM maturity.

This study aims at understanding the relation of 5 BIM maturity models with 16 Lean principles. The research shows that the principles related to flow process has the most interaction with the maturity components, where "Reduce Variability" is the principle with the highest number of interactions, followed by "Reduce cycle time" and "Design the production system for flow and value". The results also showed that "Problem solving", "Value generation process" and "Developing partners" are Lean principle clusters with low levels of interaction in the analyzed models. Future research should study the convenience of their incorporation in order to align BIM maturity improvement with Lean principles to enjoy the benefits of Lean and BIM synergies.

KEYWORDS

Lean construction, BIM, maturity models.

INTRODUCTION

One of the most important current approaches to address productivity problems in the construction industry is Building Information Modeling (BIM), with an increasing adoption rate in the last years. This high interest can be explained by BIM´s promise of improving the construction performance and efficiency (Azhar, 2011). 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, the assessment of BIM capabilities and the maturity of those capabilities is becoming essential not only for owners to select design and construction firms that may participate in their BIM projects, but also for any stakeholder to understand their situation applying BIM (Rojas et al., 2019) and thereby

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trace an action path to improve it. To assess these capabilities, academia and industry are looking at maturity models.

Maturity models can be defined as a sequence of stages that represents the knowledge and mastery in a determined area via the analysis of diverse criteria (Wendler, 2012). Its use relies on the assumption that levels are able to indicate the real capabilities of an organization and how the evolution of these capabilities should be done, bringing opportunities to improve and eliminate deficient capabilities. The evidence of the derived benefits in other industries led to BIM researchers to propose the use of these models (Chen, Dib, & F. Cox, 2014) in the construction industry at the people, organization and project levels.

On the other hand, another approach to address construction productivity problems is Lean Construction, which is a philosophy based on continuous improvement, waste reduction and value generation (Sacks, Koskela, Dave, & Owen, 2010). Different authors have studied the relation between BIM and Lean, identifying positive interactions in their combined use (Dubler, Messner, & Anumba, 2010; Hamdi & Leite, 2012; Mandujano, Alarcón, Kunz, & Mourgues, 2016; Sacks et al., 2010).

However, despite the evidence of these synergies, the literature that has analyzed and compared BIM Maturity Models (Dakhil, Alshawi, & Underwood, 2015; Giel & Issa, 2013; Wu, Xu, Mao, & Li, 2017) has not yet explored these interactions, leaving unclear how Lean principles relate to the BIM maturity assessment process. Therefore, the objective of this research is to understand the relations between existing BIM maturity models and Lean principles. Thus, this study assessed the connections between 16 Lean principles and each BIM area throughout its maturity stages for five BIM maturity models.

LITERATURE REVIEW

MATURITY MODELS

The concept of process maturity and its measurement started in 1979 with the development of Crosby's quality management maturity grid. This grid is composed of six measurement categories where each of them has five maturity stages (Paulk, 2009). The grid refers to an arrangement of categories or areas in one direction, and maturity stages in the other direction. Since then, several industries or knowledge areas have developed their own maturity models, such as software development, construction industry, public management, medical management, business intelligence, and knowledge management (Wendler, 2012). These maturity assessment methods have demonstrated that an increase in the maturity of a process can reduce its variability and improve its performance (Succar, 2014).

Maturity models establish defined areas and characteristics for which the objects of evaluation must demonstrate their maturity (Chen et al., 2014). These models define a sequence of stages (or maturity levels) where the bottom stage can represent having a few of the total capability studied and the highest stage represents the full maturity in the capability (Becker, Knackstedt, & Pöppelbuß, 2009).

These models have descriptive, prescriptive and comparative purposes. The descriptive purpose considers the maturity models as an assessment tool, defining evaluation criteria and giving a diagnostic about the current status. The prescriptive purpose aims at giving guidelines and a route for future actions, and finally, the comparative purpose uses the models to create benchmarks among the assessed elements (Pöppelbuß, Niehaves, Simons, & Becker, 2011).

In the BIM domain, the National Institute of Building Science (NIBS) (2007) developed one of the first maturity models. This model consists of a matrix where the rows represent the levels and the columns the capabilities that will be measured. In total, it defined 11 capabilities and 10 maturity stages. Other authors also have proposed BIM maturity models that look for a new purpose and try to fulfill the gaps left by the previous models (Succar, 2009; Sebastian & van Berlo, 2010; CICR, 2013; Kam, Song, & Senaratna, 2017; Indiana University, 2015).

Several studies (Giel and Issa, 2013; Dahkhil et al., 2015; Wu et al., 2017) have reviewed and compared some of the BIM maturity models for different purposes but none of these studies have related the models with the Lean principles.

BIM AND LEAN SYNERGIES

Recent literature has an increasing interest in BIM and Lean relations, demonstrating their capability to reduce the waste generated in the construction process (Dubler et al., 2010), and to improve the construction performance, suggesting further research in this area (Dave, Koskela, Kiviniemi, Owen, & Tzortzopoulos, 2013; Mollasalehi, Fleming, Talebi, & Underwood, 2016).

Sacks et al (2010) is one of the most exhaustive studies related to interactions between Lean and BIM. They established an interaction matrix that identified 56 interactions related to 24 Lean principles and 18 BIM functionalities, where 52 of those interactions represent a positive synergy. Most of these interactions were documented through evidence from practice or previous research. Mandujano et al. (2016) complemented this study by extending the concept of BIM to VDC (Virtual Design and Construction), finding 224 interactions, where 219 represent a positive synergy.

Through a case study, Hamdi and Leite (2012) studied BIM and Lean interactions from two separate perspectives: from the Sacks et al's Interaction Matrix and from the NBIMS's maturity model. In the first perspective, they studied 3 positive synergies, obtaining improvement areas in the organization. In the second one, they evaluated the BIM maturity through the model proposed by NBIMS and identified the involved Lean principle and the Lean practice that can help to improve the maturity for each area, such as 5s process, increase visualization of process or fail safe for quality and safety. Finally, notwithstanding they did not make a full use of the Interaction matrix, they found interconnections in how the Lean principles can enhance BIM maturity.

Although the above references and other literature has shown a strong evidence related to the synergies between BIM and Lean, BIM maturity models have not intentionally considered the relation between BIM competencies and Lean principles. The literature shows only two exceptions to this. The first, is the maturity model developed by the University of Salford that aims to support the joint implementation of BIM and Lean (Dave et al., 2013). However, there is limited public information related to the assessment mechanism. The second is the IDEAL maturity model that attempts to integrate BIM and Lean in the same model. However, there is information only about the definition of the maturity stages but no about of the capabilities assessed by the instrument (Mollasalehi, Aboumoemen, Rathnayake, Fleming, & Underwood, 2018).

Based on the gaps observed from the literature review, this study aims at understanding the relation between BIM maturity models and Lean principles. This understanding will contribute to choose between or modify existing maturity models. The use of proper maturity models will allow organizations to exploit synergies between BIM and Lean.

RESEARCH METHODOLOGY

Figure 1 describes the main steps of the research methodology.

Figure 1: Main steps of the research methdology

Through an integrative literature review, the authors selected BIM maturity models with available description for both the assessed areas and their maturity stages, as the lack of the description of the stages would have introduced biases in the assessment process. To identify the relations between the BIM maturity models and Lean principles, the present research used the 16 Lean principles as defined by Sacks et al. (2010) as the analytical framework, since this list was formally compiled specifically to analyse interconnections between Lean and BIM. Table 1 shows the organization of these principles.

Table 1: Lean principles and their organization (Sacks et al., 2010)

Areas	Principles	
Flow process	A. Reduce variability	F. Standardize
	B. Reduce cycle times	G. Institute continuous improvement
	C. Reduce batch size	H. Use visual management
	D. Increase flexibility	I. Design the production system for flow and value
	E. Select an appropriate control approach	
Value generation process	J. Ensure comprehensive requirements capture	L. Ensure requirement flow down
	K. Focus on concept selection	M. Verify and validate
Problem solving	N. Go and see yourself	O. Decide by consensus, consider all options
Developing partners	P .Cultivate and extend network of partners	

The analysis described in this paper assessed the connections between these Lean principles and each BIM area throughout its maturity stages for all the selected BIM maturity models. This assessment specifies whether this relation is present in all the maturity stages (F, full), only in some of the stages (P, partial), or in none of them (I, inexistent). Besides, the F and P relations specify if the relation represents a positive integration of the principle (+) (higher maturity aligns with the principle), a negative integration (-), or there is an inconsistency (+-) throughout the different maturity stages.

RESULTS AND DISCUSSION

In a first stage, the authors identified 13 maturity models with literature that support them (Table 2). Nine of these models had available information about the description for each area assessed, but only 5 of them had publicly available descriptions of each maturity stage. These 5 models are the Capability Maturity Model (CMM), BIM Maturity Matrix at granularity level 1 (BIM MM), Organizational BIM Assessment Profile (Org. BIM AP), Multifunctional BIM Maturity Model (Mult. BIM MM) and the Arup Maturity Measure (Arup MM).

Table 2: Identified BIM Maturity Models (highlighted models were used in the study)

Maturity Model (Source)	Assessment Focus	Capabilities Description	Detailed Maturity Stages Description
Capability Maturity Model (CMM) (NIBS, 2007)	**Projects**	**Yes**	**Yes**
BIM Maturity Matrix (BIM Excellence, 2016)	**Organizations, project teams and markets**	**Yes**	**Yes**
BIM Proficiency Matrix (Indiana University, 2015)	Organizations	No	No
Characterization Framework (Gao, 2011)	Projects	No	No
BIM Quickscan (Van Berlo & Hendriks, 2012)	Organizations	No	No
Organizational BIM Assessment Profile (CICR, 2013)	**Organizations**	**Yes**	**Yes**
Lean/BIM Maturity Model (Dave et al., 2013)	Projects	Yes	No
VDC Scorecard (Kam, Song, & Senaratna, 2017)	Projects	Yes	No
BIM Cloud Score (Du, Liu, & Issa, 2014)	Organizations	Yes	No
BIMCAT (Giel & Issa, 2015)	Organizations	No	No
Arup Maturity Measure (Arup, 2015)	**Projects**	**Yes**	**Yes**
Multifunctional BIM Maturity Model (Liang et al., 2016)	**Projects, companies and industry**	**Yes**	**Yes**
BIM Maturity Tool (Siebelink, Voordijk, & Adriaanse, 2018)	Organizations	Yes	No

The study of the selected models shows no agreement regarding the number of capabilities to incorporate. A characteristic of some models is the arrangement of capabilities into fields. For example, the BIM MM incorporates the technology, process and policy fields; and in addition, the user must choose an area according to the BIM capability stage (object-based modeling, modeling-based collaboration or network-based integration), and other for the BIM organizational scale (Organizations, project teams or markets) that is assessing. Additionally, the Org. BIM AP integrates BIM uses, process, information, infrastructure and personnel fields, and the Mult. BIM MM does it with technology, process and protocol fields, whereas the other two selected models do not define fields for their assessed areas.

For analysis purposes, the present research considered the BIM MM as a whole of 16 areas, notwithstanding that at the assessment moment the assessors must select one BIM capability stage and one BIM organizational scale according to who is been measured. This decision is based on the importance of obtaining the best understanding about how maturity models involved the Lean principles throughout itself.

Another special case exists with the Arup MM. This model presents 11 areas that must be assessed once for the whole project and 11 other areas for each discipline of the project (mechanical, structural, electrical, etc.). The latter 11 areas are related to some of the BIM uses and are the same for each discipline; therefore, this research considers these capabilities only once. Additionally, the public documentation about the Arup MM did not provide definitions for the whole sequence of stages in some of the areas, but in order to have a more comprehensive study, the authors included these areas under the assumption that the maturity sequences are properly defined with fewer stages.

To exemplify the assessment rationale, the following discussion describes the assessment for the “Data Richness” area in the CMM instrument, which maturity stages (MS) are shown in Table 3 (parts a and b). The definition of stage 1 does not allow determining if there is a connection with the Lean principles because it just refers to basic data, reason that eliminates the possibilities to find an F type connection. The following stages include the evolution of the data amount and its association with information, becoming authoritative, until achieving Knowledge management system, which will help to “Reduce variability” and “Reduce cycle times” (Lean principles A and B, respectively).

Table 3a: CMM Data Richness, adapted capability (NIBS, 2007)

MS	1	2	3	4	5
Data Richness	Basic Core Data	Expanded Data Set	Enhanced Data Set	Data Plus Some Information	Data Plus Expanded Information

Table 3b: CMM Data Richness, adapted capability (NIBS, 2007)

MS	6	7	8	9	10
Data Richness	Data w/Limited Authoritative Information	Data w/ Mostly Authoritative Information	Completely Authoritative Information	Limited Knowledge Management	Full Knowledge Management

The matching with these principles can be understood with Sacks et al. (2010) definitions and examples of the principles. Principle A is achieved because the authoritative information will reduce the variability in the final product. On the other hand, principle B will occur because the Knowledge will reduce the task time due to the proper knowledge transfer that requires information, and thus, it will reduce the construction total duration. For principles C to E, G to L, and N to P, it is not possible to determine whether that principle will effectively be in any of the maturity stages. The F principle, Standardize, leaves more space for interpretation, as, according to Sacks et al, (2010), this principle refers to the standardization of work, which is not possible to stablish according to the maturity sequence because it refers to what the information is and not how is it used. Sacks et al. (2010) explain that the “Verify and validate” (M) principle implies that all products should be verified against the customer requirements and specifications. Thus, having authoritative information without checking the customer requirements goes against the principle (P- interaction).

In total, the 5 selected models provided 90 BIM measurement areas where the 16 Lean principles aforementioned were assessed. The basis for these assessments was the explicit or implicit relations declared in the maturity stages definitions, which – in several occasions – were supported by BIM-Lean interactions found in the literature (Alarcón, Mandujano, & Mourgues, 2013; Sacks et al., 2010). The research studied 1440 possible connections (16 Lean principles throughout the 90 BIM measurement areas), finding 291

P+, 20 F+, 7 P+- and 1 P-. The research did not find F+- or F- connections. The principles that represent P+- interactions are Reduce cycle times (B), Standardize (F), Reduce variability (A), Increase flexibility (D), and Ensure comprehensive requirements capture (J), as Table 4 shows.

Table 4: P+- interactions breakdown

Principle	Area	Maturity Model
B. Reduce Cycle Times	Roles or disciplines	CMM
	Operational uses	Org. BIM AP
F. Standardize	Graphical Info	CMM
	Data Exchange	Mult. BIM MM
A. Reduce Variability	Roles or disciplines	CMM
D. Increase flexibility	Organizational Hierarchy	Org. BIM AP
J. Ensure comprehensive requirements capture	Project uses	Org. BIM AP

This table shows that only one area presents 2 P+- interactions, the Roles or disciplines area in the CMM. This interaction occurs because of the inconsistency in the maturity progression, which shows a variation throughout the stages in if BIM fully or partially supports the people's job and if they need to go to other products to accomplish their job, creating variability in the cycle time and in the products that the organizations can make. Despite the fact that some areas of the studied models present inconsistencies with some Lean principles, in other areas, they have positive interactions with them. This situation can lead to difficulties at the time of improving Lean and BIM maturities in the organization but does not mean the incompatibility between them.

Regarding the negative interactions, the only principle that represents a P- interaction is Verify and validate (M) principle, in the CMM. The difference between the number of positive versus negatives interactions suggests that BIM and Lean go beyond the previous positive synergies detected in the literature. In addition, they have connections in the capabilities development, meaning that as BIM capabilities grow, the interactions with Lean principles may grow as well. The much more numerous presences of P+ connections compared with the F+ connections are due in part to the way that several models define the first maturity stage. Their first stage considers no or little development of the BIM measured areas, which usually conveys a lack of relation with the Lean principles. Considering the low presence of F+ connections in contrast with the P+, this study combined both as positive interactions, and proposed these metrics to analyze them.

$$Principle\ density_x = \frac{N^{\underline{o}}\ of\ found\ positive\ connections\ for\ principle\ x\ considering\ all\ models}{N^{\underline{o}}\ of\ possible\ connections\ for\ principle\ x\ considering\ all\ models}$$

$$Model\ density_y = \frac{N^{\underline{o}}\ of\ all\ found\ positive\ connections\ in\ model\ y}{N^{\underline{o}}\ of\ possible\ connections\ in\ model\ y}$$

$$Specific\ density_{xy} = \frac{N^{\underline{o}}\ of\ found\ positive\ connections\ for\ principle\ x\ in\ model\ y}{N^{\underline{o}}\ of\ possible\ connections\ for\ principle\ x\ in\ model\ y}$$

Figures 2 and 3 depict the specific versus the model densities, and the specific versus the principle densities, respectively. The average principle density is 0.22. However, this metric has a standard deviation of 0.18, representing a significant difference between the connections that a Lean principle has with the BIM maturity models. Thus, to have a better understanding of the detected interactions, the authors clustered the principles according to their density, using the k-means method (Jain, 2010). Table 5 shows the final clusters and their associated principles.

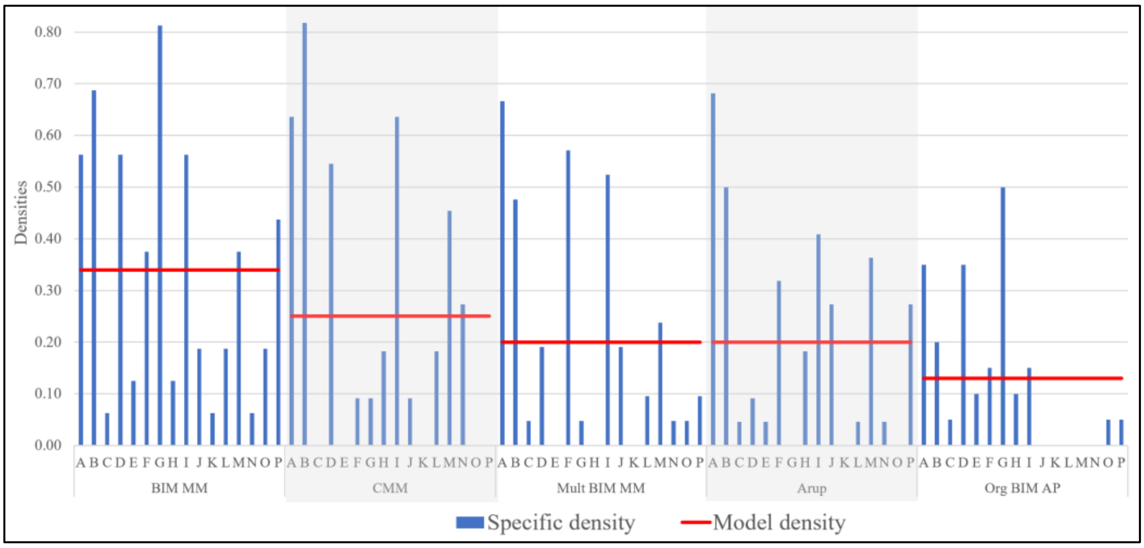

Figure 2: Specific density vs model density

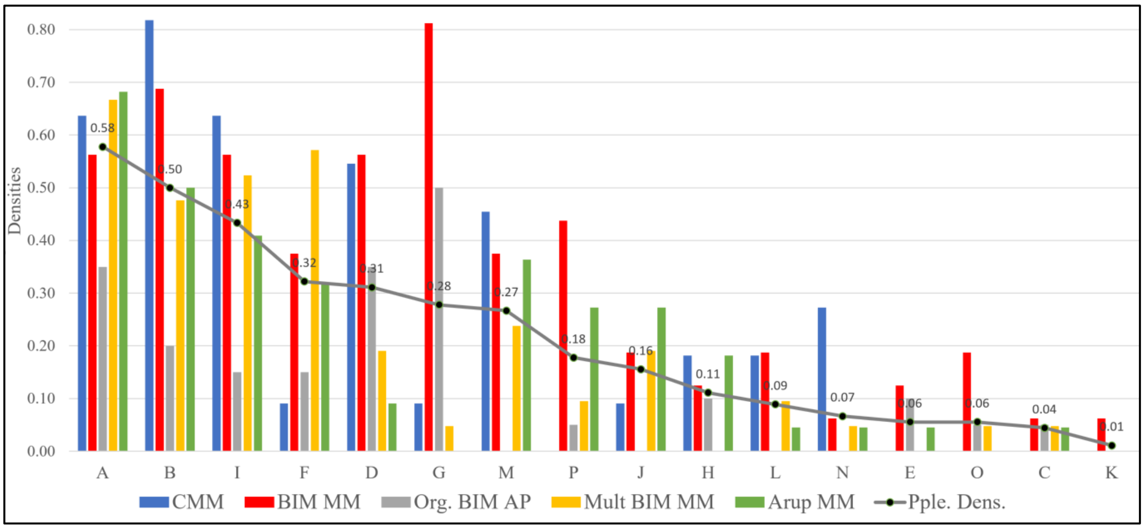

Figure 3: Specific density vs principle density

The results show that the strongest relationship is centered in the flow process principles, which implies that the improvement of their workflows may lead to higher maturities of organizations. The cluster of low principle density includes principles of the four areas. The principles with fewest interactions with the studied models are Focus on concept selection (K) and Reduce batch size (C), with densities of 0.01 and 0.04 respectively.

Analyzing by model density, the BIM MM presents the highest density, obtaining a value of 0.34 and being the only model that interacts with all the Lean principles. Also, the five models present high variability in the specific density, and all of them have a few principles with high densities, although these principles vary between the models.

Table 5: Principle clusters and their principles

Cluster	Density centroid	Principle	Principle area
High Principle Density	0.50	Reduce variability (A)	Flow process
		Reduce cycle times (B)	Flow process
		Design the production system for flow and value (I)	Flow process
Medium Principle Density	0.29	Increase flexibility (D)	Flow process
		Standardize (F)	Flow process
		Institute continuous improvement (G)	Flow process
		Verify and validate (M)	Value gen. process
Low Principle Density	0.09	Reduce batch size (C)	Flow process
		Select an appropriate control approach (E)	Flow process
		Use visual management (H)	Flow process
		Ensure comprehensive requirements capture (J)	Value gen. process
		Focus on concept selection (K)	Value gen. process
		Ensure requirement flow down (L)	Value gen. process
		Go and see yourself (N)	Problem solving
		Decide by consensus, consider all options (O)	Problem solving
		Cultivate an extended network of partners (P)	Developing partners

The use of the model density as a measure is useful to avoid biases that can be generated by the difference of the number of maturity areas of the models, and the consequent possible connections with the lean principles, allowing a normalized comparison among them. For example, the CMM present 44 connections with the Lean principles out of 176 possible connections. In contrast, the Arup MM have 72 connections out of 356 possible ones. Thus, looking only to the actual connections may lead to wrong conclusions as CMM has a higher model density than the Arup MM.

Regarding the models that have no connections with some principles, 4 of them do not include the Verify and Validate (M) principle, and 2 do not include Select an appropriate production control approach (E). The BIM Maturity Matrix is the only model that has specific densities for all 16 Lean principles.

CONCLUSIONS

Despite the evidence provided by previous research regarding the strong BIM and Lean synergies, BIM maturity models are not explicitly considering Lean principles in their assessment process and, therefore, it is not clear how much these synergies could be implicitly being considered when assessing BIM maturity. In the present study, it is possible to confirm the existence of these relations, but also that the magnitude of these interactions depends clearly on the characteristics of the maturity model. Moreover, findings exposed in the present article can help to decide what maturity model is the most suitable according to the Lean requirements that the organization or project has.

Even though none of the studied models explicitly express the aim to include lean considerations throughout its maturity stages, all of them present implicit connections with several principles. These results strengthen the evidence of BIM and lean synergies and suggest new approaches to exploit these synergies.

The studied models with focus on organizations present areas to measure management aspects, such as BIM champion, management support, or leadership, which may not have a direct relation with Lean nor express a BIM functionality. However, these could become relevant at the time to define who is in charge and solves problems, opening spaces to deeper integration with lean, and enhance the connections with principles from the Problem solving area, which is not being included in some models. Furthermore, the results do not show a difference in how a model incorporates the lean principles regarding the maturity assessment focus (i.e., projects or organizations).

Whereas a higher integration of lean principles seems to be a positive characteristic of a maturity model, the authors believe that a measurement area should not necessarily include all the principles, nor a principle must be connected with all the maturity areas. On the contrary, a parceled-out principle inclusion may create more and better synergies, i.e., improve the project results by their combined use, since a simpler maturity sequence will produce clearer improvement strategies.

Based on the obtained results, the BIM Maturity Matrix has the strongest connection with lean principles, as it presents the highest model density (0.34), and interacts with all the Lean principles. In contrast, the Org. BIM AP has the weakest connection due to its model density (0.13) and the fact that it does not include 5 of the 16 studied lean principles.

The flow process principles are the ones with higher densities, especially the principles Reduce variability (A) and Reduce cycle time (B). These two principles naturally emerge as the most related to the five studied models, as well both principles can be considered with a direct relationship with the BIM promise of improving the construction industry. However, the studied models are weak in the inclusion of value generation process and problem-solving principles. These areas may improve the performance predictability and actually do not have a strong presence in the studied maturity assessment methods. Future BIM maturity models may consider the Lean philosophy from the beginning of their development and take advantage of the BIM and Lean synergies.

Further research is necessary to understand the relation between BIM and Lean maturity, and the companies´ BIM performance in order to better inform decisions about where companies should put their scarce resources aimed at improving their maturity.

The main limitations of the present study are the lack of publicly available information that did not allow to include other maturity models, and the absence of first-hand case studies to add practical considerations in the assessment of the connections between the maturity of the BIM competency sets and the lean principles. Future research could extend these contributions by assessing the relation between BIM and Lean maturities and key performance indicators associated with BIM processes.

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IMPLEMENTING VDC

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ABSTRACT

Norwegian construction clients are demanding the use of VDC in their projects. Contractors have thus implemented VDC on construction projects. However, little research has been conducted regarding how projects should implement VDC.

The study answers four research questions to provide a set of recommendations on how VDC should be implemented in projects: (1) How is VDC implemented in construction projects, (2) Which part of the implementation had positive effects on the implementation, (3) Which part of the implementation had negative effects on the implementation and (4) How should VDC be implemented in construction projects. Three general and five case-specific semi-structured interviews were conducted.

The contribution of the study is a set of recommendations concerning how projects should implement VDC. The recommendations are based on seven key elements for implementation, ranked from most influential to least: Anchoring, Communication, Vision, Plans, Project Team, Training, and Engaging.

KEYWORDS

Last Planner® System; Virtual Design and Construction (VDC); BIM; Lean Construction; Implementation

INTRODUCTION

Norwegian construction clients require their design and build-contractors to use Virtual Design and Construction (VDC) in many of their projects. VDC can be defined as "the use of integrated multi-disciplinary performance models of design-construction projects to support explicit and public business objectives" (Kunz and Fischer, 2012). Some clients have demanded using one or two of the working methods found in VDC (Bråten et al, 2021). More recently though, clients require using all the working methods within VDC in their construction projects.

The increasing demand for VDC in Norwegian construction projects has – as a natural response – resulted in contractors implementing the VDC framework in their projects (Alarcón et al, 2010). Implementing in this context is defined as "to put into practical effect" (NUBU, 2014). VDC is thus considered implemented in a project when VDC is in practical use.

Nevertheless, implementing new working methods successfully in construction projects is a demanding process (Alarcón et al., 2010). Sufficient attention must be given to the implementation. If the implementation is not prioritized, the result may be a waste of money, time, and effort (Alarcón et al., 2010). However, little research has been

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conducted on how VDC should be implemented in construction projects to implement the framework (Alarcón et al., 2013, Mandujano et al., 2017). Until now, the knowledge on how VDC should be implemented is pretty much based on anecdotes and experiences of individuals who have implemented VDC themselves (Alarcón et al., 2013). Moreover, it appears not to exist any formal guidelines on how to implement VDC (Mandujano et al., 2017). There is a need to document practical experiences of VDC implementation.

The lack of research on the implementation process of VDC, combined with more frequent requests for VDC, led to a study of the following research questions to provide a set of recommendations for the implementation of VDC:

1. How is VDC implemented in construction projects?
2. Which part of the implementation process has had positive effects on the implementation?
3. Which part of the implementation process has had negative effects on the implementation?
4. How should VDC be implemented in construction projects?

The study is limited to four Norwegian construction projects due to a limited time frame. Betonmast was the design and build-contractor for all four projects.

RESEARCH DESIGN AND METHOD

A qualitative research design was applied. First, an initial literature review provided a theoretical framework before data was collected. This was undertaken by using the search engines Oria, Scopus, and Google Scholar. Search strings such as "Implementing VDC" and "Implementation of VDC" were used. A pilot case study was conducted to understand how Betonmast had implemented VDC in their organization. The theoretical framework was used to form an interview guide consisting of questions for semi-structured interviews with three key personnel in Betonmast, each from different projects. The pilot study identified positive and negative effects of implementation on an organizational level. Throughout the pilot study, questions arose on how VDC was implemented at the project level.

Following the pilot study, a revised literature review regarding the project implementation of VDC was conducted. The same search engines were used, but search words changed and consisted of different compositions of "project", "implementation", "construction", and "VDC". After reviewing numerous publications concerning implementation, a collection of eleven articles, books, and reports were selected. A second interview guide became the basis for interviews with design and project managers. The initial plan was to interview the design and project managers in all four case projects. However, due to a lack of will to participate, only one project manager was interviewed, giving a total of five interviews. This lack of will was maybe caused by a lack of insight in the implementation of VDC among the project managers. All interviews were conducted digitally due to the COVID-19 pandemic. Each interview was filmed and later transcribed. The transcriptions were sent to the informants to review and verify before being analyzed against the theoretical framework.

THEORETICAL FRAMEWORK

VIRTUAL DESIGN AND CONSTRUCTION (VDC) COMPONENTS

Virtual Design and Construction can be described as "the use of integrated multi-disciplinary performance models of design-construction projects to support explicit and public business objectives" (Kunz and Fischer, 2012). VDC consists of five main components: Building Information Modelling (BIM), Project Production Management (PPM), Integrated Concurrent Engineering (ICE), Client Goals and Project Objectives and Metrics (Rischmoller et al., 2018). Table 1 describes the five components of VDC.

Table 1: VDC components

VDC component	Explanation
BIM	The creation and use of 3D models. The model is an intelligent representation of the finished product. BIM is used for communication and is a tool to make informed decisions.
PPM	Organization and control of the physical work activities in the project. The methods stem from Lean, viewing the projects as a production system (Rischmoller et al., 2018).
ICE	Engineering the project collaboratively. Information is shared, actions are coordinated, problems are solved, and decisions are made in ICE sessions (Rischmoller et al., 2018).
Client goals and Project objectives	Project objectives support the client's goals. The project team defines project objectives considering the total cost and building performance (Rischmoller et al., 2018).
Metrics	Controls and monitors the project objectives. The client's goals are measured by metrics considering operations, use, sustainability performance, safety, schedule, and costs (Rischmoller et al., 2018).

VDC only occurs when the main components are used in an integrated approach, not when the components are used isolated (Rischmoller et al., 2018). The VDC tools and methods should therefore be integrated within the traditional work operations, and not exist as a parallel alternative (Andersson et al., 2016).

The Last Planner System, hereafter Last Planner, is a PPM technique described as a production planning and control system. It is based on lean principles, being a pull planning method where the project defines the project milestones and places the project's deliveries and activities according to them. The team plans its way backward, starting with the last delivery or activity. Last Planner is a good example of the strong synergy between Lean and VDC (Hamzeh et al., 2009; Belsvik, Lædre and Hjelseth, 2019).

Model Maturity Index (MMI) is a metric that measures the progress of the 3D model by determining the maturity level of its elements. The elements receive an MMI level from conceptualization (MMI 100) to as-built (MMI 600) throughout the design process (Garcia et al., 2021).

IMPLEMENTATION OF VIRTUAL DESIGN AND CONSTRUCTION (VDC)

After reviewing available literature, seven key elements for successful VDC implementation in construction projects were identified: *Anchoring, Communication, Vision, Plans, Project Team, Training, and Engaging*. These seven identified key elements for a successful implementation of VDC in construction projects are described in the following.

The success of VDC depends on how well the VDC components are integrated with each other and thereby *anchored* within the organization (Kunz and Fischer, 2012; Andersson et al., 2016). To enable integration, VDC tools and techniques should be automated (Kunz and Fischer, 2012). In addition, routine work in the project should also be automated (Kunz and Fischer, 2012). A supportive culture within the organization is further crucial for successful implementation (Ling, 2003; Blayse and Manley, 2004). Both the contractor and the client should support the implementation (Manley, 2008a). In the same way, the contractor needs to support the sub-contractors for the implementation to be successful (Manley, 2008a).

BIM, PPM, ICE, Client Goals and Project Objectives should be implemented in the early part of the engineering and design phase. It's not clearly described when Metrics should be implemented, but since they are based on the Client Goals and Project Objectives, it is considered to be implemented at the same stage as the other components. (Khanzode et al., 2006; Aslam et al., 2021).

To implement VDC, the stakeholders should *communicate* according to standards (Kunz and Fischer, 2012). National BIM specifications should also be applied to the project (Andersson et al., 2016). In Norway, the standard NS-EN ISO 19650 defines information sharing in BIM (Kodjeykova-Merriman, 2020). The implementation requires the stakeholders to share data, which could be done with IFC files (Kunz and Fischer, 2012). IFC is a unified file format that applies to most programs in the construction industry (Kunz and Fischer, 2012). Communication in BIM results in transparency and contributes to collaboration between stakeholders (Khanzode et al., 2006). Good communication platforms combined with better technological software and hardware will increase project efficiency (Andersson et al., 2016).

Creating a *vision* for the implementation of VDC is essential (Kunz and Fischer, 2012; Andersson et al., 2016). A vision creates a direction for the project team (Andersson et al., 2016). Beyond the vision, the project should set two to three goals that are challenging, yet realistic (Kunz and Fischer, 2012). The stakeholders should be involved in the development of the goals (Kunz and Fischer, 2012). The project should establish metrics for the goals and vision (Kunz and Fischer, 2012). When goals or milestones are reached, this should be celebrated (Kunz and Fischer, 2012).

Several studies conclude that creating a strategic *plan* for the implementation is crucial (Kunz and Fischer, 2012; Andersson et al., 2016; Ling, 2003). The plan should be made by the stakeholders responsible for VDC – usually the design or project manager – and delegate the responsibilities to specific project team members (Kunz and Fischer, 2012). The contractor organization – which is accountable for the plan – should also be included (Kunz and Fischer, 2012). The plan should be flexible on project level and should be continuously updated (Andersson et al., 2016; Ling, 2003). It should also include the specifications for the project in question (Kunz and Fischer, 2012). The plans should be realistic with regards to the vision and the goals for the implementation. The implementation must not be rushed, and projects with a tight schedule should not conduct an implementation (Ling, 2003).

To create good relations within the *project team*, a kickoff meeting should be arranged (Kunz and Fischer, 2012). The project's VDC tools and techniques are presented to stakeholders at the meeting, as well as a 3D model of the product (Kunz and Fischer, 2012). The project team, client and subcontractors should be located together on-site to ensure good relations throughout the project (Kunz and Fischer, 2012; Andersson et al., 2016). Members of the project team should not be chosen randomly but based on their knowledge of VDC, project type, size, complexity, client, and location, (Andersson et al., 2016). Further, a high level of interest in the implementation by team members is vital for the implementation (Ling, 2003). Lastly, the team members should receive feedback from each other and the organization (Andersson et al., 2016). The feedback becomes a quality control of the work and contributes to good relations between the team members (Andersson et al., 2016).

The stakeholders should be *trained* to interpret the visual models of the project (Kunz and Fischer, 2012; Andersson et al., 2016). Stakeholders need to understand how VDC works and have practical experience. Those responsible for developing and updating the 3D model need to be skilled users of the applied software (Andersson et al., 2016; Ling, 2003). Organizing internal training is a good way for the employees to develop and maintain useful knowledge (Ling, 2003). After VDC projects are completed, the stakeholders should reflect on lessons learned to improve VDC implementation in future projects (Andersson et al., 2016).

There are four main types of barriers that can hinder stakeholders to *engage* in the implementation of innovations, namely restrictive contract relations, disagreements concerning risk assessments, resistance between the contract partners, and lack of resources (Manley, 2008b; Rose and Manley, 2012; Rose and Manley, 2014). Restrictive contract relations concern choosing contractors based solely on price, a practice that gives few incentives to implement innovations (Manley, 2008b; Rose and Manley, 2014). Disagreement concerning risk assessments is regarding economic responsibility if the innovation fails (Rose and Manley, 2014). Distrust between the partners can prevent them from proposing and welcoming innovations (Rose and Manley, 2014). Enough resources are essential for the clients to evaluate the innovative ideas that are being proposed (Manley, 2008b). Beyond preventing barriers, one should establish incentives for the project team to engage in the implementation, and economic incentives are preferable (Rose and Manley, 2012).

RESULTS AND DISCUSSION

The main findings are represented by seven key elements for VDC implementation ranked from most to least influential: Anchoring, Communication, Vision, Plans, Project Team, Training, and Engaging. The following three research questions are answered: 1) how is VDC implemented in construction projects, 2) which part of the implementation process has had positive effects and 3) which part has had negative effects on the implementation?

ANCHORING

The results show that the many software used to anchor VDC tools and techniques are not well integrated, nor have a huge amount of automation. There is a lot of manual and time-consuming punching when using the VDC framework. This is surprising considering the importance integration and automation is given by the theory (Kunz and Fischer, 2012; Andersson et al., 2016). One would assume there exist software programs designed for the VDC framework, and questions are raised concerning the lack of effective VDC software.

One informant says the engineers and designers were forced to use VDC instead of the “the traditional way” of working. This push positively affected the implementation, which resulted in the use of VDC, as Andersson et al. (2016) suggest. The remaining informants were unsure how crucial it was that participants actually used the VDC framework besides from the ICE sessions. However, all the informants ensured that the VDC tools and techniques were used during ICE sessions.

Three informants received support from the company during the implementation, and according to the literature, this should affect the implementation positively (Ling, 2003; Blayse and Manley, 2004). One informant claimed that support from the project manager was important, even though the literature does not seem to mention support from the nearest leader as crucial.

The 3D models were implemented early in the design phase of the projects, unsurprisingly complying with Khanzode et al. (2006) and Aslam et al. (2021). One project introduced MMI and a Last Planner Software halfway into the design phase. This was too late, and the project spent resources without achieving the potential benefits. One project stopped the ICE sessions towards the end of the design phase, when most of the BIM was finished, since they were time consuming. Continuing the ICE sessions was considered as waste. The theory does not recommend stopping ICE sessions, making the finding unexpected.

COMMUNICATION

National BIM standards were not used in the projects, and one design manager didn't know they existed. This is fascinating considering the vital position standards are given in the literature (Kunz and Fischer, 2012; Andersson et al., 2016). One project created its own BIM manual describing, among other things, file formats for the project. Another developed a manual for communication to avoid information being wasted. These BIM manuals affected the VDC implementation positively.

The projects used 3D models for communication purposes, as suggested by Khanzode et al. (2006). To prevent all team members from attaining business secrets, one of the projects used email when communicating project costs.

Three of the projects used software for Last Planner instead of post-it notes on a wall due to the COVID-19 pandemic. One informant manually rewrote the activities from the Last Planner software to a 3D model software with – obviously – limited functionality. The manual rewriting was time-consuming and affected the implementation negatively.

An interesting finding is that two of the informants deliberately did not call the framework VDC. This helped implementation, as the project team accepted the new ways of working without complaining about dealing with a lot of new terms. Descriptions of similar experiences were not found in the literature. One states this "sold" the working methods to the project team. The positive effect is not enhanced in the literature. When the intention is to implement VDC, it seems counterintuitive to not make the stakeholders familiar with the term, making the finding interesting. Another informant deliberately exaggerated the potential benefits of VDC to the client to create high expectations. This pressed the project to deliver what they had promised and is also not investigated in examined literature.

VISION

Two projects had no vision for the implementation. The implementation of VDC was still successful, so a vision may not be as essential as Kunz and Fischer (2012) and Andersson et al. (2016) state. A supporting finding is that closer investigation revealed that the two projects had not formulated visions, but goals. A vision should create a direction for the implementation rather than being an achievable goal (Andersson et al., 2016). However, the goals had a positive effect on the implementation since they were accomplished. A vision for the implementation might create positive effects without being critical. One informant specified that including the client when setting the goals positively affected the implementation. Time was spent understanding the client, resulting in excluding objectives that were nice to have but not needed. Including the stakeholders and creating realistic goals are supported in the literature by Kunz and Fischer (2012).

One informant observed that goals prioritized by the project team were achieved, while those neglected were not. This is interesting since it's not established in the literature. One can argue that it's not enough to establish goals for the implementation, the project team must work targeted to achieve them. Metrics targeting the goals and visions would enable this Kunz and Fischer (2012). However, none of the projects used metrics to target the goals. Yet, it did not affect the implementation negatively. This raises questions as to whether creating metrics to achieve goals and vision is critical.

None of the projects were celebrated when goals were accomplished during the COVID-19 pandemic. They usually celebrate with cake, but the finding indicates that this may not be as important as the theoretical framework states.

PLANS

None of the projects created an implementation plan, even though it is recommended in the theory (Kunz and Fischer, 2012; Andersson et al., 2016; Ling, 2003). Implementation was not believed to suffer, hence implementation plans may not be critical for success. The implementation plan should be continuously updated (Andersson et al., 2016; Ling, 2003). Therefore, it's no surprise that even though no projects created implementation plans, other dynamic plans allocating responsibilities had positive effects. One project had a too complicated plan, and they believed the reason was the inclusion of too many project specifications, as suggested by Kunz and Fischer (2012). One solution for future projects could be to not include too detailed project specifications. One informant experienced that prioritizing one detailed specification, and neglecting others, caused negative effects. Another negative effect of the lack of implementation plans was too few milestones. It made it challenging to identify when deliveries were due. Theory does not point out the number of milestones to include in an implementation plan, making the finding interesting. A tight schedule is considered unfortunate for implementation (Ling, 2003). Therefore, it was surprising that the projects ascertain that their tight schedules affected the implementation positively. One stated: "The tight schedule created an opportunity for VDC". Questions arise about whether a tight schedule could benefit the implementation, but experiences from other projects imply that pressure on time, results in the returning to well-known routines.

PROJECT TEAM

Two projects arranged kickoff meetings that positively affected the relations in the project team, an experience that is supported by Kunz and Fischer (2012). An informant that did not arrange a kickoff meeting said this had a negative effect on the project team. However, another informant stated that they established a good group without a kickoff meeting, so the latter finding suggests that kickoff meetings are not necessary for the implementation.

Team members in two projects were put together after careful consideration. The combination of knowledge positively affected the implementation. In two projects where the teams were composed randomly, one informant says it affected the implementation negatively. This aligns with the prescriptions for team composition proposed by Andersson et al. (2016). Regarding required knowledge about VDC, the findings show that two projects had two members with VDC knowledge while two had one. Two members with knowledge had a positive effect on the implementation since these two members could support each other's efforts. Even if it's not specified that projects should have two members with VDC knowledge, the finding is not regarded as unsurprising.

In one project, the client and the project team decided not to be co-located. According to the theoretical framework, the client and project team should be co-located in VDC projects (Kunz and Fischer, 2012). However, the decision positively affected the implementation since both the client and the project team could discuss economic matters without being overheard. This suggests it may not be as crucial for the project team and client to be co-located.

Two informants experienced feedback from the organization. This had a positive effect on the implementation, just as described by Andersson et al. (2016). Two other informants received almost no feedback. On the surprising side, they stated this had a positive effect since the organization did not "surveillance" the project. However, the fifth informant experienced a lack of feedback as a problem. The project did not get the needed support from the organization. In sum, feedback from the organization might be favorable.

TRAINING

Three informants had attained VDC training, which, unsurprisingly, affected the implementation positively. The informants without training stated however that this did not negatively affect the implementation, since other team members contributed with VDC knowledge. It's interesting since the literature claims stakeholders need to know VDC (Kunz and Fischer, 2012; Andersson et al., 2016; Ling, 2003). The finding implies that some stakeholders should understand VDC, but it doesn't have to be the design or project manager. The training focused on the practical implementation of VDC, and the informants implemented VDC on projects as part of the course. This both positively and negatively affected the implementation. One said: "You're in a VDC bubble during training and it's beneficial to implement VDC while in that bubble". He admits though that VDC needs maturation, and that one is not ready to implement VDC under training. Nevertheless, practical training is viewed as positive by the literature (Andersson et al., 2016; Ling, 2003). After training, the informants got professional input from their instructors which positively affected the implementation. Further, they all will arrange internal training in the company, supported by literature (Ling, 2003).

It varies how much training the subcontractors have. However, their skills in 3D modeling software positively affected the implementation. This correlates well with literature (Kunz and Fischer, 2012; Andersson et al., 2016; Ling, 2003), which states that all the stakeholders should be able to use the program for the 3D model.

One informant said the organization will evaluate the projects ex-post for learning purposes, as suggested by Andersson et al. (2016). Another informant added that their continuous project evaluation had a positive effect on the implementation, even though this does not seem to have been studied in the existing literature.

ENGAGING

Two projects based their contracting on the lowest price. According to the literature, this will negatively affect the implementation (Rose and Manley, 2014). It's therefore surprising that it's not considered negative by the informants. There have not been any disagreements concerning risk assessments between the parties since the contract provides the contractor with most of the risk. The finding is in line with the theoretical framework (Rose and Manley, 2014). There have emerged good relations between the clients and the project teams as they used collaborative contracts. The positive effect on the implementation is stated by the literature (Rose and Manley, 2014). The projects had enough recourses for the implementation, positively affecting the process, correlating with the theoretical framework (Manley, 2008a).

An unusual barrier to the implementation was the COVID-19 pandemic. The literature does not enlighten crises; however, it has understandably affected the implementation negatively. Nevertheless, the project team has learned to work remotely. Even though crises are not welcome during implementation, they can reveal new effective ways of working. Another barrier was getting the stakeholders on board with the VDC mindset. The theory does not address this, but it has presumably affected the implementation negatively. Finally, the projects did not establish incentives supporting the implementation. Surprisingly, this did not affect the implementation negatively, contradicting the literature (Rose and Manley, 2012). According to the informants, it's enough motivation that VDC reduces costs and increases efficiency.

CONCLUSION

The conclusion answers the fourth research question about how VDC should be implemented in construction projects and fulfills the purpose of the study by providing a set of recommendations. The following table 2 presents seven key elements of VDC implementation identified through literature and findings in the four investigated cases.

Table 1: The seven key elements of VDC implementation

VDC implementation element	Recommendations for implementation, gathered from findings and literature
Anchoring	• Tools, techniques and new software • Demolish the traditional way of working • Use of 3D models from project start • ICE sessions eliminated towards the end
Communication	• Manuals for project communication (e.g., platforms used in the project) • Communicate in 3D models • Client and sub-contractors have access to 3D models • Platforms enabling VDC • User friendly platforms
Vision	• Achievable goal • Inclusion of client when setting goal • Realistic goal • Focus on reaching goal • Use of metrics to reach goal
Plans	• Dynamic plan at project level • Specify responsibility of project members • Milestones clarifies the projects deliveries • Projects without tight schedule
Project team	• Put together carefully • Some members with VDC knowledge • Feedback from organization
Training	• VDC training with practical approach • Internal VDC-training within organization • Subcontractors trained in 3D models • Feedback from instructors
Engaging	• Stakeholders • Have responsibility for the risk • Contract that encourages collaboration • Resources

The results indicate that projects should *anchor* their VDC tools and techniques in the organization. The current software is not sophisticated enough for VDC. New software should be developed, providing leaner methods to execute VDC. The project should demolish the “traditional” way of working, only offering the VDC tools and techniques. The project manager – and the organization as well – must support the implementation. 3D models, MMI and Last Planner should be implemented early in the design phase, including the software which will enable the processes. ICE sessions should be eliminated towards the end of the design phase. All software anchoring VDC to the project should be user-friendly. This to make sure time is not wasted when using the software.

The study has revealed that project-specific BIM manuals for *communication* should be created, informing what platform the communication should take place on (e. g. 3D model, mail, IFC file format, etc.). The project should communicate in the 3D model, and both the client and the sub constructor should have access. The communication platforms should be user-friendly and sophisticated enough to conduct VDC activities.

The project can use an achievable goal instead of a *vision* for the implementation. The client should be included when setting the implementation goals. The goals should be realistic, and the project team should work targeted to reach them. Metrics should be created to achieve the goals. In the case projects, they managed well without celebrating accomplished goals.

The case projects were managed well without specific implementation *plans* for VDC. However, there should be dynamic plans that delegate responsibilities between the project team members. The plans should contain detailed enough milestones for the project team to identify the project's deliveries. Projects with a tight schedule should not implement VDC for the first time, as it is tempting to return to old habits when under pressure.

The project team should arrange a kickoff meeting. The *project team* should not be composed randomly. Two or more of the members should know VDC, but all the team members do not need to have a high interest in the implementation. The client and the project team could be co-located, but they do not have to be. The project team should receive feedback from the contractor organization to enable continuous improvement.

The project team should have members that have attended VDC *training* with practical implementation. The contractor should arrange internal training for employees in the organization. The subcontractor should be trained in the software for the 3D model. After the training, one should get professional feedback from the instructors.

There was a need for *engaged* stakeholders to implement VDC. The projects based their contracts on the lowest price, but that worked since the contractor carried the main risk related to the VDC implementation. The contract between the client and contractor should encourage collaboration, and enough resources to implement VDC are necessary. A global pandemic was a barrier to the implementation but fostered new working methods that could be useful for implementation. There were no contractual incentives for the implementation of VDC, but that was not considered to be necessary since the contractor earned profit from using VDC anyway.

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INTEGRATED SCHEDULING PLATFORM BASED ON BIM AND LEAN CONSTRUCTION

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ABSTRACT

This paper presents an integrated scheduling platform (ISP) that was developed and implemented on a major health care construction project. This ISP incorporates both BIM and Lean Construction and provides a framework for developing the master schedule and the detailed schedule, as well as for monitoring the progress of on-site work. Although numerous studies present the advantages of integrating Lean Construction and BIM use, few on-site results have been quantified and published to date. This research therefore aims to identify and evaluate the impacts of using the ISP, as assessed by individuals who work on a construction site. The results obtained through interviews and questionnaires proved that using the ISP, was very positive for the project. Three major benefits were identified during the case study: planning was diligently updated, the information presented in the 3D models and in the visual schedules was always up to date and accurate, and all project stakeholders understood the schedule—which finally led to excellent project performance.

KEYWORDS

Building Information Modeling, Construction Planning, Lean Construction, Visual Schedule, Takt Planning.

INTRODUCTION

The artefact presented in this article—an integrated scheduling platform (ISP)—was developed to address a host of issues: theoretical planning does not reflect the reality of the job site, project stakeholders collectively lack proficiency with planning software, site crews spend an extraordinary amount of time each week planning and monitoring non-systematic schedules, planning is imposed on subcontractors, a lack of collaboration exists between stakeholders, and sharing planning information presents many communication challenges. These issues are usually addressed by ensuring an experienced and dedicated planning team is deployed in the project management structure (Slootman 2007). The mastery of planning software and the theoretical follow-up of deadlines provided by the planning teams satisfied the management teams, but the situation is different for the site teams. The theoretical information present in the schedules is rarely synthesized and adapted to the reality of the site crews, which creates

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a disconnection with worksite planning methods. In fact, the contribution of a team dedicated to planning within the management team, in itself, brings its share of communication problems between the teams and fortifies the silos. This statement is even more true when it comes to a mega-project where the organizational structure is more complex (Gupta 2015, Nyarirangwe and Babatunde 2019). To improve communication and partially resolve the challenges addressed, the BIM process is used to foster communication and Lean principles are integrated into practices to increase collaboration, but the complete solution is not combined with planning management practices.

To avoid this dissociation and respond to the issues, an artefact, integrating BIM and Lean principles for planning purposes was developed. Resulting from the combination of Action Research and Design Science Research, the ISP artefact is tailored to serve the various project planning phases and stakeholders involved. It provides a digital platform for the collaborative use of Last Planner System and Pull planning, integrated with BIM. To evaluate its impacts and to validate its efficiency, a case study was carried out on a major construction site during both the planning and the construction phases of the project.

The aim of the ISP application is to simplify the communication of schedules, facilitate the understanding of planning-related challenges, optimize construction sequences and ensure the schedule is updated in an efficient and seamless way for constant progress monitoring.

INDUSTRY PROBLEM AND THE CONTEXT THAT MOTIVATED THE DEVELOPMENT OF THE ARTEFACT

In construction management best practices, planning is a key element for project success. However, in the construction industry, the master schedules are often created to meet the client's requirements, while the site schedules are made in an unsystematic way by the construction crew. In fact, the construction industry has historically had a bad reputation in terms of cost, time and quality (Bertelsen 2003). A negative impact is brought also by the siloed and incoherent planning work, which does not give the project the added value that integrated planning can bring.

LITERATURE REVIEW

Although numerous studies in the last decade have presented the advantages of combining Lean Construction and BIM use, few on-site results of their integration have been quantified and published to date. The scientific literature reports positive and negative interactions between Lean principles and BIM (Sacks, Koskela et al. 2010, Sacks, Radosavljevic et al. 2010, Saieg, Sotelino et al. 2018) and gives detailed examples of improving construction through the combined use of Lean principles and BIM (Sacks, Korb et al. 2017). Bringing Lean principles to the construction site makes it possible to create added value for the client and enhances the stability of the workflow on the job site (Koskela, Ballard et al. 2002). Using Lean construction principles and applying Lean production methods to construction makes planning much more collaborative compared to conventional planning and scheduling practices.

In terms of planning, Lean Construction brings a vision focused on production and control. Planning concepts and strategies such as Takt planning—the German word "Takt" means cadence which, when used in the context of Lean Construction, addresses standardization, predictability and several other Lean principles (Haghsheno, Binninger et al. 2016, Binninger, Dlouhy et al. 2017). Production control charts and the concept of pull planning have also been developed following the principles of Lean Construction.

The BIM process, which has been described as "a verb or adjective phrase to describe tools, processes and technologies that are facilitated by digital machine-readable documentation about the building, its performance, its planning, its construction, and later its operation" by (Sacks, Eastman et al. 2018), is used in the planning methodology to help visualize and communicate and to structure project data.

Increased use of BIM has opened the door to the implementation of Lean principles in the construction industry. Although often used independently, the interaction between them influences their impact on each other. A total of 56 interactions between Lean principles and BIM functionalities were identified by (Sacks, Koskela et al. 2010), emphasizing that the full potential of this tie-in can be revealed only when their adoption is fully integrated. A recent publication gives examples of construction improvement through the combined use of Lean and BIM (Sacks, Korb et al. 2017), but no integrated planning, scheduling and monitoring platform incorporating BIM is reported.

METHODOLOGY

The methodology used in this paper combines Action Research (Azhar et al., 2010) with Design Science Research (Hevner and Chatterjee, 2010; Rocha et al. 2012) to define and develop the artefact—an integrated scheduling platform. The researcher was part of the planning team and could participate in all phases and iterations of the research project, as described by Salehi and Yaghtin (2015). The artefact's efficiency was validated using a case study. To quantify the impact of the artefact and collect the results presented in this paper, superintendents and foremen from the construction site in question were interviewed and given questionnaires after 30 months of using the ISP.

DEFINITION AND DEVELOPMENT OF THE ARTEFACT

The definition and development of the artefact is presented in three steps: it will first be a question of establishing the needs to be met by the artefact, then its theoretical definition and finally its operationalization.

This ISP artefact was first developed in the context of the second phase of one of the largest health care construction projects in North America, totalling over 3 million square feet. Contractually and contextually, it presented a number of logistical challenges, performance targets and excessively optimistic delivery milestones. Since this project is long enough to be able to develop and implement an ISP and makes intensive use of BIM and Virtual Design and Construction (VDC) (Rischmoller, Reed et al. 2018, Sacks, Korb et al. 2017), and the construction team in place is very experienced and open to innovation, it was taken as an opportunity to develop and test the artefact.

ESTABLISHMENT OF THE NEED TO BE MET BY THE ARTEFACT

A list of needs was developed by the first author of this paper through collaborative discussions with the project management team and the site crew prior to the planning phase of this design-build project. This list represents the criteria that had to be met by the ISP artefact: (1) Planning updating needs to reflect the daily activities of the job site. (2) Individuals need to understand project planning regardless of their proficiency with the planning software. (3) The amount of time site crews invest weekly to monitor schedules needs to be minimized. (4) Meetings and communications between foremen to update planning need to be structured and streamlined. (5) Subcontractors need to be included in schedule development to ensure they are committed to the schedule. (6) There needs to be greater collaboration on the job site by having discussions and ensuring a transparent process for all stakeholders. (7) The sharing of data to update planning needs to be streamlined and automated. (8) Clear and simplified visuals (including generated with BIM) need to be used to communicate the schedule to site crews.

THEORETICAL DEFINITION OF THE ARTEFACT

The resulting artefact, the ISP, proposes an application framework for using a variety of tools that are heavily inspired by Lean Construction principles, the BIM process and practices the project team had already adopted.

To create the master schedule

The first part of the framework proposed in the ISP pertains to creating the master schedule. The master schedule is produced using project input data, such as distinctive features, constraints, opportunities and the company's business strategies. Once this basic data about the project has been gathered, the framework sets out four distinct phases for creating the master schedule: the organization phase, the development phase, the validation phase and the planning optimization phase. Once the four planning phases are completed, the master schedule serves as a solid foundation to ensure BIM and Lean Construction are incorporated during the construction phase. Each of the phases—Organization, Development, Validation and Optimization—has diverse needs and uses different tools and principles as shown in Figure 1.

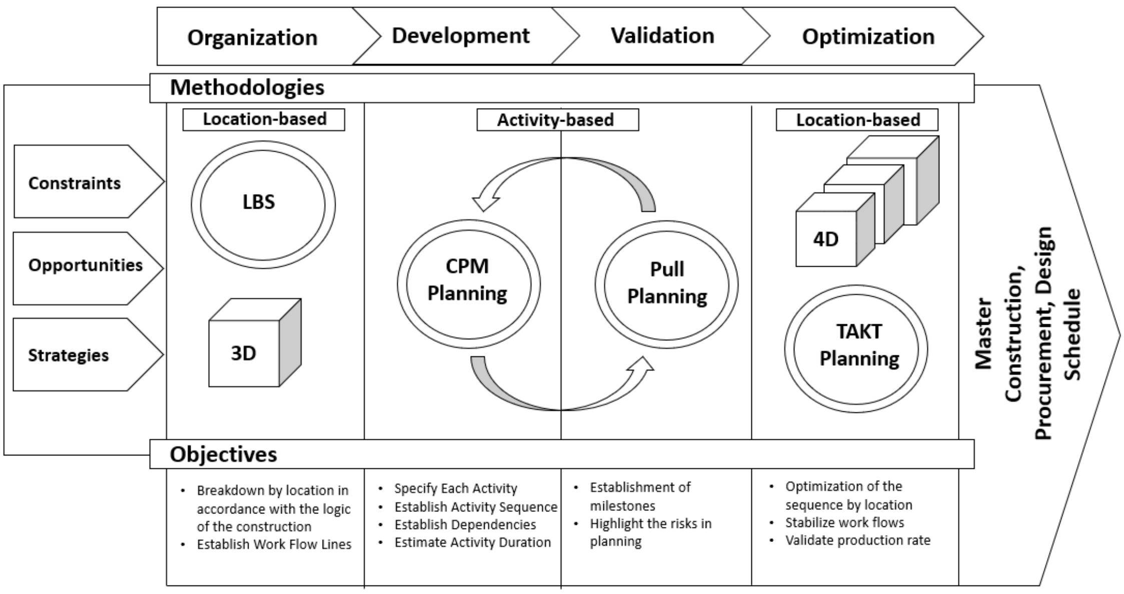

Figure 1: Framework for creating the master schedule

In the following paragraphs, these four phases of the cycle are presented in more detail:

Organization: To ensure that information is organized, the project needs to be segmented not only by work breakdown structure (WBS) for planning, but also by location breakdown structure (LBS). According to Kenley and Seppänen (2009), "location production focuses on the use of locations as the unit of analysis and tasks as the unit of control". It is essential that the site crew be involved in this segmentation phase to confirm the zones are realistically defined, accurately represent the construction sequencing strategy, and stabilize output and workflows.

Development: The critical path method (CPM) is used for planning development, meaning that construction sequences are developed, logical connections between activities are identified, and the duration of activities is determined to create the different sections of the master schedule. The location-based structure (LBS) that was previously determined with the site crew is followed when initiating the sequences, and the CPM governs the details of the schedule. It is during this phase that the schedule takes shape, following the differentiation of production-oriented planning methodologies and critical path analysis planning methods, as underlined by Kenley and Seppänen (2009).

Validation: The pull planning method, grounded in lean construction principles, is used to ensure the information structured and introduced by the CPM is validated. Pull planning encourages collaboration and ensures planning is tested, the main contractual milestones are validated, and the most critical activities are highlighted. During this phase, construction sequences are confirmed by the specialized contractors; and challenged to verify their compliance with the time constraints of the project. Validation can also be assisted by 4D simulations.

Optimization: Lastly, Takt planning is used to validate planning, productivity levels and schedule workflows to ensure planning is optimized. This key step in the master schedule creation process can undergo several iterations to ensure location, labour and productivity constraints are fully controlled.

This is how the master schedule for this project was created, and this foundation made it possible to implement the ISP combining Lean Construction and BIM on this project's construction site.

To develop the detailed schedule

The detailed schedule is developed from the master schedule once the construction phase has begun and project collaborators (subcontractors and design professionals) have joined the team. Details provided by the experts of each discipline are added to the schedule progressively—depending on how quickly contracts are awarded—and illustrate the detailed construction sequence strategy. Once the master schedule is submitted and approved, the same framework is adapted and used to ensure the detailed schedule is developed in collaboration with partners not only during the collaboration phase, but throughout all the planning phases (Figure 2).

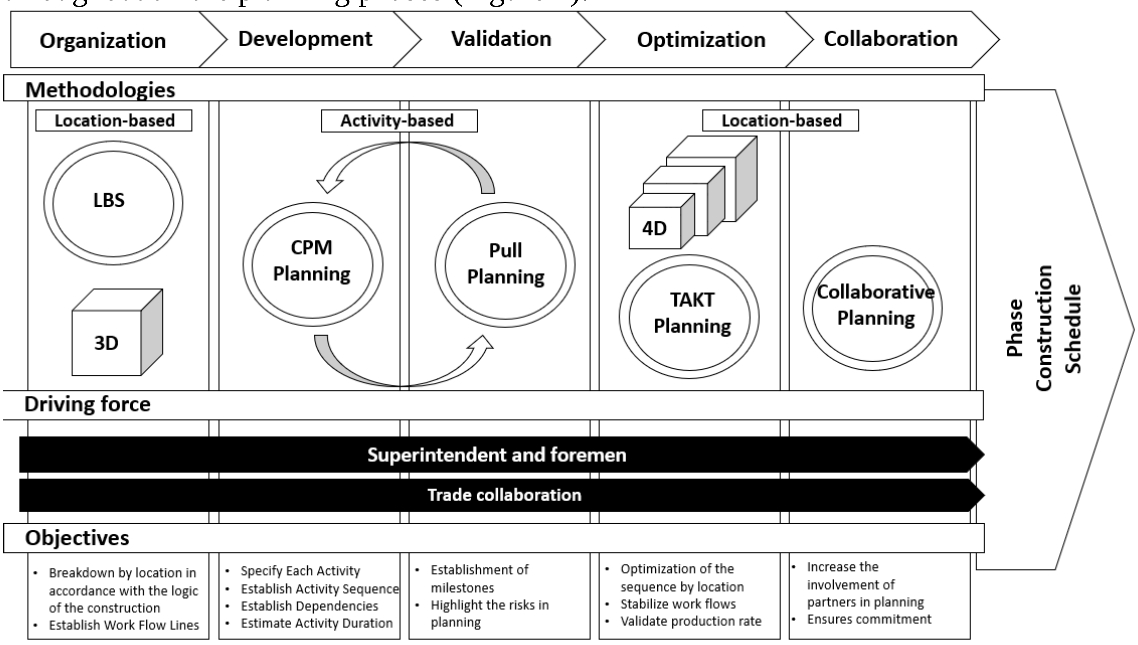

Figure 2: Framework for developing the detailed schedule

The site foremen who will directly organize the work on site must be involved to achieve better planning results and ensure the construction sequences proposed in the detailed schedule are realistic and approved by the main stakeholders. This involvement, inspired by the "decide by consensus" Lean principle derived from Toyota's practices (Liker 2004), makes it possible to leverage the experience and opinion of several discipline experts when developing sequences and deciding on the duration and interrelationship of construction activities. Taking all available options into consideration when developing the detailed schedule considerably increases the success rate of obtaining the best solution or construction sequences, as the case may be.

The framework requires partners' participation throughout the process. The project managers of the various disciplines are asked to participate in the first four phases, namely Organization, Development, Validation and Optimization, to ensure required contractual milestones are met. During the last phase, Collaboration, the trade site crews are also involved. The aim of this phase is to work with the foremen of the disciplines in question and ensure they actively participate in the planning session in the interest of increasing the success rate of obtaining a realistic schedule and increasing partners' involvement in and commitment to planning.

To produce the three-week lookahead schedule

The three-week lookahead schedule is produced by highlighting the activities to come in the next three weeks in the visual schedule of the phase in question. The phase's visual schedule is automatically extracted from the detailed schedule and represented by production control charts—a location-based tool designed to show the status of the project on one or very few pages (Kenley and Seppänen 2010).

The visual schedule, as shown in the Figure 3, is created by extracting data from the detailed schedule, which is sufficiently detailed for use on the construction site.

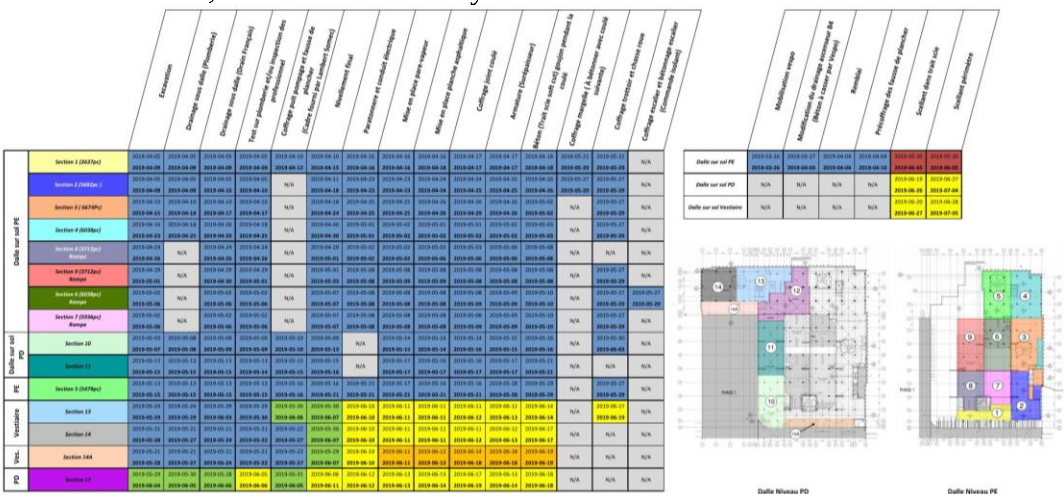

Figure 3: Graphical representation of the phase schedule with color indicators showing upcoming activities in the next three weeks

OPERATIONALIZATION OF THE ARTEFACT

Once the construction work has begun and the detailed schedule is in development, the ISP is implemented, making it possible to meet the requirements listed at the beginning:

- Ensure the information in the visual schedules and in the Takt planning matches the information in the detailed schedule and the master schedule.

- Make sure a visual schedule is automatically produced from the detailed schedule.
- Make sure the information in the detailed schedule and work progress information is applied to the BIM models and shown in 4D simulations.
- Ensure the maximum number of people understand the schedules, regardless of their proficiency with the planning software and the Gantt chart.
- Increase stakeholders' degree of confidence, knowing that all stakeholders are working with the same information during design and construction.
- Make it easier to update schedules and reduce the amount of time required to do so by proposing the option of automating the updating of activity progress using a mobile application.

As shown in Figure 4 – operationalization of the digital artefact, once the master schedule and detailed schedule have been developed with partners during collaborative planning

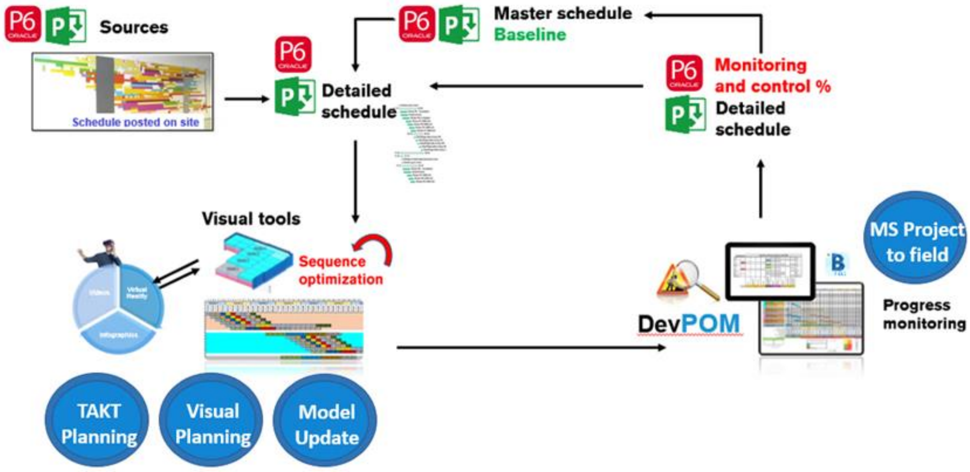

Figure 4: Integrated scheduling platform – operationalization of the digital artefact

sessions, the solution proposes to automatically extract from the detailed schedule visual schedules (by phase – to highlight three-week lookahead planning) with colour coding to indicate the progression of work. These two types of automatically generated schedules make it possible for the site crew and project stakeholders to visually understand planning and the progression of work. Furthermore, these two types of schedules are accompanied as necessary by a 3D BIM model and a 4D simulation updated with the latest information from the detailed schedule.

The last step of the ISP makes it possible for foremen to easily share the progression of work in their zone using a mobile application and for the information to automatically be logged in the detailed schedule and the master schedule.

This workflow ensures that work progress percentages are sent directly from the job site to the detailed schedule, the 3D BIM models and the 4D simulation. This flow of information makes it possible to generate in real time a simulation that represents the sequences as they are built.

ASSESSMENT OF THE ARTEFACT – A CASE STUDY

The ISP was developed prior the project planning phase of the mega hospital project, before the design and construction phases, to ensure it would be integrated and tested on the case study by the time the first draft of the preliminary master schedule was produced. This guaranteed that the construction team would follow the same structure for the entire duration of the project and for all phases. Furthermore, since the superintendents of the team assigned to the project were already used to collaborative planning, we included them in artefact development to cement their buy-in. This also allowed for the site crew, led by the superintendents involved in solution development, to be trained on the ISP very early in the planning process. Interviews were conducted and questionnaires distributed with the objective to assess the impact—of using BIM and Lean Construction together, and to measure the effectiveness of the ISP used during 30 months on this project. Members of the site crew (who used and applied the ISP on a daily basis) assessed and commented on the artefact's impact and shared their feedback with us.

DESCRIPTION OF THE PARTICIPANTS

A total of eight men, 63% of whom were foremen and 38% of whom were superintendents, participated in this case study. The average number of years of experience of participants who held a construction project management position was 13 years. The average number of years of experience of the superintendents involved in this project was 20 years. In total 5 foremen and 3 superintendents were interviewed. In terms of past experience, 62% of participants (100% of the superintendents) said they had already used a tool or methodology that incorporated one or more of the key principles of Lean Construction.

MATURITY OF THE PROJECT TEAM

The participants' self-evaluations indicated that, at the beginning of the project, the superintendents considered their level of familiarity with Lean Construction to be average (6 out of 10 on average), as the foremen (5 out of 10). To better understand the team's level of maturity and experience, we asked the 62% of participants who said they had previously used a tool or methodology that incorporated one or more key fundamental principles of LEAN Construction to identify which tools or methodologies they had previously used. Of the participants had previously used a tool or methodology incorporating key principles of Lean Construction, all said collaborative planning was a technique heavily inspired by Lean Construction, half said they had previously used visual planning to improve site crews' understanding of planning, and one had previously used 4D simulations to improve the understanding of planning. Thus, we can conclude that participants did not have to overcome a very steep learning curve to apply the ISP.

THE PROJECT TEAM'S ASSESSMENT OF THE ISP

To begin with the project team's assessment of the ISP, all participants were asked at the end of the project to assess the artefact's impact on the project after 30 months of use. On a scale of -5 to +5 (with -5 meaning negative impact, 0 meaning no particular positive impact and +5 meaning positive impact), more than half of the participants chose the highest positive impact (+5). The average assessment value was 4.9. The subsequent interviews conducted with participants allowed us to explore why this assessment was so positive. According to participants, the ISP ensured that: (1) Planning was diligently updated throughout the project; (2) The information presented in the models and visual schedules was accurate and up to date; (3) All project stakeholders understood the schedule, which led to greater trust and better communication. In the following paragraphs, these three major benefits are presented with more detail:

Planning was diligently updated: According to participants, the artefact's structure imposed greater diligence in terms of the frequency of updates to planning information. The upsides of this diligence imposing daily meetings and weekly updates were that it ensured planning was done carefully, prompted question periods regarding scheduling, and made sure there were stopping points to modify and adjust construction sequences, thus ensuring the site crew was acting proactively rather than reactively. The vast majority of participants also said that the consistency and increased diligence the ISP required represented a significant change to their work routine. The time allocated for planning during a work week became much better distributed over the week, and planning meetings became much shorter. Rather than organizing one long, intense work session per week, during which foremen and superintendents typically had difficulty staying on task and working efficiently for the whole meeting, participants appreciated the fact they could do the exercise more frequently and in a shorter, more concise format. As one participant explained, "At the end of the week, I feel freer and in control of planning. Implementing this platform makes me feel like I have one less weight on my shoulders." In fact, participants acknowledged that although they spent the same amount of time planning each week, the frequent updates lightened their workload, and in the end, they felt relieved.

The information presented in the models and visual schedules was accurate and up to date: The ISP also enabled a greater degree of confidence in the accuracy of the information displayed in the BIM models, 4D simulations and the visual schedules. Since the information is accessible to everyone as soon as it is updated and available at any time in a model viewing and document management platform, all stakeholders can always consult the most up-to-date information. Some participants also highlighted how quickly information became available after it was updated. In short, participants stated that one of the artefact's major positive impacts on the project was the degree of confidence it gave people in the information available on the document viewing and management platforms throughout the project.

All project stakeholders understood the schedule: Lastly, the third major positive impact that was mentioned by participants during the interviews centred around how easy it was to understand the information produced by the visual planning process. The fact that very simple and clear visuals were used to make planning more accessible ensured all members of the site crew and professional teams as well as the client's representatives, regardless of their familiarity with reading a Gantt chart or schedule, could access the information, and quickly and easily understand the planning, as complex as it was. This simplification of information fostered a better understanding and better communication, and in turn facilitated the achievement of the project's key milestones.

Since the ISP ensures that the information displayed in the master schedule given to the client always matches the information in the schedules used by professional partners and subcontractors on the construction site, it was noted that stakeholder collaboration was positively impacted. Also, it had a positive impact on stakeholders' level of trust in one another and on their collaboration with one another. The questionnaire given to participants indicated greater collaboration with each type of stakeholder, and notably better collaboration with subcontractors.

The relationship and level of trust and therefore collaboration between a general contractor and subcontractors can easily be negatively impacted over the course of a project by a lack of transparency and communication between the parties. Implementing the ISP early in the project enabled subcontractors and partners to quickly trust the project planning since they were involved in and consulted on the project right from phase schedule development. Their participation in planning and in toolbox meetings made it possible to build this trust and improve the team's synergy.

Furthermore, since the ISP made it much easier to read the planning documents, it was noted that many subcontractors quickly bought into the artefact and followed the visual schedules, as the latter made it possible to ensure everyone understood the information. It is important to mention that many subcontractors and workers, despite their experience, cannot read Gantt charts and have difficulty identifying planning risks for their own team when the information is not presented in a concise visual format.

IMPACT ON PARTICIPANTS' LEVEL OF TRUST IN MEETING THE MILESTONES

After assessing the artefact's impact on the project and on stakeholders' level of trust and collaboration, we looked at participants' level of trust that the contractual milestones would be met, which is a key factor for the success of the project. Participants measured the artefact's impact on their level of trust in meeting the milestones, on a scale of -5 to +5 (-5 meaning negative impact, 0 - no particular impact and +5 - positive impact). The assessment value was between 4,75 and 5 for 90% of the participants. Thus, we can conclude that the ISP had a very positive impact on participants' level of trust that the contractual milestones would be met and work would be completed on time. The subsequent interviews revealed the following main factors impacting participants' level of trust: (1) Partners were more involved in planning, which increased the accuracy of schedule sequences. (2) Stakeholders were much more willing to collaborate due to the ISP increasing transparency and communication on the construction site. (3) Lean Construction principles were applied to ensure location-based planning, thereby leading to subcontractors having a specific amount of time in a specific zone and limiting the overlapping of activities in a given zone. (4) A collaborative approach was used to develop the detailed schedule. (5) Just-in-time delivery to the site was used. (6) It was easy to make changes in the schedule and see their impacts on delivery milestones.

These factors increased participants' level of trust that contractual milestones would be met and were key to improving stakeholder relations on the construction site. To summarize, the impacts of implementing this ISP were very positive for the team. All participants stated during the interview that they would use this artefact on their next job and that they believe it provided a structure that was critical to the success of the project.

CONCLUSION

This research has studied the impacts of using the first version of the ISP on a job site. It currently focuses on the general contractor's point of view and paves the way for further research to quantify the direct and indirect impacts on the work of design professionals, subcontractors and suppliers. Implementing this artefact on a major health care construction project carried out by a large construction and design-builder company has proved to be very advantageous. As an output of the research, three major benefits were identified during the case study: planning was diligently updated, the information presented in the 3D models and visual schedules was always up-to-date and accurate, and all project stakeholders understood the schedule. The fact that the delivery milestones were achieved, despite how optimistic they were, attests to this artefact's positive impacts. In the future, a larger study will be conducted across a dozen projects completed by the company where the ISP is deployed. This larger research scope and the feedback from all site crews and management teams will define the improvements that need to be integrated in the next version of the artefact. Incorporating innovation in this general contractor's planning practices is in line with an innovation strategy that focuses on using VDC as a turning point to integrate new ideas and technologies as the main pillars of project management in order to add value to the project and deliver it on to the client.

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LPS PERFORMANCE DIAGNOSIS MODEL USING FUZZY INFERENCE SYSTEM

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ABSTRACT

The Last Planner System (LPS) has long been used in construction projects to promote reliable planning and enhance productivity. However, despite various attempts to evaluate LPS implementation efforts, the human aspect of the evaluation attempts has not been given enough attention. This issue may be tackled through Fuzzy Inference Systems (FIS) to capture more information regarding the gradual and intricate changes in scoring systems. Therefore, this paper aims to offer a standardized diagnosis model for LPS performance in construction projects. This model employs an FIS that analyzes the results of an LPS implementation for a more accurate investigation of the implementation. First, a thorough literature review is conducted to select the most prominent factors influencing the LPS implementation process, followed by expert panel questionnaire development and distribution among LPS experts to rank the selected factors. The obtained questionnaire results are then used to develop the FIS. The objective of this paper is hereby twofold: (1) to allow assessing expected LPS benefits through the qualitative assessment of the performance in the four LPS phases, and (2) to facilitate comparing past, current, and future performances throughout the organization's LPS implementation process to ensure continuous improvement.

KEYWORDS

Last Planner® System, fuzzy logic, implementation evaluation, diagnosis model, design science research.

INTRODUCTION

Having sailed into the construction industry with proven perks and inarguable successes, Lean construction tools and techniques have substantiated their efficacy among construction practices during the past decade (Stevens 2014). Lean tools and techniques range from value stream mapping, supply chain management, Just-In-Time delivery, LPS, six sigma, and more (Hanna et al. 2010). Analogous to Liker's renowned "Company X" described in his pioneering book "The Toyota Way" (Liker 2004), countless firms claim to be Lean, proudly flaunting their "Lean" projects for demonstration. However, as various researchers have repeatedly asserted, genuine Lean implementation is being confounded with mere superficial Lean tool applications (Liker 2004).

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Being a widely adopted Lean system, LPS proved wide benefits ranging from 30% increase in productivity, 17% saving in project budget, and 20% decrease in project duration to improvement in overall labour performance (Fuemana et al. 2013). Various studies have addressed investigating LPS implementations across projects, organizations, and countries, such as developing an LPS implementation health check (Power et al. 2021) and quantitative analysis of LPS implementations (Bortolazza et al. 2005; Bortolazza and Formoso 2006). Moreover, a variety of studies presented frameworks for proper LPS implementation, even in virtual environments (Salhab et al. 2021). Amidst the abundance of studies tackling measuring and evaluating LPS implementations, the need for perceiving the factors about LPS implementation as "fuzzy" or of varying degrees of applicability rather than either available or unavailable is deemed necessary. One study by do Amaral et al. (2019) has already developed a Lean score that is calculated using averages based on FIS for Lean implementations in general. However, the body of research on LPS implementation still lacks a diagnosis approach through FIS which is specifically employed in examining the impacts of influencing factors' subjective assessment in construction modelling (Sarihi et al. 2021). There is also a paucity of studies proposing an inclusive model providing a step-by-step approach for diagnosing and systematically improving LPS performance.

Built upon the firm conviction that LPS may be perceived as the gateway to Lean behaviors (Fauchier and Alves 2013), this paper aims to offer a standardized diagnosis model for LPS performance in construction projects, forming the basis for future improvements. This model employs a fuzzy expert system that analyses the results of an LPS implementation for a more accurate investigation of the implementation. First, a thorough literature review is conducted to select the most prominent factors influencing LPS implementation process, followed by expert panel questionnaire development and distribution among LPS experts to rank the selected factors. The obtained questionnaire results are then used to develop the FIS. Using the developed tool, an internal evaluation of the factors allows first determining overall performance of LPS, and second highlighting which factors to address in order to realize better improvements in performance, since different factors affect LPS performance distinctively. The objective of this paper is hereby twofold: (1) to allow assessing expected LPS benefits through the qualitative assessment of the performance in the four LPS phases, and (2) to facilitate comparing past, current, and future performances throughout the organization's LPS implementation process to ensure continuous improvement.

LITERATURE REVIEW

The Last Planner System (LPS) is a production planning and control system directed towards providing foresight for better planning and for stabilizing workflow in construction through attacking uncertainty in operations (Hamzeh et al. 2008). LPS promotes reliable planning, measuring planning system measurement, improving production performance, learning from plan failures, and preparing scheduled tasks (Hamzeh et al. 2008). It comprises four main phases: Master Scheduling, Phase Scheduling, Lookahead Planning, and Weekly Work Planning (WWP) (Ballard and Tommelein 2016). The main steps advocated by LPS comprise planning in more detail when getting closer to perform the work, developing plans with those who will perform the work, identifying and removing constraints ahead of time, making reliable promises for executing the work, and learning from plan failures (Hamzeh et al. 2012). To achieve this study's objectives, previous studies on Lean, specifically LPS, and on FIS are discussed in the following sub-sections.

LEAN PERFORMANCE EVALUATION

Various studies have attempted to assess or evaluate Lean performance generally and LPS performance specifically in construction projects. One study recently addressed specious Lean implementations across construction firms by developing a Lean Culture Index that measures its Lean culture and its readiness to apply Lean (Kallassy and Hamzeh 2021). Their study found that among the surveyed construction companies, there was still room for improvement in some areas, including enhanced training and better human focus. Another study presented an analysis of the implementation of Lean Construction and an evaluation of the potentialities that three different previously developed calculation methods provided in the diagnosis process (do Amaral et al. 2019). It was found that all three methods used to estimate the level of implementation fulfilled their purpose. Similarly, Li et al. (2017) evaluated the extent of implementation of Lean Construction and explored the influencing factors of Lean Construction. They found that different firms have different implementation extents of Lean Construction. The key determinants of Lean Construction implementation are organizational structure, knowledge of Lean Construction, organizational culture, and market factors.

Zooming into the LPS, a guideline and implementation health check for LPS was proposed to evaluate the applications of all LPS functions through case study design and data collection (Power et al. 2021). They concluded that an implementation assessment tool must be utilized to sustain consistent LPS implementation across different projects. Another study conducted a quantitative analysis of the implementation of LPS (Bortolazza et al. 2005; Bortolazza and Formoso 2006). Their results indicated a major problem in most projects: the lack of effective implementation of look-ahead planning of the LPS. A study by Soares et al. (2002) has also proposed an "Implementation Efficacy Indicator", where a set of fourteen practices are subjectively evaluated in terms of full or partial implementation. Each practice is given a weight of either 1.0 (practice is largely used), 0.5 (practice is partially used), or 0.0 (practice is not implemented). From another perspective, other studies such as Pérez et al. (2022) aimed to determine the relationships between project performance and some LPS components by establishing twenty-three metrics to evaluate six components. They found statistically significant correlations between the six components and statistically significant differences between high and low performance through six of the metrics.

FUZZY INFERENCE SYSTEMS (FIS)

It has been argued that the human thought process holds in a degree of fuzziness translated through logic with fuzzy truths, fuzzy connectiveness, and fuzzy rules of inference instead of the two or multi-valued logic (Silva 2014). Fuzzy logic originates from the need to elude the rigidity of conventional Boolean logic that evaluates any statement as true or false, allowing a degree of truthfulness when measuring the extent to which an object is comprised in a fuzzy set (Cherkassky 1998). FIS is an important aspect of fuzzy logic, and it is simply defined as a system that performs non-linear crisp mapping described using fuzzy rules that encode common-sense or expert knowledge pertaining to the problem at hand (Cherkassky 1998). Fuzzy logic applications have gone beyond representing subjective concepts, partial truth statements, and uncertain meanings into modelling complex systems in a direct and plain linguistic way (Kulkarni, 2001).

Resorting to using fuzzy logic can be attributed to its ability to handle the input data's uncertainty and turn qualitative variables into quantitative ones (Abreu and Calado 2017).

Lately, rapid growth in various fuzzy logic applications has been seen in different industries, including construction. For instance, aiming to maximize the buffers' reliability to match the real degree of variation, Farag et al. (2010) presented a study integrating LPS with a buffering assessment model based on fuzzy logic. Results show a 14% increase in the master schedule's level of reliability and optimizing the buffer sizes, leading to a decrease in overall time wasted in buffers. Moreover, acknowledging the need for continuous assessment of management performance, Li et al. (2020) developed an analytic network process-fuzzy comprehensive evaluation model to help construction enterprises evaluate and improve their management performance of Lean construction. The results are reflected in evaluating factors such as Lean quality management, Lean safety management, Lean time, and cost management, etc. Likewise, the concern of evaluating an organization's Lean thinking environment is addressed by Abreu and Calado (2017) through fuzzy logic reasoning. The authors suggested a methodology that aims to provide the organization manager with information required for continuous improvement by identifying the organization's existing constraints. The method's advantage is that it can be adjusted to be used by any organization regardless of its size, nature, strategy, etc.

RESEARCH METHODOLOGY

Design Science Research (DSR) is commonly used as a research methodology for studies that tackle real-world problems by introducing a novel artifact (Hevner et al. 2017). In this study, the addressed problem is the improper, unsustainable, or ingenuine LPS implementation across construction projects. An LPS performance diagnosis tool is developed in order to tackle this issue. The tool is part of an inclusive LPS diagnosis tool employment model that is developed to ensure a proper and sustainable LPS implementation. This study is started with a thorough literature review to select the most prominent factors influencing the LPS implementation process. Once the factors are selected, an expert panel questionnaire is developed and distributed among LPS experts to rank the selected factors. The obtained questionnaire results are then used to develop the FIS using MATLAB.

TOOL DEVELOPMENT AND IMPLEMENTATION

FACTORS AND QUESTIONS SELECTION

In order to estimate the level of genuine and sustainable performance of the LPS, a survey consisting of 20 questions that tackle tangible and intangible factors is developed. These factors are directly related to the LPS through its different phases (Hamzeh et al. 2009), vital cultural aspects, and quantifiable metrics. Such an umbrella of areas covered through the factors allows the evaluation of a deep and authentic LPS implementation that may be sustained by considering long-term aspects that are repeatedly stated as vital for Lean cultures generally. The survey questions are divided into four main categories: Phase/Pull Planning, Lookahead Planning, Weekly Work Planning (WWP), and Post-WWP. Some of the questions address core LPS practices, including the process of identifying and removing constraints, preparing a realistic and achievable pull plan, measuring PPC, … etc. Other questions, however, address the aforementioned intangible factors that are essential for ensuring a proper Lean culture for a sustainable LPS implementation. They include collaboration during the process of removing constraints and making tasks ready, performing root cause analysis for missed commitments, deciding on preventive actions for proactive planning, incorporating lessons learned into future planning, etc. Table 1 shows the different questions divided into four different phases.

Table 1 – Survey Topics and Questions

Topic	Question
Phase/Pull Planning	How meaningful is the handoff process among supervisors? How effective is the process of identifying each task's prerequisites, successive tasks, and requirements? How effective is the process of identifying the "global" constraints that impact the whole process? How realistic/achievable is the pull plan that was developed? How would you describe the load in the developed plan compared to the crew's capacity (crewing process)?
Lookahead Planning	How effective is the process of identifying constraints and screening constrained tasks during lookahead planning? How effective is the process of removing constraints and making tasks ready during lookahead planning? How collaborative is the process of removing constraints and making tasks ready during lookahead planning? How sufficient is the time available between identifying and removing the majority of the identified constraints? How efficient is the process of releasing hold points within the teams?
Weekly Work Planning (WWP)	How efficient is the process of measuring PPC (PPC is recorded weekly and accurately)? How efficient is the process of identifying deviations from the plan? How efficient is the process of taking immediate corrective actions based on the deviations? How efficient is the process of performing root cause analysis (asking why a task was not done until u get to the root cause) for missed commitments? How efficient was the process of deciding on preventive actions i.e. actions to avoid future planning failures? How many tasks are newly added to the WWP and are not previously planned in the lookahead phase?
Post-WWP	How efficient is the "continuous improvement/variance" feedback process? How efficient is the process of communicating and learning from the performance of the previous week among team/organization members? How efficient is the process of incorporating lessons learned in the past into future planning? How many tasks that are newly added to the WWP & are not previously planned in the lookahead phase have you executed?

DATA PROCESSING THROUGH FUZZY LOGIC

The two main players in this process are decision-makers and experts. The decision makers rank the importance of each sub-factor with respect to each main factor (LPS phase). The experts evaluate each sub-factor, i.e. assess its implementation in the project. The data processing methodology entails six main steps shown in Figure 1.

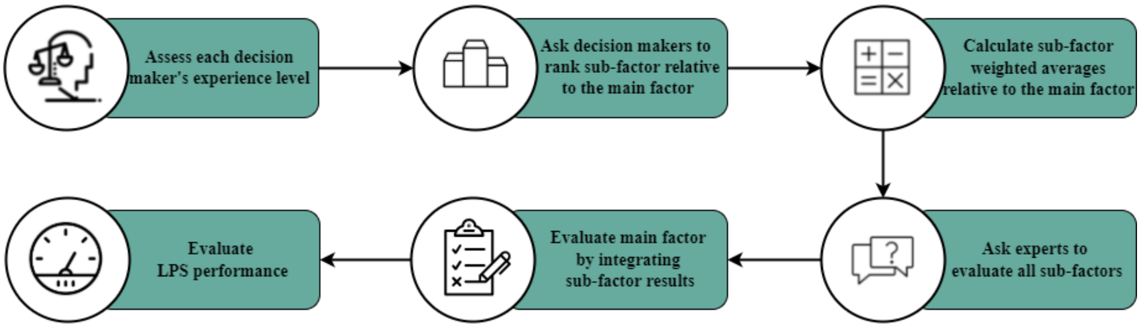

Figure 1 – Fuzzy Logic Data Processing Steps

As a first step, each decision-maker is assessed by linguistic terms (Unexperienced, Fair, or Experienced). Once the labels of the decision-makers ($\tilde{w}_i$) are identified, decision-makers provide their judgment on the importance (Least Important, Less Important, Average Importance, More Important, or Most Important) of each sub-factor ($\tilde{r}_{ij}$) relative to the main factor, where $\tilde{r}_{ij}$ is the fuzzy linguistic assessment of factor j by decision-maker *i*. Figure 2(a) presents the membership function of linguistic terms for decision-makers' experience level and Figure 2(b) depicts the membership functions for factors rating. In both fuzzy sets, the x-axis (experience level for the first set and importance level for the second set) is a rating from 0-1. The evaluation can also be done using predefined qualitative expressions instead of the 0 to 1 scale. To develop the membership function of decision-makers' experience level, the range of experience is standardized (by dividing it by 40) to fit into a rate between 0-1, and membership grades are identified using the modified horizontal method.

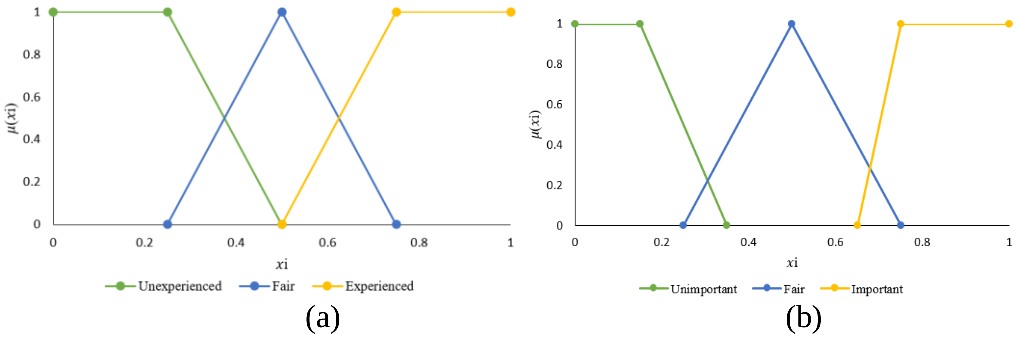

Figure 2 – Plots representing the membership function of (a) the linguistic terms for decision makers' experience level and (b) factors importance rating

When the linguistic assessment is completed, the weighted average for the importance of each factor is calculated (Dong and Wong 1987). A fuzzy number is calculated using fuzzy arithmetic that defines the overall evaluation for each factor of the assessment process. Equation 1 is used for the evaluation of the factors.

$$I_j = \frac{\sum_1^n \tilde{w}_i \times \tilde{r}_{ij}}{\sum_1^n \tilde{w}_i} \quad where\ j = 1,2,\ldots,m \qquad \text{Equation 1}$$

Once the weighted average of each factor is calculated based on the experience level of the decision-maker and the provided ratings for the factors, the fuzzy memberships are converted to crisp values by using the center of area defuzzification method (Patel and Mohan 2002). The center of area is calculated using Equation 2. This number shows the importance of each subfactor in the evaluation of its main factor.

$$CA = \frac{\sum_{i=1}^n \mu(x_i).x_i}{\sum_{i=1}^n \mu(x_i)} \qquad \text{Equation 2}$$

An FIS is then used to evaluate LPS performance. Last planners, referred to here as the experts, are asked to fill out the survey by evaluating all sub-factors as ratings from 1 to 10. As it is a rule-based approach, a set of rules must be defined for the model. The formula used for the number of fuzzy rules is the number of membership functions raised to the power of input variables. To simplify the process and to avoid having many rule definitions in the model, rule blocks are used. In this method, instead of using all the sub-factors to predict the performance, the sub-factors are only used to identify their effect on the main factor. For example, the Lookahead phase factor is evaluated by integrating all 5 questions related to this phase. For example, if there are 10 input variables with 3 different membership functions, the number of rules needed would be 3^{10}. However, if the 10 input variables are clustered into two rule blocks, the number of rules needed would be 3^5 for each rule block and 3^2 for aggregating the clusters. This method helps reduce the number of rules considerably. The rule blocking process is shown in Figure 3.

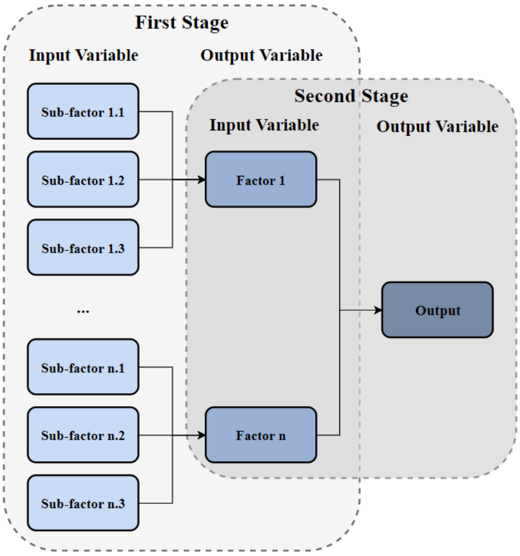

Figure 3 - The general structure of the proposed fuzzy expert system

Finally, the effect of the main factor will aid in evaluating the LPS performance. The input variables for this step have the fuzzy set of x_i and the output variable of y. The input variables are measured on a scale of 0 to 10, which is divided into 3 linguistic terms: Poor, Fair, and Good. Membership values are assigned to each linguistic term between 0 to 1 and are identified using modified horizontal method. The output variable is measured on a scale of 0 to 1, which is divided into 5 linguistic terms: Poor, Fairly Poor, Fair, Fairly Good, and Good. The output variable for this set represents the LPS performance. In Figure 4(a) and Figure 4(b), the membership functions of these variables are shown.

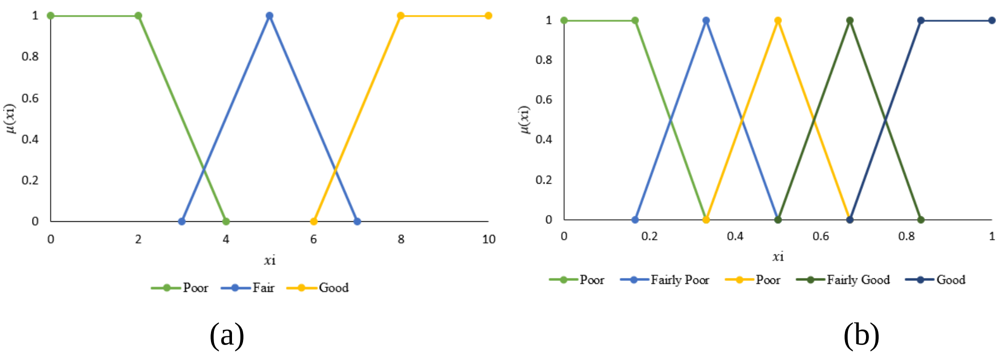

Figure 4 - The membership functions of (a) inputs and (b) outputs

In this study, to define the fuzzy rules, scores of 1, 2, and 3 are given to the term's evaluation Poor, Average, and Excellent. When a rule is defined, the weighted average of the scores is calculated and compared to the predefined value that relates to the conclusion.

TOOL IMPLEMENTATION & DISCUSSION

To ensure proper and sustainable LPS implementation within an organization, practitioners can follow the model represented in Figure 5. After using the developed tool and obtaining LPS performance result as an output, users who employ this model for the first time must analyse different possible alternatives to enhance their LPS implementation performance. Such alternatives may include training, workshops, seminars, change in supplier choice, and readjustment of the process. Afterwards, trade-off analysis is performed. Trade-off analysis entails assessing and evaluating the outcomes of the different scenarios including the analysed alternatives. Once the trade-off analysis is performed, improvements that have been decided on must be implemented. Afterwards, the tool is used again to obtain a new LPS performance result. The second round or iteration entails comparing the current performance with the past performance. If an improvement in performance is observed, the current LPS implementation protocol must be maintained with continuous improvement to ensure its sustainability. Users must then continue using the LPS diagnosis tool to monitor and control their implementation performance. However, suppose the comparison between current and previous performance did not improve. In that case, the team's LPS implementation protocol must be re-established by incorporating core LPS principles, including key cultural aspects such as sharing rewards and failures, learning from failures, taking preventive measures, etc. Once a proper LPS implementation protocol is put into place, the LPS diagnosis tool is again employed to evaluate the new protocol's efficiency.

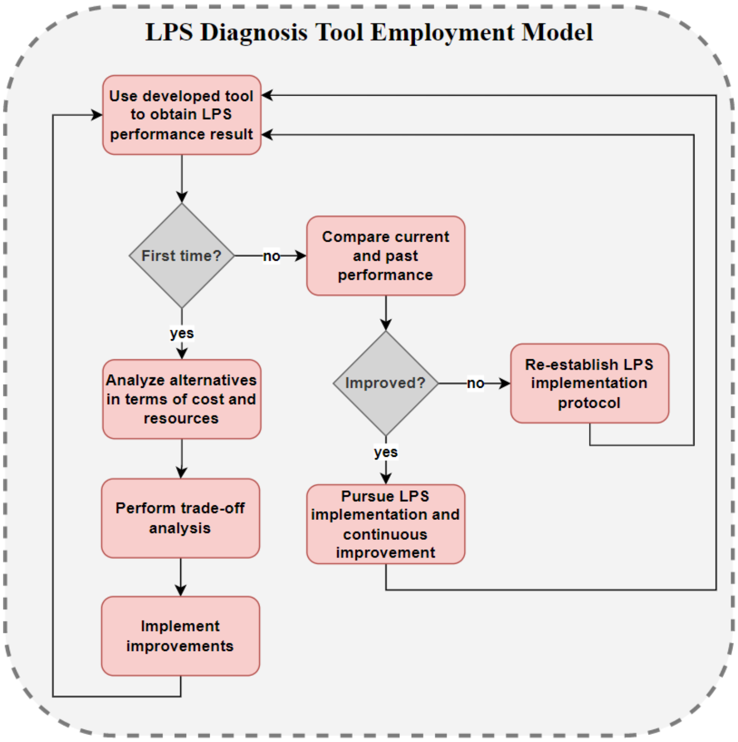

Figure 5 – LPS Diagnosis Tool Employment Model

EXPERT PANEL QUESTIONNAIRE CONDUCTION

The survey entails collecting LPS experts' ranking of the importance of the factors. The number of years of experience in LPS plays a vital role, where the higher the number of years, the more weight is given to expert's response. This part answered by three renowned academics and practitioners with sufficient experience in LPS. The number of years of experience in LPS was 12, 16, and 20 years. Two of the participants were academics with sufficient practical experience in LPS, while one participant was an experienced Lean facilitator and practitioner.

ANALYSIS

The important point about FIS is the need for calibrating the membership functions for each company and project. As the defined thresholds can be tighter or wider, in other words, what is deemed as a poor performance for a company may be a fair one for another company. Therefore, the evaluation that is done with the model should be used as a baseline for future reference and any comparison is a relative evaluation. In order to verify the developed tool, various scenarios with different values for each subfactor are randomly generated. Table 2(a) refers to the Phase/Pull Planning phase, Table 2(b) refers to the Lookahead Planning phase, Table 2(c) refers to the Weekly Work Planning phase, while Table 2(d) refers to the Post-WWP phase. The last column in each table shows the overall evaluation for the relevant phase. Only critical scenarios – highlighted in red - and other random ones were selected for comparison. As shown in Table 2(a), RPP5 is given a high score of 98 in the highlighted row. However, this value doesn’t yield a good overall phase result, where RPP score is 50. This score is considered fair according to the developed model. The reason behind this result is the LPS experts' subfactor rankings, where RPP5 is given the lowest weighted fuzzy average among this phase's subfactors. It can also be noted that RPP3 with a score of 4, has the highest weighted fuzzy average, which influences the overall phase result for the mentioned scenario. Table 2(b) shows that the same phase performance score, a score of 50 for LP for instance, can be reached through different combinations of factor performance. This implies that even if efforts are exerted to enhance one aspect of a phase, if other factors are not considered, the outcomes might not be rewarding. Furthermore, each factor has different importance relative to the phase it belongs to. Therefore, careful decisions must be made when seeking performance improvements. As for Table 2(c) representing the Weekly Work Plan phase, the highlighted scenario yields highest WWP score (76), despite a low WWP6 score (35). This result may be attributed to low WWP6 LPS expert ranking, which decreases WWP6's influence on the overall phase result. An opposite case observed is the highlighted scenario in Table 2(d), which yields lowest overall PWWP result (20.5), even though PWWP4 is given a relatively high score of 79 and the lowest LPS expert ranking among other subfactors.

Among all randomly generated scenarios, the worst, best, and average cases are represented in Table 3. The numeric LPS result is calculated by de-fuzzifying the results obtained from integrating the results from the developed models for each phase. These numeric results are then translated into linguistic terms according to the specified membership functions in the developed FIS. The expert panel members performed face validation to confirm the reliability and efficiency of the developed model. Further validation may be performed by practitioners implementing the LPS on construction projects as part of a case study.

Table 2 – Scenario Results for (a) Phase/Pull Planning, (b) Lookahead Planning, (c) Weekly Work Planning, and (d) Post-WWP

RPP1	RPP2	RPP3	RPP4	RPP5	RPP
1	1	1	1	10	16.5
3	3	2	3	64	24.5
6	9	4	9	98	50
5	8	7	9	35	76.5
9	9	9	9	90	83.5

(a)

LP1	LP2	LP3	LP4	LP5	LP
1	1	1	10	1	16.5
8	5	2	15	7	50
7	9	6	47	3	50
1	5	6	22	9	50
8	5	3	38	9	50
9	9	9	90	9	83.5

(b)

WWP1	WWP2	WWP3	WWP4	WWP5	WWP6	WWP
3	5	1	2	6	68	22.5
3	7	1	3	6	97	24
3	9	8	8	4	88	50
7	9	1	6	4	35	76

(c)

PWWP1	PWWP2	PWWP3	PWWP4	PWWWP
5	1	1	14	16.5
1	3	1	79	20.5
4	5	4	68	50
9	8	1	99	83.5

(d)

Table 3 – Final LPS Performance Results for 3 Scenarios

RPP	LP	WWP	PWWP	Numeric LPS Result	Linguistic LPS Result
16.5	24	22.5	20.5	11	Poor
76.5	50	50	20.5	50	Fair
83.5	83.5	76	83.5	66.5	Fairly Good

CASE STUDY

In order to validate the developed tool, a case study is conducted through a contracting company, where LPS was being implemented on a project. As the case is in the first stages of the implementation it can be considered as an illustrative example to present the application of the proposed tool; in later stages of the implementation, the results can be used to validate the model. LPS implementation included technical, practical, and cultural aspects. Technical facilitation included employing a software application providing a cloud-based solution supporting Lean production planning. It may be downloaded on computers, phones, or tablets, allowing for easy-to-access and real-time updates directly from the site. The company adopted the software's usage, and software developers adjusted some of the software's features to accommodate the company's needs. Cultural implementation of LPS called for adequate introduction of key project participants to LPS. Such introduction included carrying out training sessions led by LPS experts, inviting participants to attend a short online conference on LPS, and promoting some LPS concepts such as continuous improvement, learning from failures, performing root cause analysis, and planning proactively. Finally, practical implementation entailed applying LPS principles and practices, including the four major phases of LPS, reliable planning, appropriate identification and removal of constraints, and proper documentation of reasons for non-completion/noncompliance. Two out of the phases included in the developed survey were validated through project participants in this company, as the project is still in its early stages. The two phases were the Lookahead Planning phase and Phase/Pull Planning phase. The remaining two phases will be validated by conducting the second part of the survey in the upcoming weeks as part of a future research study for an all-inclusive tool validation.

CONCLUSION

Proper implementation of Lean concepts is crucial for successful implementation of LPS in construction projects. Although various studies have already tackled the issue of healthy implementation of Lean construction, no study has been found to present a generic LPS diagnosis model. Therefore, this study presents a novel artefact for standardizing LPS diagnosis process across the industry. Aiming at achieving this objective without holding the potential of excessive subjectivity, the study employs FIS to analyze experts' and practitioners' opinions on the state of various factors influencing each phase in LPS. First, a list of factors influencing LPS phases is developed based on extensive literature. Then, an expert panel questionnaire is conducted to evaluate the importance of each factor relative to the phase it belongs to. Afterwards, an FIS model is developed and randomly populated as part of the model verification process to simulate LPS performance based on different potential scenarios of factors' performances. A brief discussion of obtained results is finally presented. The developed tool can be used to evaluate the LPS implementation in the project and find the best areas to focus on, regarding the constraints of the project. Therefore, the decisions made by using this tool are project and company-specific and should be compared to the baseline conditions of their LPS performance. This study lays the cornerstone for further research, where more accurate calibrations of the outcomes' membership functions may be studied. This may help in enhancing the performance of the developed tool in diagnosing the LPS implementations. Further research can also include giving different weights to the four phases of LPS, based on criticality of each phase. For example, Post-WWP phase may be given the highest weight due to the included concepts such as learning from failures and continuous improvement, which can influence the overall LPS implementation outcome. Finally, recommendations for improving implementation performance may be suggested.

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ASSESSING QUALITY PERFORMANCE OUTCOMES AND THE RELATIONSHIP WITH STAFFING: A GENERAL CONTRACTOR CASE STUDY

Elizabeth Gordon[1], Keila Rawlinson[2], Neha Dabhade[3] and Dean Reed[4]

ABSTRACT

This paper describes a methodology for understanding how staffing projects may be assessed and considers how it may relate to project team performance when project teams implement a Systems Approach to Quality (SAQ). This paper expands on the 2021 paper "The Impact of Implementing a System Approach to Quality: A General Contractor Case Study" where the authors compared project performance outcomes and team cultural assessments for 11 projects that had implemented SAQ, the Intervention group, to a similar set of projects that had continued with a specification compliance -based approach to quality, the Control group. This study reflects organizational learning in a continuous improvement process and helps clarify distinguishing features of staffing for this General Contractor. The authors findings suggest that applying SAQ can help sustain a project team through the phases of ever-changing project life cycles and contribute to more reliable outcomes when staff is engaged earlier in the project and supported with Virtual Design and Construction (VDC) and outside project management resources.

KEYWORDS

Organizational change, quality, data, staffing, impact

INTRODUCTION

This is the fourth paper in a study series to document and study one US based General Contractor's (GC) quality approach focused on achieving "zero errors, zero defects, zero rework and zero surprises" (Spencley et al. 2018). This GC's quality approach required the organization and project teams to shift from assuming stakeholder expectations and only tracking lagging indicator issues to focusing on setting up systems and routines that prompt collaboration to define measurable acceptance criteria with tracking, to act on these leading indicators (Spencley et al. 2018, Gordon et al 2021a).

Projects consist of complex networks that can be influenced by many different factors (Bertelsen 2003a; Bertelsen 2003b; Bertelsen et. al 2005). This Systems Approach to

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Quality (SAQ) also accepts that construction projects are complex and dynamic (Gordon et. al 2021a). 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 SAQ, the Intervention group, to a similar set of projects that had continued with a compliance specification-based approach to quality, the Control group. The projects that had implemented this GC's SAQ had significantly better outcomes for cost growth, fee gain, schedule growth at mobilization, change percent duration, value of percent changes and the value of claims as percentage of contract cost (Gordon et al. 2021a). In this new paper the authors wanted to understand if project staffing and resourcing had any distinguishing differences between the two groups.

Staffing of projects is important to this GC because project records indicate that project teams have historically identified staffing as a top three reason for project fee loss. More recently, staffing has been named as the second leading cause of fee loss for open projects. Understanding how staffing influences project performance outcomes is important work for this industry. However, a review of the IGLC database showed that actual staffing data and correlations to project performance has not been explored. This study is foundational work for other staffing and resourcing studies. Furthermore, this work has created new organizational tools that the GC can use to understand and influence project workflows.

To align on terminology, the authors consider staffing to be the labor hours associated with personnel assigned to the project to administer construction management and planning activities, commonly considered general conditions. In contrast, resourcing is related to the corporate workgroup support. This GC has a strategy enabling project delivery through corporate workgroups gathering and sharing knowledge with projects. The workgroups develop methods that the project teams apply by developing their own routines and processes. Resourcing is also used to describe engagement of the organization's subsidiary companies to support project management and deliverables.

In this practice-oriented paper, the authors first discuss the complexity of construction projects and staffing to describe the foundation for the methodology. In this complex environment, the authors explore and analyze the questions:

- Did the projects that implemented a Systems Approach to Quality have different staffing profiles compared to Control projects?
- Did projects in each group have the same staffing hours and staffing roles at the same times in the project lifecycle?
- Were there discernable differences in staff experience between the groups?

Then, through the rest of the paper, the authors describe their methodology to investigate answers to these questions, qualify the limitations of the data, review the findings from their analysis, discuss the findings, and finally present a conclusion for future workflow and further research.

CONSTRUCTION PROJECTS

A COMPLEX & DYNAMIC PROCESS

Many of Bertelsen's IGLC papers have demonstrated how the construction process is not a linear, ordered process, but rather "exists on the edge of chaos" and should be viewed through a complex system perspective (Bertelsen 2003a). In his work, Bertelsen reviewed the construction production system and the industry of construction against 14 characteristics of a complex system described in The Philosophy of Complexity by Lucas (Bertelsen 2003b; Lucas 2000). After comparing and discussing the construction process through this lens, Bertelsen concluded that construction projects should be seen as a "complex dynamic phenomenon" and management systems should reflect this understanding (Bertelsen 2003b). Projects can experience many different and ever-changing challenges. Since the construction industry's interwoven network is not completely transparent, one project's logistical issues, supply chain issues, and skilled labor shortages can be affected by other local on-going work and/or issues in other parts of the world. Also, each project's team is unique and forms a temporary organization which brings its own set of team characteristics and demands. Additionally, stakeholder indecision and changes can cause delays. And there is of course unexpected weather and natural phenomena that forces the project to adjust its course (Bertelsen 2003a; Bertelsen 2003b; Bertelsen et. al 2005).

STAFFING A COMPLEX AND DYNAMIC PROCESS

Recognizing that construction projects are complex and dynamic, a GC project's staff form a major cost center that determines project overheads and can influence project outcomes. "Appropriate allocation of supervisory staff for a project could ensure the successful administration of the management functions, such as planning, organizing, leading, and controlling throughout the construction stage, and thus could reduce unnecessary waste for resources and assure high productivity" (Leung et. al 2008).

An IGLC paper search with the keyword "resource" located 216 papers and "staff" found 28 papers. Many of the papers explored topics of knowledge management, profiles of lean staff, case studies of lean principles, and VDC and production planning concepts. A keyword search of "staffing" found 2 papers. One paper was a case study that analyzed actual project staffing records for different standardized prefabricated housing units in Hong Kong (Leung et. al 2008). This case also studies actual project staffing records collected by a GC and attempted to correlate staffing strategies to the scale of the project. However, a search of the IGLC database for project staffing and project performance did not produce any results.

A SYSTEMS APPROACH TO QUALITY

This GC's quality approach reflects Bertelsen's views and the understanding that construction projects and construction organizations are complex and dynamic. SAQ foundationally promotes the integration of identification of Distinguishing Features of Work and risk across all workflows, such as safety, quality, project, cost, and logistics, with all stakeholders to understand and align on acceptance criteria through each phase of work for the highest likelihood of achieving reliable outcomes. (Spencley et. al 2018; Gordon et. al 2021a). These principles can be applied to project workflows, as well as, how leaders approach and manage the work through their Business Unit or Region.

The authors have worked to understand how project teams and the organization has implemented SAQ over the past six years (Gordon et. al 2021b). During this time three of the authors were part of corporate workgroups that developed methods for projects and supported project implementation of SAQ. To learn from staffing and resourcing of these complex and dynamic projects, the authors applied the methodology below.

METHODOLOGY

DIVING INTO THE PROBLEM STATEMENT & MAPPING A PATH FORWARD

To understand the implications of SAQ on staffing and resourcing, the authors applied 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). The author's process included six steps. The first step involved framing and reframing the problem through use of a tool called "web of abstraction". The web of abstraction tool enables understanding problem statements found in many different, yet interlinked, problems and enabled the authors to explore multiple perspectives around understanding staffing and resourcing.

The authors then interviewed Subject Matter Experts (SMEs) within the company to gather knowledge and to understand: How are complex and dynamic projects currently staffed? How might we evaluate and plan for the cost of staffing? How might we understand how well people are integrating and implementing the systems? The SME included a regional operations leader, mechanical preconstruction leader, and business process analyst. The key beliefs that emerged from these interviews: 1) all project staff have an assigned role 2) the company tracks years in the construction industry and years at the organization 3) projects can be supported by external project management and technical resources 4) it is important to consider the contract value and duration of the project to help understand the context of staffing 5) a key characteristic of successful projects includes the project's ability to sign the contract in a timely manner 6) VDC represents a fully integrated Systems Approach to Quality.

After interviewing the SME, the third step involved imagining and designing ways to explore the questions. The fourth step involved locating data sources and mapping information to investigate the questions. Next, the authors prototyped the proposed data mapping through visualization tools. Finally, the data was analyzed.

PHASE 1: STAFFING & RESOURCING HOURS INVESTIGATION

To understand staffing and resourcing differences between the two groups of projects, the authors first compared the cost codes that staff documented in their weekly billing submissions and recorded in the enterprise labor tracking system. The resources used for staffing projects were either administrative hours or craft hours. Administrative hours describe the roles of management positions that typically work in the office to purchase, manage, and coordinate the project through responsive communication tools. Craft hours describe the roles of skilled and unskilled production execution positions that put construction work in place.

Next the administrative office hours were categorized by standard work roles: Project Accountant, Project Executive, Project Manager, and Project Engineer. And the administrative field hours were categorized by standard work roles: Superintendent, Assistant Superintendent, and Foreman. Lastly, the administrative roles were identified by organizational discipline workgroups: RISQ – Risk, Insurance, Safety and Quality resources; PSPP – Production, Scheduling, and Production Planning resources; VDC – Virtual Design & Construction resources; MEP – Mechanical, Electrical, and Plumbing resources, and SPW – administrative and craft resources dedicated to Self-Performed Work (SPW) functions and outputs. For each SAQ project, this breakdown of GC hours was reviewed and compared to its counterpart in the Control project group.

To assess this information for projects, the authors used the organization's integrated operations data application. The application was designed by the second author on a data visualization platform for operational leaders in the organization. The application assembles data from the many different software tools project teams use and relates the information by project lifecycle, core market, geography, customer, and other project attributes. It provides views of project information across measures of safety, quality, cost and schedule, objective indicators of project performance. The tool also provides relatable information from project timecard entries summarized by date and cost code.

To compare the differences between the Intervention and the Control group of projects, the hours were compared between two standard project milestones, actual mobilization, and actual substantial completion project dates. The actual mobilization date is the date the project team "mobilizes on-site," and actual substantial completion date is the date "when the Work or designated portion thereof is sufficiently complete in accordance with the contract documents so that the owner can occupy or utilize the work for its intended use" (DPR 2018). These standard milestones are routinely collected from project teams through a monthly status reporting process.

New coding was built into the operations data application that allowed filtering of GC staff time by 1) administrative or craft and then by 2) roles and workgroup categorization. The data was then exported to a spreadsheet application where it was further analyzed.

To compare project hours, all project timelines were divided into four quarters: 1) actual mobilization date – 25% of the project timeline; 2) 25% – 50% of the project timeline; 3) 50% – 75% of project timeline; and 4) 75% – actual substantial completion date. For each project, the dates associated with each project milestone were computed. The project's staff hours were allocated to the appropriate quarters. Then, the percentage of staff hours spent for each quarter out of the total staff hours was calculated. This information was also broken out for each workgroup to understand the subject matter expert (SME) resourcing. This enabled the authors to view the data as 1) count of hours 2) as a percentage of total hours for the project for GC administrative & sub-tier filtering. This data, for each group, was also represented in box and whisker charts. These findings are compiled in Figure 2.

PHASE 2: ADDITIONAL STAFFING CHARACTERISTICS INVESTIGATION

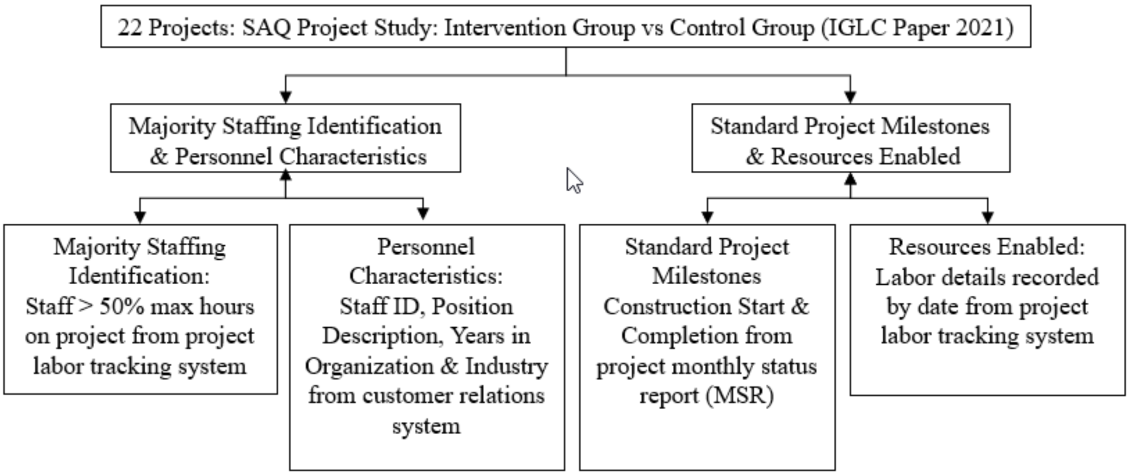
To understand more characteristics about the GC's staff, the authors tallied the numbers of each role on the projects. To study the experience of the staff, the authors compiled time in industry and time at this GC in years. The authors wanted to look at the experience of those that had a reasonable level of influence on project systems and routine behavior, "Majority Staffing." Therefore, the authors looked at the individual who recorded the most hours spent on the project, and the experience of the staff that had spent at least half that amount. Staff data was analyzed from the standard project pursuit workflow system where staff experience is represented by both years of recent experience at the GC and in the industry. Through the integrated operations data tool, the authors understood staff roles and assignments for each project. Then, the category, role, and experience level for each staff was compiled for review. The findings of this investigation are summarized in Table 1.

The SME interviews had highlighted three additional data points to investigate: 1) the date the Guaranteed Maximum Price (GMP) was signed 2) the project's use of VDC and 3) outsourcing of project management resources. This GC has a subsidiary company in India that focuses on providing "services and solutions to the Construction industry in the area of Virtual Design and Construction (VDC), Project Controls management, Accounting and Software Development" (vConstruct 2021). The findings of this investigation are summarized in Table 1.

LOCATING AND MAPPING DATA SOURCES TO INVESTIGATE QUESTIONS

Analyzing the data consisted of understanding project workflow and understanding potential workgroup resourcing, project key roles and understanding standardized project milestones tracked across all projects organizationally and understanding of the organizational data workflows. Figure 1 shows the information mapped by this data study.

Figure 1: Variables mapped to data sources.



LIMITATIONS OF THIS DATA

The projects in the SAQ Intervention group all demonstrated, through discussions and sharing at a company-wide meeting called the "Monday Quality Calls", how they implemented the principles of a SAQ and their results (Gordon et al.2021b). Each SAQ project was matched with a project of similar contract size, in the same core market, completed or within 90% of completion in the last five years and when possible, in the same geographic region (Gordon et. al 2021a) The limitations of these data sets are: 1) it is a small sampling of projects, and a case study; 2) the projects are classified as having implemented or not implemented SAQ; 3) the data on staffing comes directly from the GC's platforms and the reporting from project teams. The project teams can categorize staffing based on what the customers expect staffing categories to be versus actual project needs and the individual's actual role designation in the company; 4) Not all data for each characteristic was available; 5) The data collected for administrative staffing hours is based on a forty-hour work week and is not reflective of total hour effort. The GC's administrative staff often spends more than forty hours per week working on the project; 7) contractual distinctions between projects was not studied; 6) the staffing experience data does not recognize a specialized experience or expertise of individual staff members.

DATA FINDINGS

PROJECT PERFORMANCE METRICS & STAFFING HOURS

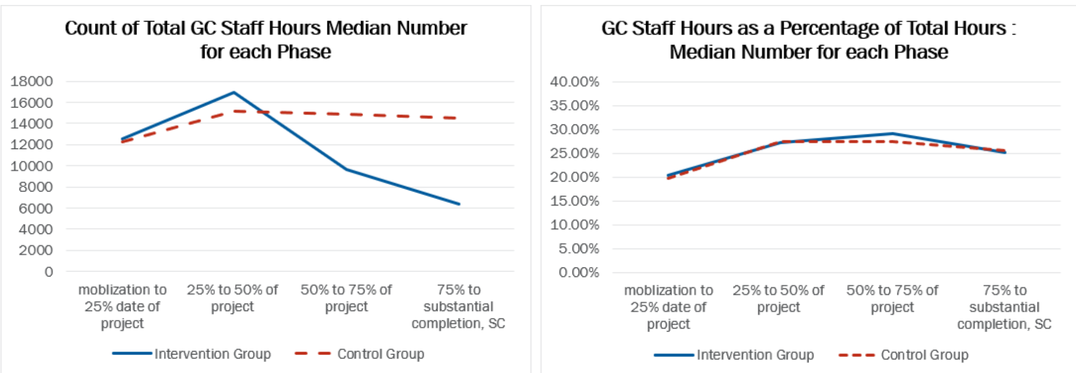
Through previous research, the intervention and Control group performance metrics and cultures were assessed. The IGLC paper "The Impact of Implementing a System Approach to Quality: A General Contractor Case Study" reported the following:

- 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 Intervention group was 11% and 18% for the Control growth.
- Change Management: The median value of contract changes was 5% for 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 value of claims as a percentage of contract cost for Intervention group was 0.14% and 0.87% for Control group.
- Project cultures: Using Quinn's Competing Values Framework (CVF), the Intervention group reported more collaborative cultures (Gordon et. al 2021a).

For this study, the authors also analyzed the date the contract and Guaranteed Maximum Price (GMP) was agreed to and signed by all parties. Signing the GMP is a key Point of Release (PoR), when work is released to the next phase of the project to be built upon. Signing the GMP demonstrates alignment of contractual terms and conditions, a fundamental execution of SAQ principles. For GMP signed date as % of project duration, the Intervention group median value was signed at 0.9% of project duration, close to the project mobilization date. The Control group's median value was 19% of project duration, nearly 80% through the first quarter of the project.

Figure 2 summarizes the data observed from the time entries for project staffing and resourcing for the Intervention and Control groups. The x-axis represents the four quarters of the project. The first graph plots, for each of the project quarters, the median value of total staff hours for each group. The second graph plots the median value of staff hours for each quarter of the project as a percentage of the total hours.

Figure 2: Project Staff Hours Over Time Graphs.



For the two project groups, three views of the count of total staff hours were compared: 1) comparing counts of total hours by quarter 2) plotting the median values for each quarter shown in Figure 2, left graph and 3) through bar and whisker charts for quarter. Although the Intervention group had better outcomes for cost, schedule, change management, quality (Gordon et. al 2021a) and alignment on contractual terms, the Intervention group reported 10% more total staff hours. In reviewing the count of hours by quarters, the first and second quarter the Intervention group had 13% and 18% more hours. In the third and fourth quarters, the Intervention group reported 4% more hours. The plot of medians in the left graph shows greater differences between the group's median values in the third and fourth quarters demonstrating this wider range of variability in count of hours for the Intervention group. The bar and whisker charts also show that the Intervention group had wider variability of total staff hours for all project quarters, while the ranges for the Control group were much tighter.

The right graph shows that the median values for the percentage of total hours spent during each quarter is similar for both groups. However, graphical analysis shows the Intervention group experienced more variability for staff hours as a percentage of the total hours in the second and fourth quarters of the project, suggesting staff and resources were allocated as required to adjust to project needs. In the left graph, the Intervention group spent a higher median of hours in the second quarter only and achieved lower median resource demands in the third and fourth quarters, also suggesting that their implementation of SAQ, and more time spent in the second quarters, enabled greater alignment on product deliverables.

These observations demonstrate that there was more variation in staffing in the SAQ, Intervention projects. The authors believe this is due to the complex nature of the projects and in recognizing the risks, these projects were allocated needed resources. Since the median value of the GMP for the Intervention group was signed within 1% of actual mobilization, and the median value of GMP signing was 19% of project duration for the Control group, this demonstrates that the SAQ GC teams were able to get alignment on conditions of engagement sooner, resulting in fewer distractions for the project teams. The Intervention group also reported more collaborative cultures (Gordon et. al 2021a).

ADDITIONAL STAFF AND PROJECT CHARACTERISTICS

Table 1 shows the additional staff characteristics and resourcing for each project that were explored. The table shows the median number for each group for each characteristic.

Table 1: Additional Characteristics Compared between Project Groups.

Staffing Characteristic	Metric	Median	
		Intervention group	Control group
Staff hours per week	Total staff hours / Duration in weeks	509	495
Staff hours per $M contract	Total staff hours / Contract Value	441	573
Count of Staff	Office (Project Executive, Manager, Engineer, Accountant)	8	9
	Field (Superintendent, Foreman)	10	16
Experience of Staff	Office staff years in Industry	14	18
	Office staff years at DPR	8	9
	Field staff years in Industry	22	20
	Field years at DPR	6	7
VDC Hours	VDC hours as % of total staff hours	2.0%	0.5%
SPW Hours	SPW hours as % of total staff & SPW hours	15%	14%
Project Management Outsourced contracts	contracts as a percentage of total contract value	0.08%	0.0%
	Total cost of outsourced contracts in dollars	$61,539	$0

When comparing average staff hours per week, both groups had similar median values. In comparison, for average staff hours per contract costs, the Control group had a higher median value and more variability in range, likely due to the increased project durations.

While the Intervention group and Control group had a 10% difference in total staff hours, and similar average staff hours per week, the Control group had 28% more total staff count. The median value for the count of field staff was 63% higher for the Control group, suggesting the field had more staff turnover. The authors believe the higher amount of change and change management the Control projects experienced during construction led to more staff turnover.

Overall, there was a negligible difference in the median values of experience of staff measured as years in the industry and years at the GC organization. This suggests that staffing experience was not an influential factor for this study.

The authors also noted two significant differences in resourcing 1) the use of VDC and 2) the use of external project management services. The SAQ projects, Intervention group, had a larger total and range of VDC usage. These projects had developed processes and routines for collaborating with project stakeholders with visualization. Thus, demonstrating one form of systemizing of measurable collaboration. Team members from the GC surveyed through Quinn's CVF in previous research also rated their projects as more collaborative, suggesting that the use of VDC was an important factor that contributed to this culture. In review of the data, the authors found that for projects under $150M there was very little time coded to VDC. On a deeper dive into the time entry data, the authors found that VDC time entry for an Intervention project under $150M was coded to project engineer's time. Also, both groups of projects had similar use of SPW to suggest SPW was not a factor in project outcomes for these data sets.

While the contract values of the projects were similar, and the Intervention group's total count of staff hours was 10% more, the Intervention group also contracted with more external project management support resources. This is interesting as the Control group projects were experiencing more changes (Gordon et. al 2021a). The Intervention group, aligned on contractual terms sooner, experienced less change management and contracted with more external project management support resources. This shows that there was aligned and agreed upon project management workflows with all stakeholders that allowed for work to be outsourced to free up the project team's time to focus on other aspects of construction.

CONCLUSION

NEW INSIGHTS

From this study of 22 projects representing nearly $4B of contract revenue, the authors observed that the projects that applied SAQ achieved GMP sooner, experienced less change in contract value, higher fees, were closer to forecasted schedule milestones, had less claims, fewer staff turnover and experienced more collaborative cultures. This suggests the timeframe in which projects achieve acceptance of GMP is a leading indicator of project outcomes and can be tracked to aid the organization's strategy of staffing and resourcing projects. This study also suggests the timeframe of achieving GMP acceptance is also a leading indicator of project culture experienced by the GC.

Furthermore, the authors observed the Intervention group had a higher count of hours during the first and second quarters and had less percentage of their total hours in the fourth quarter. This suggests Intervention projects spent more time adjusting and responding to challenges earlier in the project.

The other key staffing and resourcing differences between the groups included: 1) systemization of measurable collaboration, evidenced by the increased use of VDC in the Intervention group. VDC is a vital quality tool as it provides visualization of project needs and requirements to assist communication and alignment amongst stakeholders; 2) the higher use of project management outsourcing which also demonstrates systemized and standardized project workflows. This suggests, developing standard workflows for VDC and project management for outsourcing, are two key characteristics that support success of complex and dynamic projects for this GC.

Still, the authors' takeaways are that there is not a simple staffing formula that guarantees reliable performance metric outcomes, and an expanded study is needed. The authors acknowledge that a GC data model designed to provide key data across various related platforms used by different workgroups, using normalized and standardized perspectives, is instrumental in doing staffing studies at organizational scale with reduced effort. The authors recommend an integrated data model that represents project lifecycle workflows based on work being released from phase of the project lifecycle to the next, will better utilize real-time data for analysis and evaluation. Integrated enterprise dataflow tools improved processing speed, reflection and learning whenever it was available. Visualization of GC data can create baselines to compare actual workflows.

With this experience, the authors recommend that an integrated operations data portal include all major systems. Finding common connections across these enterprise systems helps to clarify expectations amongst project team members, especially during transfers of information and deliverables. Integrating data conversations may also help different workgroups at the corporate level of the organization discuss the data they are collecting. These views may help them to consider how their data might benefit other workgroups, to further support project teams.

FURTHER RESEARCH

For further research, the authors suggest analysis of the outsourced project management processes relative to the project lifecycle to understand the differences in the project processes and daily routines that enabled measurable collaboration. The authors also suggest using a similar lens to review trade partner commitment trends and project cash flow to illustrate distinctions between the two project groups and the measurable collaboration associated with work authorizations, and billing and payment practices.

Furthermore, the authors would also like to explore how to utilize AI and machine learning to perform real time assessments on forecasted and actual staffing compared to organizational benchmarks observed in other similar projects considering the unique sets – by customer, by type of building, by contract value, and by location – to name a few. This would aid more informed decisions around present and future staffing using objective criteria and past performance benchmarks.

Widening the study within the organization and performing multivariable statistic techniques to gain further insights, the authors suggest added benefit from collaboration with other GC organizations applying the principles of SAQ to explore other staffing and resourcing characteristics related to core market, type of building, and decision-making maturity of customer, project team measurable collaboration skills, SAQ implementation experience, previous experience of the team working together and the social network that supported the SAQ implementation.

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COLLABORATIVE PROJECT DELIVERY WITH EARLY CONTRACTOR INVOLVEMENT AND TARGET COST

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ABSTRACT

Lean and collaborative project delivery aim to increase productivity and create value in construction projects. Early contractor involvement and target costing are key elements in collaborative delivery. This study explores how early contractor involvement and target cost has been implemented, and the effects of these elements, in the collaborative delivery of a building in Norway. After two months of daily observations and a literature study, further data was collected from the main stakeholders through a document study and sixteen semi-structured interviews. Establishing a reasonable scope, allowable cost and procurement strategy in the front-end was identified as important. Early contractor involvement was determined to have improved constructability, commitment, cost estimation, and team building during the design phase. A balanced, equitable and clear risk distribution in the target cost, and continuous involvement of the client and senior management, was identified as important for collaboration in the execution phase. External factors beyond the control of the project group were found to have been impactful throughout the project. The study calls for more research on the impact of external factors, and the involvement of architects, consultants and subcontractors, in Lean and collaborative project delivery.

KEYWORDS

Target cost, Open book, Collaboration, Commitment, Early contractor involvement

INTRODUCTION

The Architecture, Engineering and Construction (AEC) Industry has room for improvement when it comes to optimizing value in projects. The Lean Project Delivery System (LPD) is a Project Delivery Method (PDM) developed for this purpose. Key characteristics of LPD include early involvement, relational contracting, and shared risk (Alarcón et al. 2013; Ballard 2008). Ways of doing relational contracting include partnering, alliancing and Integrated Project Delivery (IPD), and these may in turn be referred to as Collaborative Project Delivery Methods (CDMs) (Engebø et al. 2020;

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Lahdenperä 2012). Interest in Lean and collaborative delivery is growing in Norway (Lohne et al. 2021).

Early Contractor Involvement (ECI) and target costing have been identified by practitioners in the Norwegian AEC Industry as the highest priority elements in collaborative delivery (Hosseini et al. 2016). Previous research has called for more case studies on the implementation and effects of Lean and collaborative elements (Engebø et al. 2020; Tillmann et al. 2017). The purpose of this study is to examine how to optimize early contractor involvement and target cost in collaborative project delivery. By way of a literature review and a case study on a collaborative construction project, this paper seeks to fulfill this purpose through answering the following research questions:

1. How has early contractor involvement and target cost been implemented in collaborative project delivery?
2. What are the effects of early contractor involvement and target cost in collaborative projected delivery?

In this study, a CDM is characterized by its emphasis on improving stakeholder collaboration through increasing stakeholder integration, with cost and stakeholder collaboration being the CDM effects to be measured. The research questions are studied from the perspective of the key players from the client, the architect, the consultants and the design and build contractor. The project was not finished when the data was collected, but the key players had an understanding of how the final results in terms of cost and created value would become.

THEORETICAL BACKGROUND

LEAN PROJECT DELIVERY SYSTEM

According to Alarcón et al. (2013), the Lean Project Delivery System (LPD) can be distinguished from traditional PDMs by a collaborative organization, a flow centred operating system, and relational commercial terms. Key characteristics of LPD include early involvement, integrated teams, value-based procurement, relational contracts, and shared risks and obligations.

Main LPD methods include the Last Planner System (LPS), Target Value Delivery (TVD), and set-based design. An essential aim of LPD is to improve collaboration between project participants through increased integration, and thereby optimize value creation (Ballard 2008).

COLLABORATIVE PROJECT DELIVERY

The term Collaborative Project Delivery Method (CDM) embraces a number of relationship-based PDMs, including partnering, alliancing and Integrated Project Delivery (IPD), with the latter having its roots in Lean Construction (Engebø et al. 2020). Key characteristics of CDMs include early involvement, transparency, shared risks and joint decision-making (Lahdenperä 2012).

Among academics and practitioners alike, a wide array of terms and definitions are used for CDMs (Engebø et al. 2020). Tillmann et al. (2012) found that IPD contributes to collaboration and value generation, while also being demanding to management. Hosseini et al. (2018) identifies the lack of a universal definition of partnering as an obstacle to optimizing its implementation.

To gain a clearer understanding of CDMs, several studies on CDM elements and their effects have been carried out. Hosseini et al. (2016), identified early contractor involvement and target cost as the two highest priority partnering elements. Studies on Lean have examined how collaborative elements such as Virtual Design and Construction (VDC), Integrated Concurrent Engineering (ICE) and Building Information Modelling (BIM) can be integrated with LPD (Fosse et al. 2017).

Competence, trust, top management support and continuity of personnel has been identified as key success factors in Norwegian construction partnering (Engebø et al. 2019; Falch et al. 2020; Haugseth et al. 2014; Simonsen et al. 2019).

EARLY CONTRACTOR INVOLVEMENT

Approaches to Early Contractor Involvement (ECI) and their relation to Lean have been studied by Wondimu et al. (2016b). Sødal et al. (2014) identified improved constructability, cost estimation and risk management as key advantages with ECI. They identified potential disagreements between contractors and consultants during the design phase as a major disadvantage. Involving the contractor at the right time with strong contractual incentives for collaboration and trust were identified as key success factors.

Wondimu et al. (2016a) identified sufficiently early involvement as the main success factor with ECI, while noting that too early involvement may give the contractor too much influence at the expense of the client. Manageable risk transfer was also determined to be important, as it makes projects more attractive for contractors and facilitates cooperation. Reducing uncertainty before involving the contractor, and having a balanced compensation format, were suggested methods to achieve manageable risk transfer.

TARGET COSTING

In Lean Construction, the application of target costing is referred to as Target Value Delivery (TVD). In the TVD process described by Pennanen and Ballard (2008), an allowable cost is set by the client in the front-end of the project, and the project is subsequently steered towards it. Once the estimated cost is lower than the allowable cost, a target cost lower than the expected cost is set. The target cost serves as a constraint towards which the design and construction can be steered.

Lahdenperä (2016) established a two-stage target cost contractual framework (2STC) with the intention of improving collaboration and avoiding cost overruns. He argued that a 2STC should be adaptable to change, and incentivize the service providers to be cost effective.

Numerous case studies have found that TVD results in lower project costs without compromising either schedule or quality (Do et al. 2014; Zimina et al. 2012) However, Ballard et al. (2015) found that about 15% of TVD projects fail to reach cost targets. The study identified shared commitments as crucial for TVD success, and suggested early involvement and the contractual right to remove people as ways to achieve this. Tillmann et al. (2017) identified early involvement and shared risk and reward between key parties as crucial factors for successful implementation of TVD and IPD. The maturity of TVD implementation in Norwegian public building projects has been studied by Smoge et al. (2020).

Torp (2019) noted the importance of realistic cost estimates in the front-end of TVD projects. Engebø et al. (2021) studied collaborative challenges in a TVD project caused by estimated costs that significantly exceeded allowable cost during the design phase. The study recommended clients to set a realistic allowable cost in the front-end of TVD projects, and prevent drastic increases in scope and expected costs during subsequent design.

RESEACH GAPS

In a scoping review of CDMs, Engebø et al. (2020) found that there is a research gap on how CDM elements impact project performance. Noting the importance of early involvement and shared risk management, Tillmann et al. (2017) calls for further case studies on the internal and external factors influencing TVD and IPD, and the adaption of these methods to non-IPD environments.

RESEARCH METHODS

RESEARCH DESIGN

A qualitative research design was chosen due to the qualitative nature of the research questions and available data (Fellows and Liu 2015). In order to enhance the reliability of the study, data was collected through a triangulation of research techniques (Yin 2017).

LITERATURE STUDY

A literature study was conducted for the purpose of establishing a theoretical framework and identifying research gaps (Fellows and Liu 2015). A preliminary literature search for papers about CDMs, and CDM elements such as ECI and TVD, was done at IGLC.net. Through a snowballing approach, additional papers of relevance were identified. Subsequent searches for papers were conducted in five databases (Scopus, Web of Science, Oria, Dimensions and Google Scholar).

DATA GATHERING

Description of case

The project to be examined in this case study is the construction of a large and complex building in Norway. It is being delivered through a CDM in which the client and the design and build contractor are the key parties. The project is regulated by the Norwegian Law of Public Procurement and a Norwegian quality assurance (QA) scheme. These regulations impose constraints on the procurement strategy, delivery model, choice of concept and allowable cost in large public projects (Lædre et al. 2006; Welde et al. 2015).

The main author held a summer internship as an assistant project manager for the client in 2021, which provided an opportunity collect empirical data. This, combined with the scope, complexity and relevance of the project, made it a suitable choice for a case study. For the purpose of enabling detailed descriptions of stakeholder perspectives on collaboration, the project and its participants have been anonymized.

Document study

A significant part of the empirical data stems from a document study (Yin 2017). Access to the web hotels of both the client and the partnering group was given through the internship. With permission from management, several documents of importance were studied, including the procurement strategy, the contractual documents, and the minutes from bi-weekly partnering meetings.

Interviews

The main source of data for the study stems from semi-structured interviews with the key participants in the project (Fellows and Liu 2015). An interview guide was developed to guide the interviews. It was structured after the research questions and included questions about various Lean and collaborative elements found in the literature and case documents.

The interviewees were selectively sampled, with interview requests being limited to invitees to the partnering meetings who were either regular attendees at these meetings or members of the steering group. Sixteen individuals were interviewed, including members of the client and contractor organizations, and architects and consultants.

A substantial majority of the interviewed individuals belonged to the client or contractor organizations, as those organizations had greater involvement in the steering group and partnering meetings. Subcontractors had no involvement in neither and were thus not interviewed. A limited amount of perspectives from architects, consultants and subcontractors thus constitute a limitation for this study.

Observations

During the internship the main author was involved in the daily work at the construction site with the contractors, and participated in various meetings with management, including partnering meetings, steering group meetings, and a partnering workshop. Thirty pages of notes with observations and reflections was produced. These observations served as an additional source of triangulation when evaluating data.

DATA ANALYSIS

The empirical data gathered from the case study was coded in a framework adapted to the research questions. The empirical data served as a basis for creating an illustration and timeline for the project. The model was drawn by the main author on the basis of qualitative and quantitative data. It shows key events internally and externally connected to the examined CDM, and illustrates the effects of these events on the development of cost and culture. Culture is here understood as the quality of collaboration between stakeholders. It should be noted that the recorded effects may be connected to events not mentioned in the model, and that the events may have had other notable effects.

The model incorporates findings from the front-end of the project but focuses on events and effects since contractor involvement. The sample size from the front-end was insufficient for modelling the project culture during this phase. Limited data from the front-end thus constitutes a limitation of this study.

During the rounds of interviews, the model was tested on the interviewees and modified in accordance with their feedback. The model was used as a framework to discuss the findings and look for causality.

FINDINGS

PROCUREMENT

The procurement strategy for the project was established in the fall of 2017 at the end of the pre-project phase, during which it had grown considerably in scope, detail and expected cost. This growth had been supervised by the client and their consultants and architects, in cooperation with public authorities.

The bidding competition was announced the next spring. It followed the specific partnering contract of the client, which in turn is largely based on the Norwegian Standard Design-Build contract (NS 8407). Procurement was to be value-based, with 70% emphasis on quality and 30% emphasis on price. Partnering experience was considered a key element in quality. Contractor involvement was to happen in two stages. The first stage being the signing of a partnering contract for the detailed design of the building. Project cost was to be estimated successively with four budget prices, culminating with the signing of a target cost contract with shared bonus/malus and the subsequent transition to execution phase. During this transition the contractor would assume control of the consulting engineers and risk for all designed material.

The bidding competition attracted one bidder, who highlighted conceptual solutions for this type of building which they had developed with years of experience with partnering. The offer included suggestions to implement a series of Lean and collaborative elements, including LPS, ICE and BIM. The contract for stage 1 was signed in June 2018. It consisted of a series of contractual documents, including an agreement containing the quantity and unit price for the contractor and subcontractor personnel. Their work was to be done on open book.

EFFECTS

Phase 1

Phase 1 began with a start-up workshop in August 2018, in which a partnering declaration was signed by key stakeholders. A steering group consisting of the project managers and senior management from the main stakeholders was established.

Soon after the beginning of collaborative design, the contractor suggested to modify the design in accordance with their concept, which they believed would enhance constructability. The architects and consultants were sceptical of these modifications, and collaboration in the design team became challenging. Meanwhile, the external quality assurers reported higher costs and uncertainty than what the consultants had estimated in the pre-project. Soon afterwards, the main contractor presented budget price (1), which estimated even higher costs and uncertainty for the project. With the aim of reducing uncertainty, increasing value, and improving collaboration, the client and the steering group became increasingly involved. The design phase was extended, the team partially reorganized, and a design combining the solutions of the architects, consultants and contractors was chosen.

The interviewees from all stakeholders agree that these measures greatly improved collaboration and performance. They also noted that the measures probably would have been less needed if the contractor had been involved even earlier in the project, as this would have facilitated even better team building and constructability. According to the interviewees from the client, the fact that the front-end of the project consisted of a single phase made it difficult to find a suitable time for earlier contractor involvement. The interviewees from the contractor generally argued in favour of earlier involvement and greater influence on the procurement of consultants, while the interviewed architects and consultants instead emphasised the importance of early involvement on equal terms. They also noted the importance of formulating the procurement strategy early, so that the design can be aligned with it.

In the spring of 2019, design was progressing, and budget price (4) was estimated at an uncertainty workshop involving the key members of the project group. While uncertainty had been reduced and value increased, the estimated cost was significantly higher than the estimates which had previously been presented to the public. As a result, the authorities hesitated to initiate execution, and commissioned external quality assurers to verify the estimates. In the meantime, the client gave the design team the go-ahead to complete detailed design. The interviewees from the design team concur that shared commitments and support from the client was instrumental in securing strong collaboration during this process. They noted that the postponement of execution probably would have been shorter if the early cost estimates for the project had been more realistic.

As detailed design was being finalized, the client and the contractor opened target cost negotiations. During these negotiations, the client argued that the project was sufficiently specified to set the uncertainty at a low level, but the managers from the contractor could not agree to set uncertainty as low due to corporate rules. In order to secure a target cost acceptable for all stakeholders, several elements of the target cost were separated and made fully cost reimbursable.

Phase 2

In the spring of 2020, the cost estimates for the project were verified by the external quality assurers, but the setting of allowable cost by the authorities was delayed, largely due to the onset of the COVID-19 pandemic. To keep collaboration strong, the client independently provided funding for the contractor to initiate execution, and allowable cost was set by the authorities a few weeks later. During this transition the contracts with the consultants were transferred from the client to the contractors, while the architects kept their contract with the client. Several new individuals joined the project organization, while others left it, requiring increased emphasis on team building and continuity.

As the execution phase progressed, Norway repeatedly went into lockdown, making schedule planning more challenging. As the subcontractors began installing technical installations, discussions arose concerning design constructability. Since all stakeholders had been involved in the design during phase 1, the project group had a shared commitment to the design, which encouraged them to seek shared problem solving. However, the contractor believed that the design would have been more constructible if detailed design had been carried out in phase 2, during which the contractor had the contracts with the consultants. At this time the client organized a partnering workshop for the involved stakeholders, which according to the interviewees significantly improved collaboration and performance.

As the lockdowns continued, inflating prices for construction materials and services, and disadvantageous changes in currency values, resulted in higher-than-expected costs. While the contractor sought to handle many of the growing costs through the cost reimbursable elements of the target cost, the client argued that cost increases avoidable through design or execution should be handled through the contingency. The interviewees noted that these discussions would have been easier to resolve if the risk distribution in the target cost had been more balanced and clearer. Active involvement of senior management in the steering group helped ensure constructive collaboration at this time, and open book helped maintain trust. The contractor agreed to spend more of the contingency to alleviate costs increases, while the client successfully requested the authorities to increase the allowable cost. The importance of early involvement of stakeholders in ensuring optimal collaboration is summarized by an interviewee from the client organization:

> A key argument for early involvement in collaborative project delivery is the fact that it enables the stakeholders to get to know each other and the project, and to develop shared commitments. This ensures that when challenges occur, we avoid pointing fingers at one another, and instead focus on solving things together. These principles have been perfectly exemplified in this project.

In the spring of 2022, as the project was reaching delivery, the client and the main contractor signed a partnering contract for the construction of an additional building of the same type. The new building will according to interviewees be delivered through a similar model, but with earlier contractor involvement, greater contractor influence on the procurement of architects and consultants, a more balanced risk distribution, and an earlier target cost agreement and transition to phase 2, which will encompass both detailed design and execution.

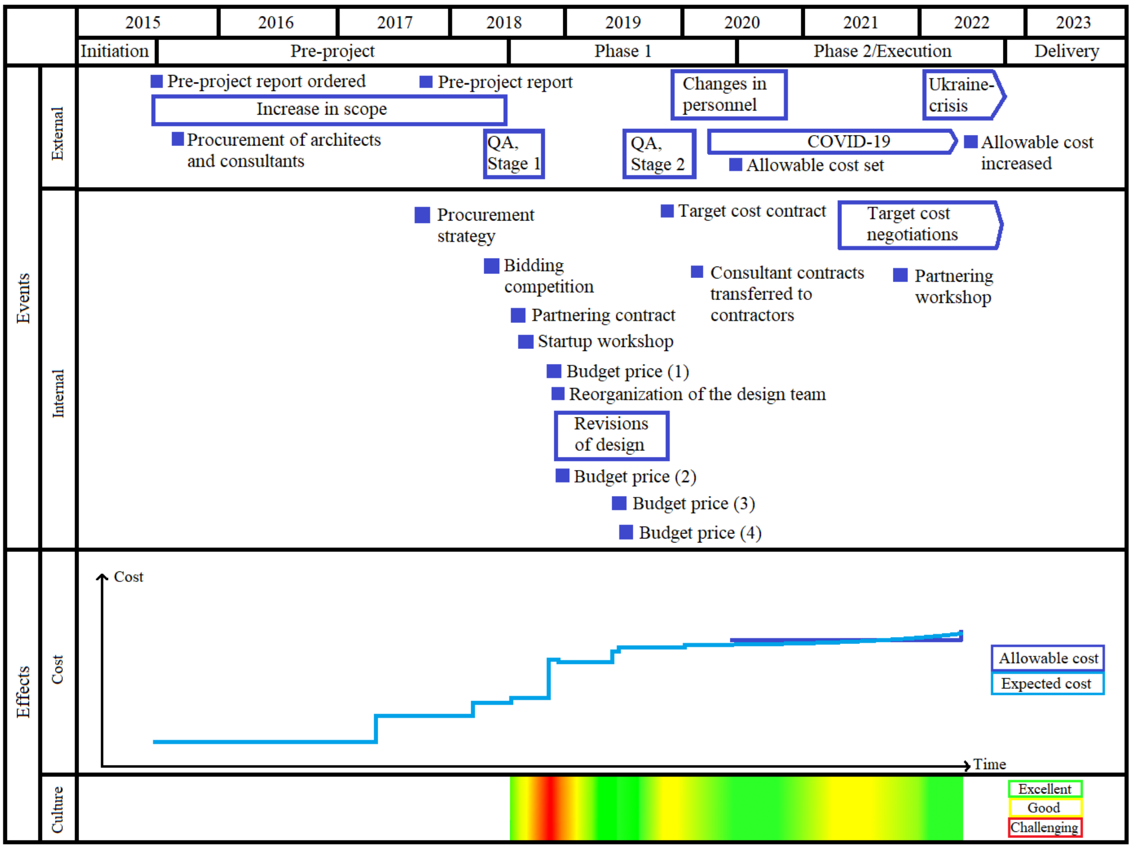

Figure 1: Timeline of events and effects in the examined case.

DISCUSSION

PROCUREMENT

Figure 1 shows that the project jumped straight from initiation to the pre-project phase, and that the pre-project phase continued for a long time until the procurement strategy was formulated. This in turn influenced the design and the timing for contractor involvement in the project, suggesting that the front-end is essential in optimizing collaborative delivery.

The finding of Sødal et al. (2014) that ECI may make architects and consultants feel marginalized is corroborated in this case. Nevertheless, it is noteworthy that the interviewed architects and consultants endorsed ECI in collaborative delivery as long as contractor influence remains limited. Rather than immediately giving the contractor direct control of the consultants, it may be a better idea for the client to involve both stakeholders at an early point on equal terms, and thereafter work on team building on a collaborative basis. By having a sufficient number of increments in the delivery model, decision makers can facilitate an incremental increase in contractor responsibility. The identification of sufficiently early involvement as a key success factor in ECI and LPD corresponds with the findings of Wondimu et al. (2016a) and Tillmann et al. (2017).

PHASE 1

The observation from phase 1 that ECI ensured greater design quality, cost estimation and collaboration correspond with the findings of Sødal et al. (2014). That there is a connection between collaboration, and increases in scope and expected costs during design, is in line with the findings of Engebø et al. (2021).

The effects in the later parts of phase 1 illustrate the importance of having a realistic cost estimate in the front-end, as noted by Torp (2019). However, while the target cost contract in the project observed by Engebø et al. (2021) was reduced through reducing project scope, the case studied here secured a contract through transferring risk from the contractor to the client. If the initial cost estimates had been more realistic, the client and the contractor would probably have been able to negotiate a target cost contract at an earlier point in time, and the client would have had more flexibility in negotiations, which may have resulted in a more balanced, equitable and clear risk distribution, and thereby better collaboration.

The characteristics of the studied delivery model are in line with the characteristics of LPDs described by Ballard (2008) and Alarcón et al. (2013), and the characteristics of CDMs as described by Lahdenperä (2012). However, the degrees of early involvement, team integration and risk sharing vary significantly among the key stakeholders in the examined project, and it thus differs somewhat from theory in that regard. In addition, the late setting of allowable cost and increases in expected costs differ significantly from the TVD methodology described by Pennanen and Ballard (2008). The identification of ECI and target costing as key partnering elements are in corroboration with the findings of Hosseini et al. (2016).

PHASE 2

Figure 1 suggests that collaboration in phase 2 became more challenging at a point when COVID-19 was impacting cost performance. At this time the pandemic was also impacting schedule, while new personnel entered the project and subcontractors began installing technical installations. There seems to be a combination of underlying reasons for the challenges, which may have arisen independently of each other, with external factors having a major effect. That partnering can be more challenging during execution is nevertheless also observed by Falch et al. (2020). However, it is noteworthy that the early part of the execution phase was characterized by optimal collaboration. This suggests that more attention should be given to optimizing collaboration in the later part of the execution phase. As ECI secures greater commitments and team building, it may be a key element in securing such optimization. Involving subcontractors in the target cost could perhaps have increased shared commitments even further.

As can be seen from Figure 1, target cost discussions among management in phase 2 were opened at a time expected cost was nearing allowable cost. This suggests that optimizing collaboration requires optimizing the setting of both expected cost and allowable cost. The right level of allowable cost was difficult to foresee in this project, given external world events that have happened during execution. Having a more balanced, equitable and clear risk distribution in the target cost would nevertheless have made the delivery model more resilient to the mentioned external factors. The observed importance of shared risks and reward for collaboration are in line with the findings of Tillmann et al. (2017). The risk distribution of the target cost contract was in turn decisively influenced by front-end decisions, which underscores the influence external factors have on the implementation and effects of LPDs and CDMs. In the studied project, continuous involvement of senior management in the steering group ensured constructive collaboration despite the challenges. The steering group therefore appears to be a key element in optimizing the resilience of CDMs and target cost contracts to external factors.

The fact that the client and the contractor during the end of the execution phase signed a contract to construct a similar building with a similar delivery model is noteworthy. It is also significant that the delivery model for the new project has been modified in the sense that it aims to secure earlier involvement, more joint decision making and a more balanced sharing of risks. These modifications make the model more in line with Lean and collaborative delivery as described in theory.

CONCLUSIONS

THEORETICAL CONTRIBUTIONS

Through examining a complex construction project with many Lean and collaborative elements, this study provides empirical data that can further develop theory. The study substantiates benefits and pitfalls found in previous studies. Another significant find is the fact when the stakeholders in the studied case decided to collaborate on a new project with a similar delivery model, the modified delivery model for the new project further approached Lean and collaborative delivery as described in theory.

PRACTICAL IMPLICATIONS

To optimize collaborative project delivery, it is important to establish a realistic allowable cost and clear scope in the front-end of projects, and then align the design with these constraints. Such alignment requires active participation of the client and senior management, and benefits from early involvement of key stakeholders.

Procurement strategies should be considered early and adapted to the specific project, and the delivery model should be incremented in a way which enables early and incremental involvement. In value-based procurement, collaborative competence should be strongly emphasized, and stakeholders should be made to feel that they are included on equal terms.

When negotiating target cost contracts, the stakeholders should ensure that the risk distribution is balanced, equitable and clear. Management should avoid specifying a project in too much detail before negotiating a target cost, as this may result in disagreements over uncertainty and increased vulnerability to external factors. Continuity between phases ensures greater commitment and collaboration.

Collaborative project delivery with early contractor involvement and target cost helps ensure improved design, commitment, risk management, team building and cost estimation, and is therefore found to be useful for the delivery of complex projects such as the studied case.

FURTHER RESEARCH

The front-end and external factors appear to have a major influence on the implementation and effects of Lean and collaborative elements. The generalizability of this should be tested through further case studies. The connection between the elements and created value for various stakeholders should be examined further. Also, more attention should be given to the role of architects, consultants and subcontractors. More specifically, methods for involving these stakeholders in collaborative projects, and target cost contracts in particular, should be subjected to further study.

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CAPACITY BUILDING: LEARNING FROM CORPORATE SUCCESSES OUTSIDE CONSTRUCTION

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ABSTRACT

Industrialization is a response to low productivity and shortage of skilled labour. Advancement in technology is associated with the growing trend. Thus, industrialisation requires upskilling the whole workforce – literacy, numeracy, technical and trade skills. This crisis is exacerbated by the casualization of construction labor over the last ~60 years which means construction companies do not see it as in their interest to upskill those they do not employ. Even though "*with every pair of hands comes a free brain*" (Henry Ford), the construction sector seems to find it acceptable to do little or nothing to use and develop those brains, to tap into this unused talent. Motivated by these insights, we ask, *what can we learn from corporate success outside construction that might help improve industrialised project delivery in construction?* This qualitative exploratory analysis of successful major transformations in other sectors uses selective literature review, categorical aggregation of case studies and inductive reasoning. The findings underscore the importance of leaders with 'constancy of purpose' driving system change in order to build the capacity and competence of workers. In construction this may mean decasualising labour which will require the creation of pipelines of work to ensure a steady workload. The paper concludes with suggestions for further research and validation in the field.

KEYWORDS

Organization, Culture, Industrialisation, Collaboration, Capacity building.

INTRODUCTION

Industrialisation seems to have advanced rapidly in the last 2-3 years. In the construction sector, industrialization is in part a response to low productivity and shortage of skilled labour, a global phenomenon. Advancement in technology is associated with the growing trend which in turn requires workers to upskill at a faster pace. What is our industry doing to address these concerns? What are the criteria for capacity building of workers? What are some if the existent issues? These intriguing questions, propelled us to explore further.

A preliminary literature review shows that shortage of skilled labor in construction was a 'crisis' for at least the last 20 years. Many construction workers have short careers brought on by the hard physical labour involved and the physical conditions of the work.

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Construction workers, and particularly unskilled labourers, join the sector with little education, low literacy and poor numeracy skills (Kahn, Alam and Ahmed 2015).

In practice, construction workers are generally *told* what to do by middle managers based on a Critical Path (CPM) schedule prepared by other people (Mossman and Sarhan 2021). With CPM, the sector is, as the late Greg Howell frequenly said "*a commitment free zone*". It is as if construction workers are speechless. In certain parts of the world they are certainly not expected to speak up, to say 'no' or to object in any other way to the instructions they are given by trade crew leaders, supervisors or managers. This can even be true when they don't understand the instructions they have received – because, for example, they do not share the instructor's mother tongue (Mossman & Ramalingam 2021a). Extreme examples of construction workers who are not expected to speak up include those who are engaged in forced labour, bonded labour or debt bondage (Von Elgg 2016). Often referred to as *Modern Slavery*, this happens in Europe, North America as well as in other parts of the world and is often associated with trafficking of individuals. All this contributes to rework, cost and delay. Taken together these conditions make it easy to treat these construction workers as an exploitable and expendable commodity and may help to explain the poor quality of much work done in construction. The cost of that poor quality is significant (Mossman & Ramalingam 2021b).

Even with significant industrialisation, to enable work to flow smoothly through the system, construction will still be a people business. Many in the construction sector appear to operate as if the workers only bring a pair of hands to work. These hands are told what to do by managers and supervisors, a very passive activity (Marquet 2012, 138). Changing that requires mutual respect of managers and workers. Yet as Henry Ford quotes, *"with every pair of hands comes a free brain"*. Few acknowledge those brains, let alone engage them. In some cultures and in some markets (e.g. parts of India, in Gulf states, as well as in the parts of the United States and Europe) workers are sourced from distant places where education is limited and, often, where languages are different.

Intereventions in other sectors over the last century have sought to capitalise on those brains. As in other sectors, it is the workers (operatives, laborers) who create the value that has been promised to customers by senior leaders. Some leaders have created significant success for organisations as well as developing the skills of individual workers. Holistically, we need a capacity building process. Capacity building is a systematic process to improve worker's knowledge, skills, understanding, values, attitude, motivation, and capability necessary to perform well at work. We feel that now is time to learn from successful labor development programs in other sectors so that the construction workforce are able to use their brains confidently — and ensure that '*One bad apple* does not spoil the barrel' (Mossman & Ramalingam 2021b).

Motivated by these insights, the aim of this paper is to understand the ways in which construction leaders might enable capacity building to *build* their workers (as Toyota do) so as to improve worker effectiveness as they adapt to industrialised construction and delivering ever better quality and productivity. Specifically, we explore, *what can we learn from corporate success outside construction that might help improve industrialised project delivery in construction?*.

METHOD

Many project learning reviews focus on learning from mistakes. Learning from mistakes is the norm on most projects and particularly following project failures – like the Chernobyl nuclear tragedy, the NASA Challenger space shuttle explosion or the time and cost overrun issues in the Sydney Opera House project. This paper focuses on learning from project success stories. These are limited in construction (e.g: Delhi Metro project and Alandur PPP project in India) and often ignored. Following Creswell (1998) and Stake (1995) this is an exploratory case-study analysis of 7 success stories from other sectors with data from multiple sources including white paper reports and news articles as well as literary evidences. The cases were then categorically aggregated and thematically analysed using an inductive reasoning approach to interpret the findings in the context of construction. The learnings from this paper are thus based on a method of inquiry, inductive reasoning and interpretive analysis of success stories from all domains supplemented with the experiential insights of the first author. This is a conceptual paper and the findings will have to be validated on construction projects in future.

The length of the paper means that only the briefest of information about each case is presented. Each is much more complex than we may suggest. Find more in an appendix at https://bit.ly/3a25nwi .

THE CASES: SEVEN SUCCESS STORIES

1. TRAINING WITHIN INDUSTRIES — E.G. BOEING, AMAZON FULFILLMENT

The Training within Industry (TWI) program standardises training programmes and assists frontline managers in quickly and effectively teach new operations to workers. It is sometimes referred to as *the foundation of lean* (Dinero 2005). Founded in 1940 in the US during World War 2 (WW2), TWI built on Charles Allen's experience in US shipyards during WW1. In both wars it was necessary to ramp up both civil and military production quickly using workers with little or no previous relevant experience. The TWI program covered 1. How to train workers so as to reduce defects, rejects, rework, accidents (all things of concern to constructors); 2. How to systematically improve the way work is done; 3. How supervisors can get the facts, weigh them carefully, make a decision, take action, and check results (Dinero 2005).

After WW2 TWI skills were taught in Japan to help rebuild the economy and Toyota and other companies have been using them ever since (Huntzinger 2006; 2001). TWI programs covered, among other things: Pre-employment and on-the-job training; Developing all-round craft worker skills through an accelerated apprenticeship; Problem solving skills; Safety; Preparing instructors to deliver effective training; Supervisor selection; Improving job relations; Plant training plans; Strengthening the managerial organisation to support whole company program (Dinero 2005).

One example of a WW2 TWI success was Boeing. In 1941 Boeing faced a challenge: a rush order for B-17 bombers using existing production facilities and 33,000 unskilled workers 50% of whom were Seattle area housewives and the rest cowboys, fishermen, farmers and lumberjacks. By 1944 these people had increased output from 75 planes a month to 364 – a 485% increase – while reducing labour hours per plane by 60% and costs by 43%.

The program continues to this day — the *TWI Institute* is working with Amazon Fulfillment among others. [https://www.twi-institute.com]

2. HARLEY DAVIDSON

Following a leveraged buyout in 1981, senior leaders visited Honda's motorcycle plant in the US. This visit helped them realise that they faced a crisis – Harley Davidson had to radically change their own operations if they were to survive. They developed a new approach that focused on 1: Employee involvement; 2: Just-in-time inventory practices (they called it *Materials-as-Needed)* to reduce work-in-process inventory and make quality problems more apparent so that employees were more likely to take action; and 3: teaching employees Statistical Process Control (see e.g. Wheeler & Chambers 1992) to help them systemically investigate and improve product quality.

Kotha & Dutton (1996) reported that senior leaders came to understand that production line workers had a better idea of what worked and what did not than they did. When Rich Teerlink, formerly CFO, became CEO in 1989, he was aware that Maslow had suggested that people willingly commit to what they help create (Teerlink 2000). With these ideas in mind Teerlink reinforced the turnaround by *engaging* the whole workforce — both salaried and hourly paid — in developing a vision for the company. To make it safe for people to make suggestions *quality circles* of manufacturing workers were made directly responsible for improving product quality. These changes rapidly made a difference. Quality improved and so did productivity, market-share and profits while waste fell — and the company became more customer centred.

Subsequently, Teerlink reports (2000), senior leaders began working to create an environment where employees want to do better, care about the company on a personal level and work together to improve both individual and overall performance.

Ten years later, when Teerlink retired as CEO, Harley-Davidson were doing well, and the process was still improving. *Nothing is so good that it cannot be made better*.

3. FAVI

In the early 1980s Jean-François Zobrist, became CEO of Favi, a French bronze foundry producing specialised castings for the automotive, aeronautical, health and other sectors. He realised that he trusted the people who created the company's wealth (Carney & Getz 2016). He then gradually removed every impediment to the workers: no more inspections, no more time-clocks, and no more locked warehouses — and no more managers. FAVI became a collection of autonomous teams delivering great quality and service to their international customers. Believing that "*People always tend to act as they are considered"* Zobrist helped the organisation shift from structures that assumed 'humans are bad' to one based on 'humans are good' (Minnaar and de Morree 2017). By 2000 FAVI had 50% of the European automotive market and a substantial proportion of the global health market without exporting work to low cost manufacturing countries. Employee turnover was very low, they never delivered late and never increased the prices of their products.

Zobrist retired in 2003. A decade later he noted that humans are formatted for uncertainty. Both as hunters and as farmers, humans look for weak signals and listen to intuition – i.e. *tacit* knowledge (just as in construction). In hierarchies, those weak signals rarely make it to the senior leaders as they are focused on efforts to create certainty.

After Zobrist retired and after ownership of the company passed to the previous owner's grandson and others, the new shareholders forced the new CEO to destroy the unique culture based on freedom and trust and to outsource manufacturing to Asia. As a consequence product prices rose, many workers left the company and profit margins and net cash flow decreased quickly, leading to even tighter control. (Minnaar and de Morree 2017). Success was over when the system change and assumptions were reversed.

4. NUMMI

In 1962 General Motors opened a new production facility in Fremont, California. By the early 1980s that factory "had the worst record of management/labor conflict of any U.S.

automotive plant" (Ranney 2009). In 1984 GM was considering closing the plant and at the same time Toyota was looking for a place to experiment with production in the US. Toyota agreed a joint venture with GM and New United Motor Manufacturing Inc. (NUMMI) was born using 85% existing labour. Toyota started by taking employees to Japan to experience how Toyota produce vehicles with teamwork and collaborative problem solving and to think about the end users of the vehicles they produced. Everything focused on quality. This importantly included *management doing what they said they would do* (Ranney 2009). At NUMMI, Toyota produced their own vehicles and a GM small car in the same plant. Quality, productivity and employee pride in their work increased dramatically. Within a couple of years the number of defects per vehicle were on a par with a similar model produced in Japan! All this required that workers were willing and able to stop the line to fix problems rather than passing on defective product. There are excellent descriptions of how the transition happened in *The American Way* (2010) and in Shook (2009).

GM pulled out of the joint-venture in 2009 and Toyota closed NUMMI in 2010 – the only plant it has ever closed. Tesla bought the NUMMI site later in 2010 and it now produces the Tesla range. With learning from the NUMMI experiment, in 1986 Toyota successfully created its own plants in North America (in Kentucky and in Ontario, Canada), and later in other parts of the world.

5. ALCOA

In 1987, newly appointed CEO of Alcoa, Paul O'Neill chose to focus on safety. He wanted to make Alcoa the safest company in America. O'Neill announced his intention on an autumn day in 1987 in a speech to Wall Street investors and stock analysts. Profits, he said, didn't matter as much as safety. Back in Alcoa, O'Neill toured the plants with the same message. On the basis of what he said many of his audience sold their Alcoa stock or recommended that others did, yet, within a year, Alcoa's profits hit a record high and by the time he retired in 2000, the company's annual net income was five times larger than before he arrived, and its market capitalization had risen by $27 billion, a nine fold increase.

"The key to protecting Alcoa employees, O'Neill believed, was understanding *why* injuries happened in the first place. And to understand *why* injuries happened, you had to study *how* the manufacturing process was going wrong. To understand *how* things were going wrong, you had to … educate workers about quality control and the most efficient work processes, so that it would be easier to do everything right, since correct work is also safer work." (Duhigg 2012)

O'Neill shared his home phone number with plant managers and others across the business. Six months later, in the middle of the night, a plant manager called. An extrusion press had broken and an operator had been killed trying to fix it. The following day plant management and Alcoa senior leaders reviewed all the information they had and O'Neill concluded "*We killed this man, it's my failure of leadership. I caused his death. And it's the failure of all of you in the chain of command*." That shocked the room and that's when things started to change.

6. USS SANTA FE

In 1999 David Marquet became the commanding officer of the USS Santa Fe even though he had been trained over the previous 12 months to take command of a different class of submarine. He quickly discovered that commands that made sense on the submarine he'd been trained for didn't work on the *Santa Fe*. That was his epiphany. He decided that there was only one order that he was qualified to give – the order to use lethal weapons. For all other actions he communicated his intent so that his crew could initiate action to realise that intent.

Marquet's epiphany led him to create a way to develop leaders. He describes his approach as **leader-leader**. He writes about how he focused on three things: 1. **Moving authority** to where the information is while (this in effect gave those with authority the power to say 'NO'); 2. using **certifying** – the person responsible for the delivery team asks them questions to assess their understanding of the intended outcomes and competence to perform. Unlike *briefing*, this is an active process, everyone has to prepare. 3. **Emancipating the team**. Working with a team to identify and remove the shackles and obstacles that prevent them from doing the good job that they want to do when they come to work (as Zobrist did in Favi). *This is much more than empowerment and, like briefing and moving authority to where the information is, it builds the competence of the organisation as a whole.* (Marquet 2012)

In this way he moved from the situation where he was a leader with 134 followers on the submarine he commanded, to one where there were 135 leaders. In the process he *turned his ship around* — it went from the worst rated submarine in the fleet to the **best** — and *USS Santa Fe* created significantly more future submarine commanders than others in the fleet (Marquet 2012).

7. ANGLO AMERICAN

In 2007 Cynthia Caroll was appointed CEO of Anglo American (AA) a diversified mining company based in South Africa. Over 200 employees had died while working in the company in the preceding 5 years and its safety performance was improving. Caroll chose to focus the company on zero harm. Just in South Africa worker engagement was difficult because of the 13 national languages and low literacy. **On top of that the workers didn't feel safe to speak up.** Amy Edmondson (2019, 138ff. & 165) Caroll (2012) and three Harvard Business School Case studies (Mukunda et al 2013) describe how Caroll worked to help employees at all levels feel safe so that they were willing to engage in the improvement process.

Soon after her appointment there was yet another death at Rustenburg, the largest platinum mine in the world. Caroll declared "I simply cannot support operations that are killing people" and, even though no-one knew if it was possible at such short notice, she decided to shut it down. The decision marked the start of a major change process within AA that had a significant impact on the mining sector across South Africa and beyond (Mukunda 2020).

Unlike many of her peers, Caroll refused to accept that fatalities were an inevitable by-product of mining and wanted an indefinite shutdown, during which the mine would fundamentally overhaul safety procedures with a top-to-bottom audit of processes and infrastructure followed by a complete retraining of the workforce. The costs would be enormous. This was not a popular decision.

Rustenburg produced ~US$8m *per day* revenue and it remained closed for 7 weeks (→ ~€350m lost revenue). It led to revised safety practices in mines across the world. In the short term, it prompted complaints and resistance within AA. Many employees were not prepared to change, and almost all the managers at that mine were replaced.

The review of safety procedures and issues, meant 30,000 workers needed retraining before production at Rustenburg could resume. Small-group meetings and face-to-face communication between executives and individual employees were used to identify what had gone wrong in the past and **to instill personal and group responsibility**. Caroll (2012) goes on to describe how she worked with Government, the Unions in SA – and ultimately AA's competitors to raise the game for the mining sector as a whole.

WHAT DO WE LEARN FROM THESE EXAMPLES?

Many of the cases are examples of what David Burkus (2020) described as "*The whole industry finds this acceptable, and we refuse to accept that".* In short, aggregating the preliminary insights from these cases and performing a thematic analysis, it is observed that each of these successes feature a strong leader demonstrating '*constancy of purpose'* (Deming 1994, 51); many of them chose not to accept the way things were done elsewhere in their sector; all of them actively involved the workforce in the change so that the workers were able to become the change. As Deming makes clear, purpose defines the system. All required time and a crisis, to enable workers to understand that management really DID want to hear their ideas for improving the way work (i.e. creating value for customers) is done.

Each of these cases includes a significant system change that upskilled the workers and increased their sense of self-worth, pride in workmanship and the quality of the work delivered. Most of the system changes were stimulated by crisis or a 'burning platform'. WW2 created a production 'crisis' in the US and the 'Training within Industries' program helped unskilled recruits quickly get up to speed and then improve on the performance of the workers who volunteered for military service; in the 1990s in South Africa, Anglo American used a safety crisis to change the relationship with workers so that they felt able to improve much more than safety (much as was done in Alcoa a decade earlier); In Harley Davidson a financial crisis in the 1980s led to the company engaging workers in improving all aspects of the business (just as Toyota learnt to do following a financial crisis in the late 1940s); a leadership crisis on the worst performing US Navy submarine in 1999 enabled a very different approach to leadership and quickly 'turned the boat around'. All of these involved some sort of crisis and a consequent system change that gave workers much more authority and control. All had strong and focused leaders with unique leadership traits such as commitment, quick decision, leading by action, strong advocacy, strong will, perseverance etc. Each improved effectiveness, productivity (with the possible exception of USS *Santa Fe* – how do you measure the productivity of a nuclear submarine?) and reduced costs.

Among other things Harley Davidson shows the value of engaging the whole workforce and acknowledging that people at the workface have information that managers do not. Harley, NUMMI and Favi illustrate the value of pride in work and focusing on quality. NUMMI, Favi and USS *Santa Fe* all illustrate that workers can be trusted when they have the necessary skills and information. Alcoa and Anglo American show the value of worker safety as a starting point for a deeper quality intervention that quickly improves corporate productivity and profitability. Harley, NUMMI, Favi, and USS *Santa Fe* clearly illustrate the value of moving authority to where the information is (rather than the more normal moving information to where the authority is). Workers generally need to *feel* safe to speak up even when managers are actively encouraging it as can be seen in Harley, NUMMI, Alcoa and Anglo American particularly. Building the trust so that people feel safe takes time.

MOVING THESE IDEAS TO CONSTRUCTION

In India much unskilled construction labour travels hundreds of kilometers from communities in other states to work on projects for months at a time. In the Gulf, many unskilled workers travel from Southern Asia for long periods of work. *The whole industry* seems to *find it acceptable* to do little or nothing to improve the working conditions let alone the skills and knowledge of the workers employed. Russell Waugh, Managing Director, Leighton Contractors (India) Pvt Ltd noted in 2011, there are few, if any, companies training workers, "possibly owing to a lack of recognition that *an absence of skill contributes to escalating costs and delays among other things*" (our emphasis). For labour-only suppliers there may be no advantage to improving the literacy and numeracy of such workers, particularly if they are exploiting them using forms of forced labour, bonded labour or debt bondage.

Unless customers have required contractors to provide training, apprenticeships, etc. as part of the contract (as some, particularly public sector, customers do), the only people contractors and some specialist trade sub-contractors invest in are their own staff. Labour only contractors appear to have no interest in training the people they provide to projects, yet industrialisation will require upskilling the whole workforce – improving literacy, numeracy as well as technical and trade skills.

Combining basic education with on-the-job training in trade related skills could be of significant advantage to the general contractor and trades through improved quality of work leading to reduced delays and costs (Mossman and Ramalingam 2021b) – and when the workers return home there will be more that they can contribute in their family and home community. Much of the required basic learning for construction workers is tacit – that is why it is important that it is learnt on-the-job. TWI would be an excellent way to do this.

Why do so many constructors accept that casual, unskilled labour on a complex fast-moving construction site is both *acceptable and safe*? What stops senior leaders acting on the idea that improving skills helps improve quality (by reducing costs, delays, mistakes, etc.) and improve productivity?

DE-CASUALISATION

Green (2011, 60ff) was critical of the effects of casualisation of labor, the hollowing out of construction firms. He describes the outsourcing of functions and associated staff to specialist subcontractors beginning in the early 1970s. "*Especially stark*," he noted "*was the declining number of directly employed operatives in proportion to the number of administrative, professional, technical and clerical employees*." In time the new subcontractors themselves started to rely on labour only subcontractors. Originally intended to push costs down, as Deming (1985,3) predicted it is now pushing quality down and costs up as groups of poorly skilled workers are assembled afresh for each new project. This fragmentation in the sector makes it much more difficult to coordinate the work of people, let alone machines.

It would be easier for contractors and major sub-contractors to directly employ workers if those companies had a steady, 'level-loaded' pipeline of work to keep their employees busy. A level-loaded pipeline requires either a vertically integrated business (as Katera attempted to be) *or* both constructors and their customers to change the way they do business.

In the UK, Laing O'Rouke, a major contractor, believed that it had cracked this problem in the early 2000s and recruited workers from a number of trades. In the global financial crisis this strategy came unstuck as work dried up. In the Netherlands a house building subsidiary of BAM created a pipeline of work building homes for developers. Developers had to agree to the houose builder's program if they wanted to join the pipeline.

DISCUSSION

Construction is a people business. The pandemic brought in a major crisis. Industrilization and automation exaberate the labour shortage and skilled worker issues. However, even as the sector becomes more industrialised, it will still be a social process. It is vital that machines, algorithms etc. are subservient to the intentions and preferences of people, so that they cannot become the boss (Russel 2021, lecture 4). When every job is automated it will still be necessary to coordinate the work the robots and other systems managed in many different ways to ensure that work is flowing smoothly through the site. At least initially it is likely that specialised robots will be managed by 'trade' specialists. The work of one robot may adversely affect the work of another and the "conflict" will need to be resolved by their handlers. As a number of authors have shown, when you change the technology within a system, you will change the system and, particularly, the social relations, the roles, within the system (e.g. Trist & Bamforth 1951).

What can we learn from corporate success outside construction that might help improve industrialised project delivery in construction? Through inductive reasoning and reflecting on experiential insights, it is clear that strong, committed leaders with a will to change and accept change, leaders with strong advocacy who take quick decisions will be instrumental in bringing a safer and conducive learning environment for the workers, for it is evident that: 1. Workers know more than managers about what needs to be improved in production processes; 2. People are more likely to commit to improvements that they have had a hand in designing; 3. Developing people so that they have the skills and knowledge to act on the information they have at the workface will help them solve problems; 4. Managers can help workers improve the way work works by removing obstacles and by helping them learn to solve problems (and this will help them take pride in their work); 5. TWI is a great way to help workers learn specific manual skills (tacit knowledge) so that they can operate effectively and safely; 6. Building trust, building respect and building the skills of people at all levels in the project team will help deliver construction projects more safely, more quickly, with fewer defects and at lower cost. Each of these is true for Toyota too.

In order to provide predictable production the ability to make reliable promises is critical (Flores 2013). You cannot trust the promise of someone who feels that they must say 'yes' to every request. Saying 'no' takes self-confidence and self-esteem. Education does not guarantee the ability to do that. It does help people understand why that is important and to speak up. And it is not just the unskilled workers who need to change, learn and develop. As the late Sven Bertelsen noted almost 20 years ago (at IGLC 2004), those with the most significant challenge are middle managers. They have to switch from directing workers (telling them what to do) to supporting their learning and improvement; removing whatever limits workers' ability to deliver quality work right-first-time; to helping workers improve their work processes; i.e. coaching, guiding and being consultants to the workers who create the value that the customers want to receive.

As construction projects become ever more complex and as customers want them delivered ever more rapidly with the aid of industrialisation, it is important that construction workers who create and shape the value that customers want from their investment in the built environment have the skills and knowledge to work effectively "at the edge" (Alberts and Hayes 2002) with the ability to make decisions that support the delivery of the whole project. This is no different from what happens in the military, what happened on the USS *Santa Fe*.

Wherever they are in their organization**, managers can improve the system within which their people work.** What a middle manager can improve is often limited by the constraints imposed by more senior managers. As Prof Dr Myron Tribus wrote in 1988, "***People work in a system. The role of managers*** (and leaders) ***is to work on the system, to improve it — with the help of those who work in it"*** — i.e. emancipation.

In a very small way, in 2009, the first author saw what could be achieved on an enabling project for an opencast mine high on the veld to the east of Johannesburg, South Africa. None of the managers or foremen spoke one language that everyone understood. Three of the six foremen were functionally illiterate, yet together they were able to plan the project using Last Planner System (LPS), deliver it 2.5 months early (despite an extended wet season) and, correctly, tell the engineers that there was a mistake in the design. They planned and replanned collaboratively as a project team.

CONCLUSIONS

Construction is a people business, a social process. Industrialisation will not change this. Industrialisation is one of a number of responses to the global shortage of construction workers. Many workers currently have short careers in construction brought on by the hard labour and physical strength involved and the physical conditions of the work. Industrialisation has the potential to reduce the physical stress on construction workers and extend their construction careers. To build the capacity for unskilled workers to become full players in an industrialised construction sector, they need help to improve their literacy, numeracy and general educational achievement as the basis for equipping them to systematically improve the way construction work is done. This requires changes in the way workers are trained and supported; in the responsibilities they are given as well as the skill development necessary to take that responsibility will require strong willed champions able to lead with *constancy of purpose*, commit to change and act quickly, decisively so that, when appropriate, workers will feel confident to stop production rather than passing on defective product to later trades. This will support (and be supported by) a shift in the roles of middle managers from directing to listening, supporting and coaching. Learning from the cases, this study shows that a leader with 'constancy of purpose' can be instrumental in bringing in such a system change that builds both worker capability and capacity.

OPPORTUNITIES FOR FURTHER RESEARCH AND VALIDATION

To help the sector learn from success elsewhere, this paper is built around a number of challenging and successful cases from sectors other than construction. It is easy to present improvement ideas and claim they have an established theoretical base. We make no such claim. That is a topic for further research.

The opportunities for scholars to work with practitioners to study experiments in this field are significant. Such studies are likely to bring together the skills of ethnographers, anthropologists and other social scientists with construction management specialists to explore the cultural, social, managerial and technological dynamics of the construction sector to help understand how this capacity building can be beneficial to the industry.

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PREFABRICATED REINFORCEMENT IN CONSTRUCTION USING VDC: CASE STUDY OVALO MONITOR BRIDGE

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ABSTRACT

In construction projects, there may be rework and delays associated with construction processes with a low level of industrialization, resulting from the lack of constructability of the designs. To promote industrialization and improve the project's constructability, we implemented the Virtual Design & Construction (VDC) methodology, combined with a system of prefabricated reinforcement cages (PRC) elements in constructing an 870-meter span bridge located in Lima, Peru. The objective was to reduce structural rebars' assembly times, replace the traditional on-site processes of cutting, bending, and assembling steel with an industrial process based on systems of PRC steel elements. As a result, the assembly times of the structural item were reduced by 31%, thanks to the use of PRC elements. In addition, due to the VDC methodology, a 100% buildable design of the PRC elements was achieved.

KEYWORDS

VDC, BIM, bridges, industrialized construction, prefabricated reinforcement.

INTRODUCTION

Traditional construction systems can imply unnecessary expenses and loss of resources, either in labor or in materials and tools, which can affect the quality of the final project (Penadés Martí, 2002). Therefore, humans have always sought to improve and optimize every process they perform, eliminating waste. Construction is one such process, which has been subjected to several changes and revolutions (López Flores, 2018).

In recent decades, there has been a growing interest in advances in industrial construction. As Qi et al. (2021) explain, industrialized construction integrates design and optimization tools to solve complex challenges in construction projects. The most discussed benefits of industrialized construction are cost reductions, productivity improvement, and the reduction and optimization of construction times.

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The prefabricated reinforcement cages (PRC) for reinforced concrete elements are essential for precast concrete and, therefore, for the construction industry. According to Simonsson and Emborg (2007), approximately 50% of the total construction cost of a bridge infrastructure comes from reinforcing steel and pouring concrete *in situ* and comments that from an ideal theoretical point of view, the time reduction on-site can reach up to 80% savings. This means that implementing construction methods that reduce time and costs is essential to maximizing the project's profit. PRC can reduce construction costs and time while improving fabrication quality and safety (Devine et al., 2018).

According to Acevedo Díaz (2009), in traditional construction work, the cutting, bending, assembly, and installation of rebar is done manually, with these tasks being carried out by the construction workforce. So, as on-site steelmaking is a craft job, removing these activities from the main production line (construction site) helps mitigate potential accidents and decreases the workload of the general contractor, allowing greater focus on other areas of construction.

The alternative of preassembling the steel bars in a workshop allows for overlapping activities and saves time in the construction. By migrating these activities to the support production lines, the time used to execute the jobs will not be greater than in systems that do not use preassembled rebar cages (Espinoza Conislla, 2012, p. 83).

Another significant aspect of the construction industry is project management - more collaborative and inclusive management where all actors collaborate towards a common goal. Collaborative management is crucial to reduce costs and avoid schedule delays because it involves all stakeholders, reducing risks and increasing efficiency in decision-making (Kunz, & Fischer, 2020). One of the methodologies that promote collaborative management is the Virtual Design & Construction (VDC) methodology.

VDC is known as the use of models under multidisciplinary performance in a different design - construction projects, work process flows, and the organization of the design - construction - operation team, including the product, to achieve business objectives (Kunz & Fischer, 2020). The VDC methodology is presented through a VDC framework with its three components: ICE (Integrated Concurrent Engineering), BIM (Building Information Modeling), and PPM (Project Production Management).

We present the Virtual Design and Construction (VDC) methodology as a point of interest to the AEC industry. From the literature review, few research papers discuss the time benefits of implementing the VDC Framework with a pre-assembled industrialized process. These help to optimize construction processes through the standardization of pre-construction of structural elements and the collaborative management of the project (Corrales Tamayo and Saravia Torres-Llosa, 2020).

Motivated by those above, we present how PRC elements and the VDC methodology benefit the construction of an 870-meter span bridge located in Lima, Peru.

DEVELOPMENT

Industrialized construction, also called construction 4.0, refers to adopting technologies and digital tools to optimize construction processes. This industrialization implies that the infrastructures to be built are processed as manufacturing processes rather than as independent projects (Villena Manzanares et al., 2020, p. 425). This means that it is made more efficiently, reducing on-site construction work.

For Xue et al. (2018), the construction sector is one of the industries known for its scarcity of innovation. This is due to the unique nature of projects relying purely on on-site productions, various stakeholders involved, etc., which causes a low integration of the new industrialized construction methodologies (remaining resistant to change from conventional practices), affecting the quality of the final product. In the same way, Qi et al. (2021) mention that industrialized construction also faces specific problems and obstacles, which injure efforts to be fully implemented and subsequently adapted within the construction sector. Despite the benefits that can be obtained, there is still a lack of communication, a lack of quality inspection systems for manufacturing and installation activities, and poor efficiency concerning the supply chain (Qi et al., 2021).

PREFABRICATED REINFORCEMENT CAGE (PRC) ELEMENTS

The preassembled elements are generally carried out outside the building/site. The final placement is the only on-site task to be carried out (Espinoza Conislla, 2012, p. 75). On the other hand, all the work is done in traditional assembly. A work area must be freed up to cut and bend the steel and then assemble it at its final point, piece by piece. Subsequently, the formwork of the element is completed, and then finally, the concrete is poured. So, outsourcing the cutting and bending of steel allows for increased productivity, quality, and safety, reducing costs, construction time on site, and labor inspection (Devine et al., 2018).

In traditional systems, the steel bars and stirrups will have to be transported individually, probably with the support of cranes. On the other hand, the crane can move the material in a single movement by having the entire element already prefabricated and ready to install (Acevedo Díaz, 2009). This is more efficient and reduces machine usage time per batch.

A substantial benefit of pre-assembly is carrying out different activities simultaneously. In a project with traditional reinforcement, the reinforcement of the beams of a slab cannot begin until the beam bottom formwork is installed (Espinoza Conislla, 2012). On the other hand, it is possible with the assembly in a factory. Allowing formwork and steelwork to be done simultaneously helps eliminate wasted time. The assembly is no longer dependent on the formwork subcontractor. Having the shaft preassembled and available generates a minimum inventory (PRC element available and ready to install) to have a buffer and transport the structural elements from the workshop to the construction site when needed, avoiding wasted time. On the contrary, the inventory could also be held on-site, ready to be installed when available. The drawback is the valuable space it would occupy when it remains as inventory.

Devin et al. (2018) found through a qualitative survey that the work time of the workforce for the mooring of the bars is reduced by 27% when the prefabrication of the elements is carried out. But once the additional time consumed in transporting the preassembled components is considered (transport from the supplier to the factory and then from the factory to the construction site), the total savings are reduced to approximately 1-14%.

Simonsson and Emborg (2007) state that outsourcing the prefabrication of rebar cages is usually connected to using better tools, automated equipment, and skilled labor to operate them, minimizing failures and improving quality. Therefore, industrialization means a more controlled and specialized work system.

Likewise, contracting PRC reduces the variability or uncertainty of the general contractor regarding the items of reinforcing steel since there are fixed delivery dates coordinated with the supplier (Acevedo Díaz, 2009). Whereas with a non-industrialized construction, the assembly of each element would depend not only on the delivery of the material (rebar) by the supplier but also on the contractor in charge of fitting and assembling the element. Furthermore, there is a substantial difference in material loss. The study conducted by Kim et al. (2013) noted an expected loss of steel of 10% in traditional systems. In contrast, this loss estimate drops to just 3% in an industrialized system.

The pre-assembly of rebar cages is a construction process that brings many benefits to the construction project; however, there may be some drawbacks, such as:

- The tower crane must move the steel elements, and, therefore, any other activity that requires the use of the crane must wait its turn (Espinoza Conislla, 2012).
- A possible problem faced by the assembly of construction bars in a factory is the movement of the longitudinal and transverse elements in the transport to the construction site and the subsequent assembly to its final position (Devine et al., 2018). Therefore, the tie given to the bars with the stirrups must be carried out with due care to avoid the bars' final spacing that does not violate any standard or affect the structural stability of the element.
- In the case in which the pre-assembly is carried out on the same land as the building or infrastructure project, space will have to be assigned to carry out this work (this is not a problem if the work is outsourced to a subcontractor with his workshop) (Espinoza Conislla, 2012).
- Another problem that could arise is that the design of the PRC is not compatible with those delivered by the supplier. This is due to issues with blueprint readings and poor communication between stakeholders. Fortunately, this can be identified in advance and avoided through collaborative work management (Acevedo Díaz, 2009).

Maciel and Corrêa (2016) state that deficiencies in steel cutting and bending in pre-assembly factories may be related to poor management, communication, and information exchange between stakeholders, and steel designers, builders, and manufacturers. It is necessary to manage this industrialized construction process in a more collaborative, efficient, and effective way, using Virtual Design & Construction methodologies detailed below.

VIRTUAL DESIGN & CONSTRUCTION (VDC)

The main components of VDC are the following:

a) Client and Project Objectives

Both the client's and the project's objectives must be aligned to meet the goals. The VDC framework makes teams focus on determining the desired performance of the task and the total cost as a whole. In addition, the project must be considered usable, buildable, operable, and sustainable (Rischmoller et al., 2018).

b) ICE (Integrated Concurrent Engineering)

ICE is derived from the so-called "External Collaboration" methods, an initiative carried out by NASA's Jet Propulsion Laboratory (JPL). For Chachere et al. (2009), ICE works as a methodology that overcomes the traditional isolated way of working. This component applies engineering analysis, along with communication and decision making.

c) BIM (Building Information Modeling)

For Qi et al. (2018), the main essence of BIM is information management and project visualization. This contains certain information in detail and with a higher integration of all the specialties. These details make transparent communication between stakeholders possible. On the other hand, it is stated that the main reason for this information management is to help decision-making by the work team and other stakeholders, which ensures that all project information is always available.

d) PPM (Project Production Management)

There are three general dimensions cataloged as problems within this industry in all construction projects: stakeholders, the organization of the internal activities of the work team, and governance. For this topic, Lean Construction encompasses these three dimensions and is complemented by PPM, whose scope focuses on both the organization and the activities of the project teams. This component focuses on controlling the tasks (to improve time, cost, and quality) or actions of the work in each project and its organization. PPM delves into the achievable limits of the job functions to be carried out and ratified in several possible scenarios. It also optimizes performance, work processes, and capacity through specifically defined parameters to improve costs, time, and the defined scope of the projects (Shenoy, 2017).

e) Metrics

Metrics are based on milestones to give a better and more consistent view of the project. This generates a higher probability that the teams involved will complete the project more efficiently on budget and schedule while maintaining the quality of the work (Majumdar et al., 2022). This must be translated according to the client's and project's objectives for use, functionality, and sustainability in quality, health and safety, cost, and time (Belsvik et al., 2019).

In general, VDC methods demonstrate different benefits, such as better visualizing the project and integrating information to forecast the project's results and manage performance and expected outcomes (Hassan et al., 2018).

METHODOLOGY

This research is based on a quantitative approach. The literature is reviewed, and a theoretical perspective is built to support the data collected from a case study. From this, the data was evaluated through the production metrics.

Study Area

Information related to the Ovalo Monitor Bridge project in Lima, Peru, has been compiled to carry out this work. As shown in Figure 1, this work was developed at the intersections of the avenues Palmeras - Javier Prado Este - Golf de Los Incas (Ovalo Monitor) that involve the districts of La Molina and Santiago de Surco, having a projection of about 2 kilometers.

Figure 1: Aerial view of the in-development Ovalo Monitor Bridge project (Google Earth, n.d).

Stages, processes, techniques, and tools used for the research

1. In the first stage, a bibliography inquiry was carried out in internet-based sources regarding the keywords relevant to the research topic. These were "VDC," "bridges," "prefabricated reinforcement," and "rebar cages." This search was done primarily in the Scopus and Web of Science databases and other sources such as institutional repositories of universities. Based on this information, the approach to the research problem, justification, and background of the work was developed.
2. Then, in the second stage, we focused on data collected from the Ovalo Monitor Bridge Project in Lima, Peru. This is a project managed with VDC and built with PRC. The level of industrialization (prefabricated reinforcement cage) was monitored between January 2021 and January 2022 (initial coordination of work and pre-design, design, construction, and assembly), as follow:
    - Collection of agreements and observations with the client regarding the prefabricated reinforcement cage and its delivery times.
    - Collection of changes in the design related to the use of reinforcing steel (PRC).
    - Collection of the industrialized parts of the project supported by the BIM model.
    - Collection of the percentage of industrialization concerning the entire project and by structural element.
    - Collection of client's and project's objectives to develop the VDC Framework of the project.
3. In the third stage, this information was used to identify the benefits of industrialization over a traditionally built and managed project through data processing and analysis. The metrics used are described in the next section.
4. In the fourth and last stage, the research work results, discussions, and conclusions are presented.

RESULTS AND DISCUSSION

The data collection structure consists of monthly data tracking production metrics and controllable factors according to the VDC application for the Ovalo Monitor Bridge project. The following VDC Framework was proposed based on the information collected.

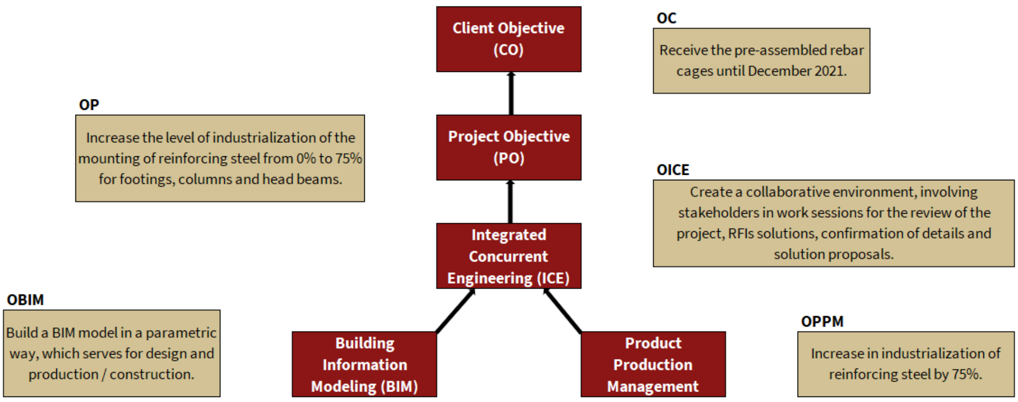

Figure 2: VDC framework proposed for the Ovalo Monitor Vehicular Bridge project.

This framework was developed according to the client's objectives, project, ICE, BIM, and PPM. The project's production metrics and controllable factors were developed in Table 1 to provide an adequate follow-up of the VDC implementation in the design, construction, and assembly of pre-assembled rebar cages (PRC).

Table 1: Production metrics and controllable factors (ICE, BIM, PPM).

Objective	Metrics	Goal
PM_ICE: Facilitate and integrate the activities and tasks of the teams involved in charge of the project (delivery of PRC elements).	$\%PPC = \frac{\#\text{Activities completed}}{\#\text{Total activities to be completed}} \times 100$	100%
CF_ICE: Promote the participation of all teams involved in each ICE session.	% Attendance at each ICE session	100%
	Frequency of ICE sessions	2 per month
PM_BIM: Measure the scope of the BIM model to quantify the elements that will be preassembled.	$\%PM = \frac{\text{PRC to be modeled in BIM}}{\text{Total elements modeled in BIM}} \times 100$	100%
CF_BIM: Define LOD to be used.	Minimum LOD required	350
PM_PPM: Reduce the construction time of the structural item by 25%.	% Reduction Time	≥ 25%
PM_PPM: Increase the level of industrialization of reinforcing steel assembly in the substructure by 75%.	% of industrialization	≥ 75%
CF_PPM: Follow up on weekly progress.	# Weekly progress monitoring review days	1 per week

%PPC: Percent Plan Complete
%PM: Percentage Modeled
LOD: Level of Detail

From ICE, we registered the comments and the agreements with descriptions of the information related to incompatibility, conflict points, and proposals for improvements. To overcome the identified issues, ICE sessions were conducted with the support of a collaborative environment and the assistance of the stakeholders. Figure 3 presents the production metrics and controllable factors from January 2021 to January 2022.

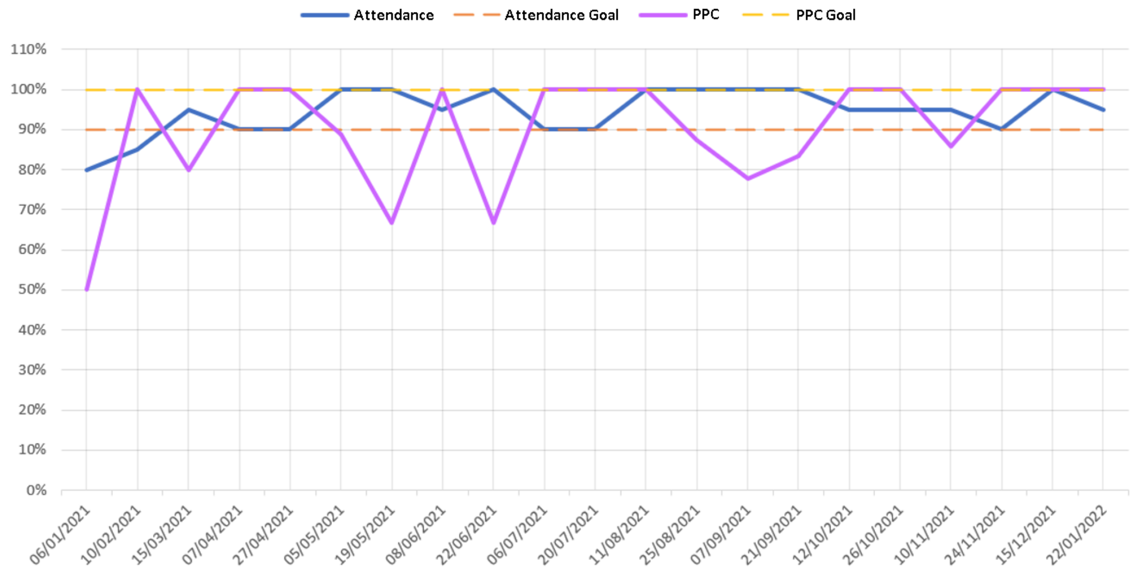

Figure 3: Production metric and controllable factor for ICE: Attendance and %PPC.

Figure 3 shows 80-100% attendance across all ICE sessions held in 2021 and 2022, with an average of 95%. With 72 queries received, 100% of them have been resolved. These queries discussed in ICE sessions were noted and monitored, classifying them by the type of change required by the project. This list of observations was directly related to the ICE metrics and controllable factors identified in Table 1. There was a focus on the resolution of comments and on reducing the response time of those decisions.

Concerning the BIM component, in Figure 4, all PRC proposed elements were modeled with a minimum LOD 350. The modeling of each section of the structural item of the Ovalo Monitor Bridge was obtained, and the LOD 350 and 400 were developed as follows. For Section 1, the modeled time was from April 19th to September 6th, 2021. For Section 2, from July 5th to November 22nd, 2021. For Section 3, from July 12th to November 29th, 2021. For Section 4, from August 8th to December 22nd, 2021.

Each section consists of a partial milestone in the bridge's 870-meter length (going from west to east). A breakdown for each structural element preassembled was 100% available for all stakeholders to visualize and understand each element.

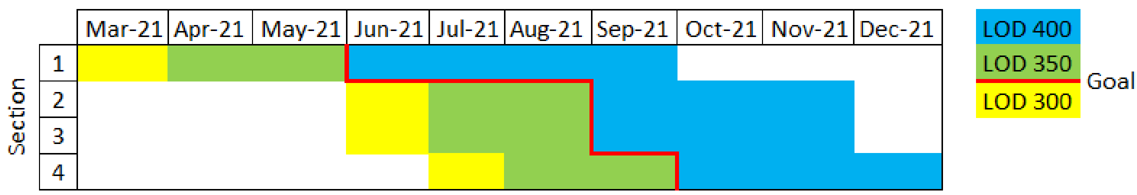

Figure 4: Controllable factor for BIM: BIM model progress based on LOD requirements.

The Level of Detail refers to the level of detail that a BIM model needs depending on the focus of the work. The LOD 350 required as a minimum refers to a level of detail of the precise BIM model that must be used to carry out the PRC (Hinostroza Quilli & Romero Falcon, 2019). This is to compatibilized the information of the blueprints that were made in the BIM models.

Figure 5 shows that the time saved in the structural item by using PRC elements and implementing a VDC framework was 31%. This was thanks to the appropriate use of the tools provided by each VDC component. The BIM models helped to visualize better the PRC elements that would be pre-assembled. The ICE sessions promoted collaborative meetings to carry out the necessary consultations among the stakeholders and to be able to resolve these consultations in less time, which helped to make better decisions in less time. PPM provided an improvement in terms of detailed tracking of the progress of PRC elements to know their status for each week of progress (Look Ahead).

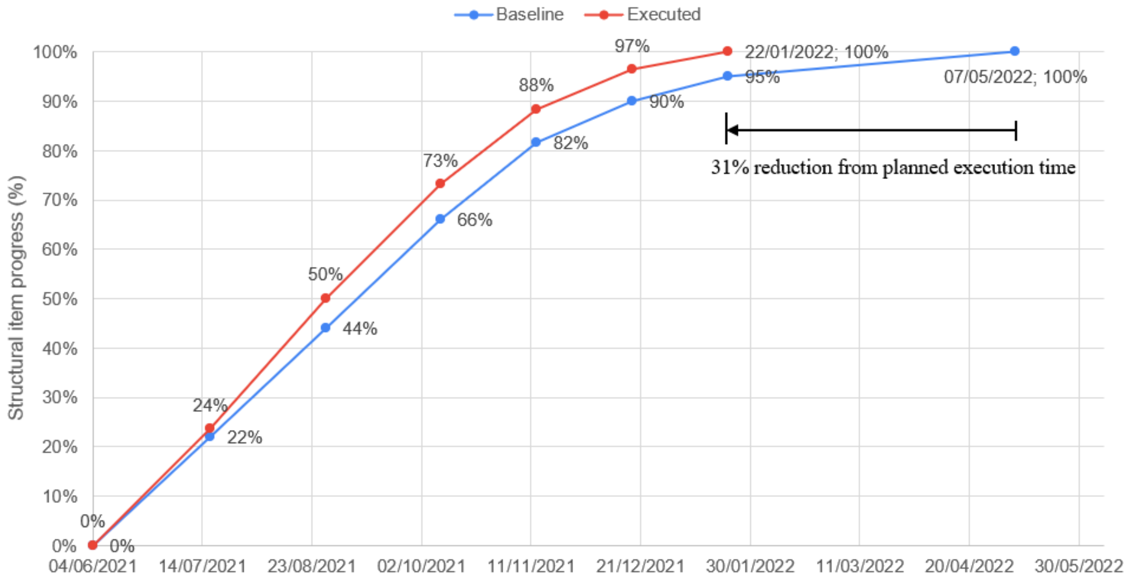

Figure 5: Production metric for PPM: Reduction Time (%) in structural item supported in PRC elements.

Figure 6 shows the percentage of industrialization of the preassembled elements for each type of structure (substructure and superstructure) over time for the PPM component. 85% was reached for the substructure, exceeding the industrialization goal for the elements that compromise this structure: footing, column, and header beam. Also, it is possible to visualize how this percentage has increased over time, which has helped reduce the assembly of these elements in the field.

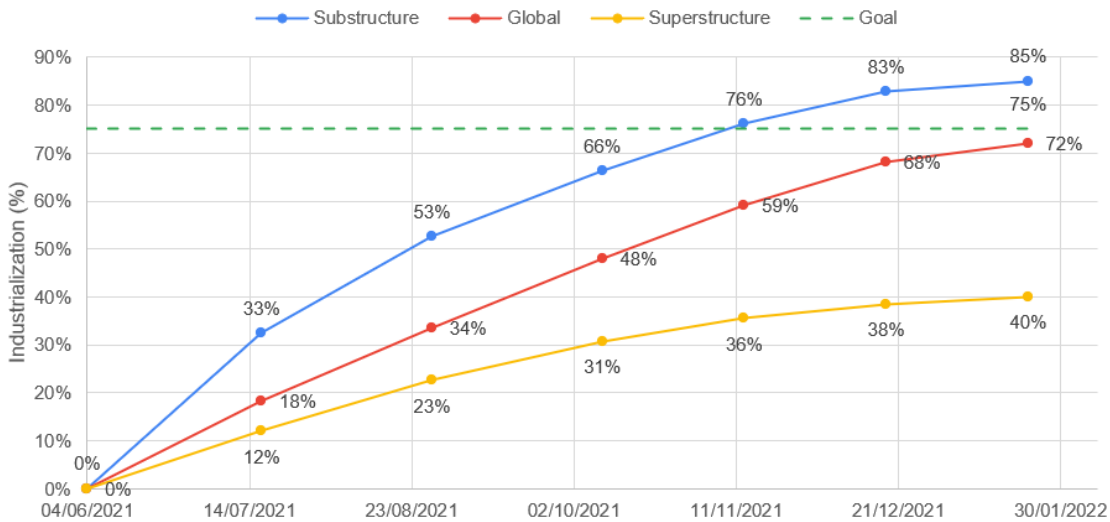

Figure 6: Production metric for PPM: Industrialization (%) based on steel weight (ton).

A 75% industrialization target was defined as an action to reduce project execution time. This percentage is measured according to the weight (ton) of the PRC elements that will be pre-assembled concerning the total reinforcing steel intended to be used.

According to Porras et al. (2014), Lean Construction is considered a philosophy oriented to production management in the construction sector. Its primary objective is to reduce or eliminate tasks or activities that do not add value to the project. In this way, PPM helps meet the Lean objectives of focusing on ridding activities or processes that do not generate value for the project. Table 2 shows a follow-up of the overall progress of the PRC-related activities to the Ovalo Monitor Bridge project, which allowed the value-adding and waste-reduction monitoring of the project to take place. The goal was to do a weekly follow-up throughout 2021 and the beginning of 2022. Only six weeks were missed in the entire period.

Table 2: The controllable factor for PPM: Follow up on weekly progress.

W/M	1	2	3	4	5	6	7	8	9	10	11	12	13
1	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓
2	✓	✓	✓	✓	✗	✓	✓	✓	✗	✓	✓	✓	✓
3	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
4	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	
5			✓			✓			✓			✓	

W: Week (rows)
M: Month, from January 2021 to January 2022 (columns)

CONCLUSIONS

The results discussed in this research showed that the VDC methodology, in conjunction with the industrialization of the structural construction process, brings time-saving benefits to a construction project, as was the case study: the Ovalo Monitor Bridge in Lima, Peru. The time saved concerning the assembly and installation of prefabricated reinforcement cage elements was 31%, close to the 27% found by Devine et al. (2018).

The industrialization percentage of 85% for the superstructure (footing, column, header beam) was measured up to January 2022, overcoming the 75% target defined in the project's objective. This was due to the involvement of the leading stakeholders in the ICE sessions to propose constructability improvements and resolve observations regarding the detail of the PRC elements.

With BIM integrated into the VDC framework, the prefabricated reinforcement cage elements were ordered with exact measurements, eliminating any issue related to change orders. In addition, all elements were prefabricated from the information provided by the BIM model, with zero rework. This also helped the stakeholders better understand what was to be prefabricated and assembled on site.

PPM provided weekly monitoring of the progress of the PRC elements deliveries, which allowed to improve this process and make better decisions as the project progressed.

Finally, implementing collaborative management and industrialized construction methods can minimize rework and reduce time compared to traditional approaches.

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ADDRESSING WASTE DURING THE DESIGN PHASE: A MATRIX MODEL FOR THE INTERACTIONS BETWEEN ROBOTIC SYSTEMS AND LEAN PRINCIPLES

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ABSTRACT

This paper aims to provide a visual model with design parameters that are specific to manufacturing to reduce waste in the design stage of a construction project. More construction companies are interested in reducing waste and increasing efficiency. However, one of the main barriers that prevent the construction industry from adopting more technological solutions for its projects is not being clear about the direct benefits that would be obtained. This paper proposes using design parameters applied in a user-friendly visual model to choose the benefit to obtain for designing a construction project. These benefits are displayed as key performance indicator (KPI) options for the construction project. An analysis was carried out in a matrix to obtain the most relevant design parameters for a robotic cell in offsite construction from a manufacturing (not architectural or visual/aesthetic) point of view. Additionally, the visual model is designed using a data visualization structure. The limit of the investigation involves not having the visual tool validated in a case of a real construction company. Additionally, the visual tool is only a guide that is not quantified.

KEYWORDS

Key Performance Indicator, Design parameters, Construction industry, Lean, Industry 4.0.

INTRODUCTION

Errors and inconsistencies in the design are the most frequent factors contributing to the generation of waste in construction projects (Bajjou & Chafi, 2021). The efficient use of project resources depends mainly on the decisions made at the design stage (Sfakianaki, 2015). In an industry as competitive as construction, to survive, it is recommended to use

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new design technologies to consider environmental issues (e.g., environmental deterioration) at the design stage (Bajjou & Chafi, 2021).

Being an industry that involves projects of such great magnitude, such as buildings or hospitals, among others, that require so much labor that the traditional way of carrying out construction is no longer enough to meet the delivery of quality projects on time (Huang et al., 2021). Causing late delivery of projects that end up exceeding both budget and waste levels (Ofori-Kuragu & Osei-Kyei, 2021). The construction industry is being pushed to modernize and become more efficient (Bogue, 2018).

A technological advance that benefits quality and, at the same time, increases efficiency and reduces waste involves both robots and the application of lean principles (Huang et al., 2021). This combination allows a paradigm shift in the construction sector by introducing technologies that work together to eliminate waste (Ramani & KSD, 2019).

Robots play a crucial role in overcoming the limitations of traditional construction. Its use has several benefits: (a) reducing waste, (b) speeding up processes, (c) reducing costs, and (d) reducing production dependence on human labor (Bogue, 2018). The use of robots in offsite or on-site construction production frees up workers' time to focus on more value-added activities for the process (Gusmao Brissi et al., 2021).

The application of lean principles in the construction industry encompasses the benefits of (a) minimizing construction waste, (b) increasing customer satisfaction, (c) higher productivity and reliability, and (d) more safety (Khaba & Bhar, 2017). This application includes a wide range of techniques such as just-in-time, six sigma, and pull planning that is related to (1) design and engineering, (2) planning and control, (3) construction and site management, and (4) health and safety management (Gusmao Brissi et al., 2021).

The main problems architects/managers face in the design stage are last-minute changes by the client, followed by design changes and detailing errors. Which ends up using more time to develop the project and a huge generation of waste (Olanrewaju & Ogunmakinde, 2020). It is important to note that making bad decisions at the design stage results in a significant increase in the amount of waste that will be generated throughout the project (Othman & Abdelrahim, 2019).

On the other hand, one of the main barriers to countering the problem of waste generation at the design stage is the lack of construction waste minimization training and waste accepted as inevitable. As a result, we will concentrate on the design stages of a construction project since it is one of the most challenging where it is required to have a good level of adaptability to adjust to the changes requested by the client without this representing an increase in the waste levels of the project (Olanrewaju & Ogunmakinde, 2020).

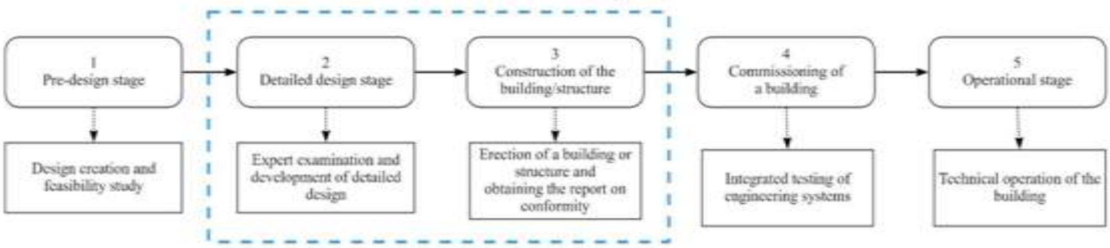


Figure 1: Sequence of construction phases, adapted from (Topchiy & Kochurina, 2018).

The relationship between waste and efficiency during the design stage of a construction project has not yet been clarified when linked to the outcomes that are expected from the building. Therefore it is not evident which path needs to be followed to meet the project's outcomes while facing the previously mentioned challenges regarding last-minute changes without causing errors and reducing important related factors such as waste in the construction operations during the design phase. As shown in Fig. 1, steps 2 and 3 are the focus of our process, these construction phases start as a linear sequence, but in the two previously mentioned steps it is where they go back and repeat themselves due to last-minute modifications, which are costly and wasteful. The objectives of this project are: (a) The definition of the relationships between design parameters of the robotic cell and processes derived from KPIs of manufacturing processes. (b) The outcome of a matrix model is linked to a system through a visual tool. This implementation aims to validate the presented approach and open the discussion of addressing construction waste during the design phase.

METHODOLOGY

The presented research study is based on the findings reported in (Gusmao Brissi et al., 2021) on the interactions between robotic systems and lean principles (Gusmao Brissi et al. 2021). The authors performed a systematic literature review to identify the journal papers that addressed the interactions between automation and lean, then focused on the under-researched topic of robotic systems. This allowed the categorization of construction automation and the presentation of the different interactions between lean and robotics in a matrix.

Table 1: Integration of the interactions of the lean and robotic system following the methodology adapted from (Gusmao Brissi et al., 2021).

Principal area	Approach
Eliminate waste	*Reduction of waste during the design phase* Reduction of construction waste through the application of the analysis result shown by the interactive visual tool in the construction project.
Flow process	*Increased flexibility* Increase of design adaptability in last-minute changes through the dynamics of the visual tool where the user can change a specific parameter and in real-time receive an update of what other parameters must be reduced or increased in order to continue meeting the selected KPI.
Value generation process	*Ensuring accurate design parameters capture* Use of established design parameters that cover the different data that are needed to be able to fulfill a KPI.
Problem-solving	*Evaluate parameters decision* Decision by consensus, consideration of all options (reduction and/or increase of a design parameter) in order to define what is the best decision for the development of the construction project.

It was argued that the interactions between lean principles and robotics were more noteworthy in the manufacturing stage and on-site construction phases; however, it should enhance construction operations from the design phase of the construction project. This study explores the methodology used by Gusmao Brissi et al., describing in more detail the interactions described between lean and robotic systems as a matrix (Gusmao Brissi et al., 2021). The developed approach is then implemented in a robotic cell in an offsite manufacturing environment for producing the required panels for a construction project during the design phase. Table 1 summarizes the presented approach from a lean perspective following the reported methods.

ROBOTIC SYSTEMS AND LEAN INTERACTIONS - MATRIX MODEL

As aforementioned, a matrix model is proposed to describe how the design parameters (DP) for a robotic cell in offsite construction interact with major lean wastes (LW) that are applied to the pre-defined key performance indicators (KPI). This project is not focused on the initial design of the product but on the part of the design for manufacturing of construction components. This matrix is an initial proposal covering a series of parameters related to robot selection criteria, cell requirements, and lean wastes; but does not try to be a comprehensive list of all the possible design parameters as that task could prove itself gargantuan.

Table 2: List of the design parameters and lean wastes used for the matrix model in this study.

Robot selection criteria	Production requirements	Cell requirements	Lean wastes
D1 – Robot payload	D6 – Time in of the input material	D15 – Area of the robotic cell	L1 – Inventory wait time
D2 – Robot accuracy and reach	D7 – Cycle time for each process in a station	D16 – Total number of robots in the cell	L2 – Transport time
D3 – Robot speed	D8 – Changeover time	D17 – Number of tools used by a specific robot	L3 – Non-value-added motions
D4 – Number of axes of the robot	D9 – Idle time	D18 – Tool accuracy	L4 – Robot(s) idle time
D5 – Robot linear motion speed	D10 – Stock size of the product	D19 – Total number of tools used to produce one unit	L5 – Defective parts - rework
	D11 – Size of the product	D20 – Distance between the stations	L6 – Defective parts moved to scrap
	D12 – Scheduled maintenance time	D21 – Traveling speed of linear motion systems	L7 – Material waste produced
	D13 – Minimum number of cycles required per day	D22 – Total number of operations required to produce one unit	L8 – Over-processing
	D14 – Scrap removal time for one cycle	D23 – Total number of workstations	L9 – Underutilizing the robot capacity
		D24 – Path efficiency	L10 – Machine downtime
		D25 – Number of operations required for providing the input material	

The design parameters are classified into three categories: (a) robot selection criteria, (b) production requirements, and (c) cell requirements. The design parameters and lean wastes are identified through previous exhaustive literature reviews and observations of industrial robotic cells. One of them is later used as a case study. A list of the design parameters is provided in Table 2 alongside the major lean wastes targeted for this study.

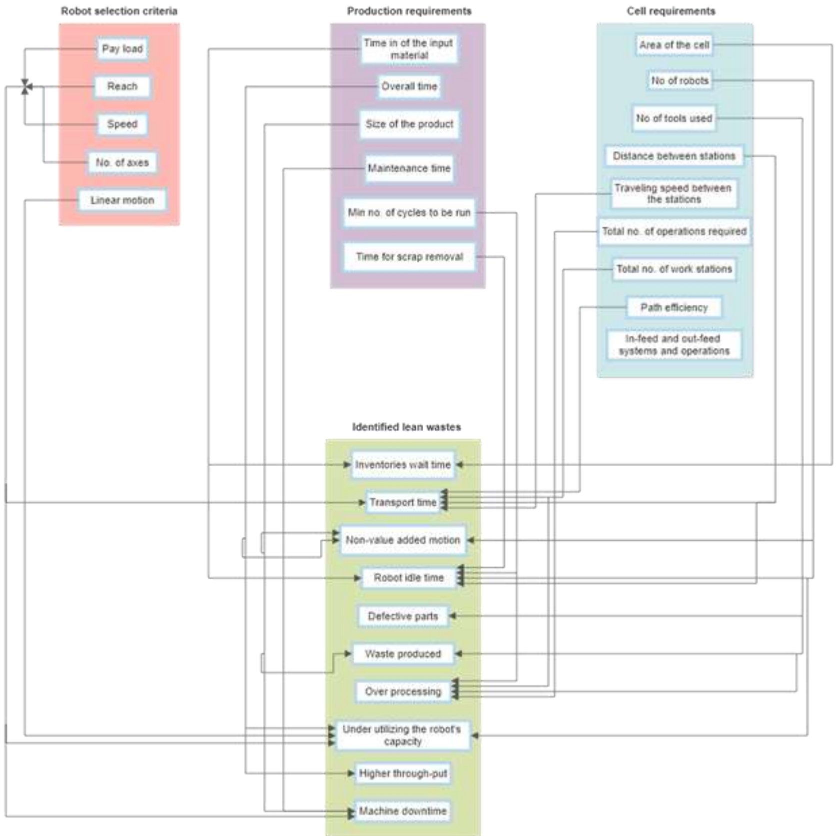
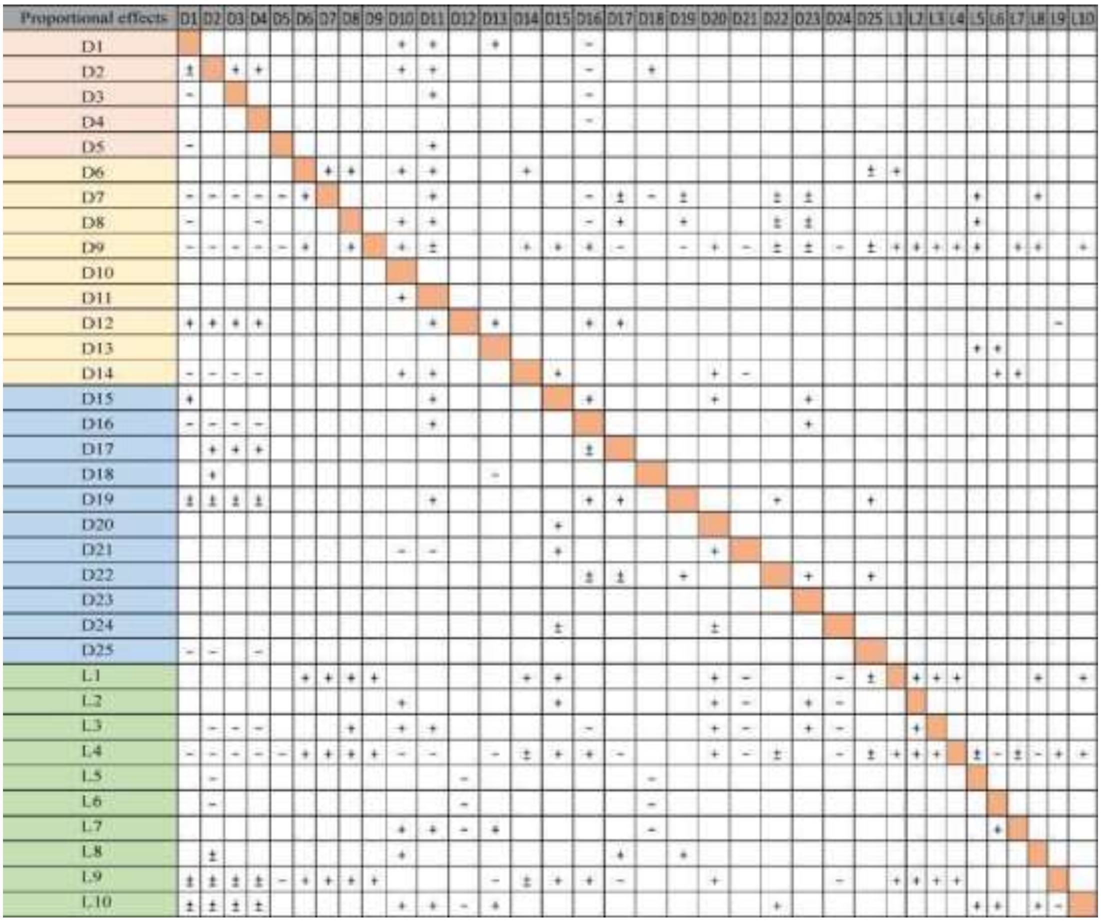


Figure 2: Various effects of design parameters on lean waste.

The matrix model then represents how the different parameters and lean wastes interact with each other on a one-on-one basis. Figure 2 shows the internally generated links between all the design parameters and the lean wastes. Figure 3 illustrates the model generated for the parameters in Table 2. This model determines how the different parameters influence others; the "+" symbol represents a positive interaction (e.g., proportional increments), whereas the "-" symbol represents an inverse interaction. A blank space represents that there is no known effect or correlation between parameters, and, in the case of a "±" symbol, it indicates that a known effect is known but is either not measurable or variable; therefore, it changes its interactions depending on the conditions of the other parameters.



Proportional effects	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20	D21	D22	D23	D24	D25	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10
D1										+	+		+			−																			
D2	±		+	+						+	+					−		+																	
D3	−										+					−																			
D4																−																			
D5	−										+																								
D6							+	+		+	+			+											±	+									
D7	−	−	−	−	−	+					+					−	±	−	±			±	±							+			+		
D8	−			−						+	+					−	+		+			±	±							+					
D9	−	−	−	−	−	+		+		+	±			+	+	+	−		−	+	−	±	±	−	±	+	+	+	+	+		+	+		+
D10																																			
D11										+																									
D12	+	+	+	+							+		+			+	+																	−	
D13																														+	+				
D14	−	−	−	−						+	+				+					+	−										+	+			
D15	+										+					+				+			+												
D16	−	−	−	−							+												+												
D17		+	+	+												±																			
D18		+											−																						
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D22																±	±		+				+		+										
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D24															±					±															
D25	−	−		−																															
L1						+	+	+	+					+	+					+	−			−	±		+	+	+				+		+
L2										+					+					+	−		+	−											
L3		−	−	−				+		+	+					−				+	−		+	−			+								
L4	−	−	−	−	−	+	+	+	+	−	−		−	±	+	+	−			+	−	±		−	±	+	+	+		±	−	±	−	+	+
L5		−										−						−																	
L6		−										−						−																	
L7										+	+	−	+					−													+				
L8		±								+							+		+																
L9	±	±	±	±	−	+	+	+	+				−	±	+	+	−			+				−		+	+	+	+						
L10	±	±	±	±						+	+	−	+									+								+	+		+	−	

Figure 3: Matrix model describing the interactions between the design parameters and lean wastes selected.

For example, looking at the first row of Figure 3, the representation indicates that when parameter D1 is considered, design parameters D10, D11, and D13 are conditioned to proportionally behave in the same sense, i.e., an increase in D1 means an increase in D10, D11, and D13, while the inverse relationship can be observed with parameter D16. Similarly, suppose an increment is chosen for the parameter D2. In that case, it is expected that D3, D4, D10, D11, and D18 will also increase, whereas D16 will decrease, and D1 will be surely affected, but it is not possible to determine in which way.

Note that for the parameters that do not contain any symbol on them on each row, it means that a change in that specific parameter does not have a meaningful impact on those parameters. In that sense, one can identify parameters that are more "risky" or "interesting" as some change has an impact on many other parameters while others may be easier to control as changes may impact one or two parameters. In that sense, this matrix model enables designers to understand the implications of design decisions regarding robotic systems and their impact on waste. Therefore, construction companies will benefit from having this information to make the best decisions for the development of their projects.

MODEL VISUALIZATION

In order to facilitate the use of the matrix model in a more interactive way for designers and practitioners, a dashboard is designed that integrates the model information and allows designers to include their end goals for redesign or specific target areas of improvement. The model is then linked with an interactive dashboard for a user-focused approach to robotic system redesigning. An interactive visual tool is developed through Dash Plotly, which is a structure for building data apps in Python (Plotly, 2022) to test parameters' dynamics based on user input.

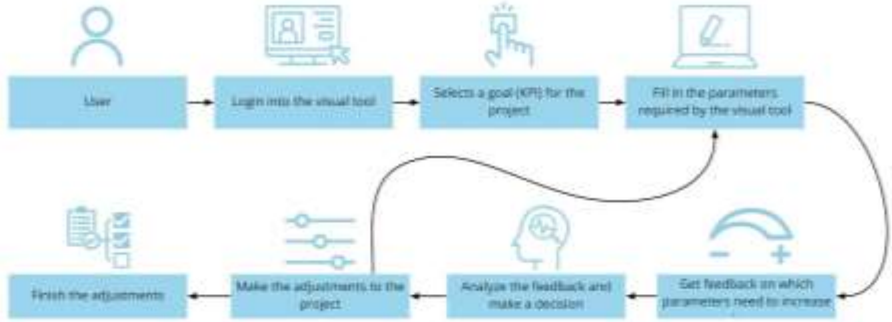

Figure 4: Steps to use the visual tool from the user perspective.

The interface is divided into two sections: the top side includes all the information related to user preferences and design goals. For example, a design analysis could be performed to target specific pre-defined objectives, such as: (1) minimize overall time, (2) maximize productivity, (3) minimize defects, (4) minimize the overall material waste produced, or (5) minimize overall waste, among other options.

Given a specific design goal, the user can choose which parameters are affected by the design changes, e.g., if the designer decides to pick a bigger size robot, then the design parameter D2 (related to the robot reach) can be assumed to increase. The design parameters previously listed in Table 2 are presented to the user to immediately have an answer to which parameters are directly affected by that change following the matrix model. Following that, the impact on the waste-related KPIs is presented, summarizing which wastes are being targeted by the redesign proposal and which areas can be further improved.

In summary, the dashboard allows the user entering the visual tool to choose the KPIs they want to focus on. Once the KPIs are selected, the design parameters that directly affect the selected KPIs are displayed for the user to enter the corresponding data. Once the data is received, the visual tool gives the user feedback on the design parameters that change following the matrix model and suggestions on further improvements to achieve redesign goals for the selected KPIs.

CASE STUDY

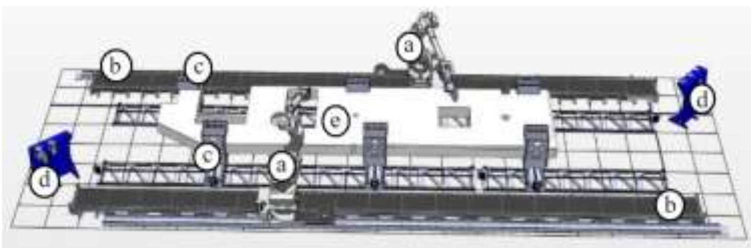

Figure 5: Automated robotic machining cell for cross-laminated timber panels. (a) Robot ABB® IRB 7600; (b) Track motion ABB® IRBT 7004; (c) Flexible clamping System; (d) Tool stand; (e) Minimum viable product (taken from Villanueva et al., 2021 with permission).

To validate the proposal, the redesign of an automated robotic machining cell for cross-laminated timber panels is used (Villanueva et al., 2021). This redesign aims to increase the robotic system's productivity, quality, and flexibility. Figure 5 shows the representation of the automated robotic cell, consisting of two robot arms that are positioned side by side on top of the track motion system allowing them to reach all areas of the workpiece. The design is simulated in @RobotStudio (design and simulation software), and the design parameters used for the design project are utilized as the input information to test the interactive dashboard.

Figure 6: Visual tool when selecting an objective.

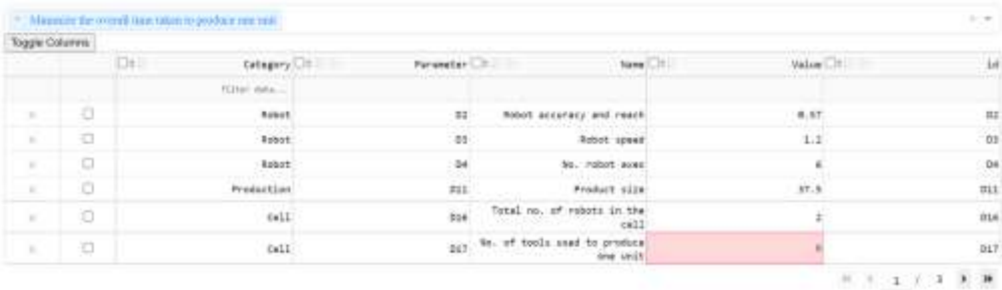

Figure 7: Visual tool with design parameters data table.

The first step was to select an objective to be addressed; in this case, KPI (1) related to minimizing overall time was selected, and subsequently, as shown in Fig.6. Subsequently, the dashboard displayed the design parameters that were conditioned to reach the chosen goal: D2, D3, D4, D6, D7, D8, D9, D10, D11, D14, D15, D16, D20, D21, D23, and D24, this can be found in Fig.2. Once these parameters were displayed, the design parameters that the project did have were filled in, where D1= 500kg (non conditioned parameter), D2 = 0.57mm, D3 = 1.2m/s, D4 = 6, D11 = 37.5m2, D16 = 2, D17 = 6, D23 =1. Once the data was provided, the feedback received specified that parameters D2, D3, D4, and D16 must decrease; indicating that the robot accuracy, reach, speed and the number of robots and robot axes considered for the design stage of the construction project should be reduced. Furthermore, it suggested that D11 must increase, stipulating that the construction panel/product should be expanded to achieve the KPI of Minimizing overall time for the project.

DISCUSSION

Using the proposed user-friendly visual tool for construction projects implies benefits where the user can directly understand the benefits that it can have for the project, and in the same way, he/she can decide what benefit he/she wants to obtain by selecting the KPI that most interests him/her for the project during the design stage that is manufactured in a robotic cell, and in this way evaluate the recommendations obtained. Additionally, the use of this interactive dashboard provides the characteristic of adaptability in the construction projects where it is used; if the project needs a change by the client, they only have to enter the new data in the dashboard to obtain what other parameters should be increased or decrease to continue meeting the objective selected for the project.

In this way, having to deal with last-minute changes by the client will no longer have such a significant impact on the project's development since immediate recommendations on how to act will be obtained. For example, if there was a last-minute change involving a different dimension from the panel for the construction project and the selected objective is "Minimize the overall time taken to produce one unit", the user only has to access the visual tool, update that parameter (D11: Product size) and the visual tool will automatically give feedback on which parameters need to be increased or reduced to continue meeting the initially selected objective. This means that the response time to know how to restructure the project properly will be fast and precise, avoiding, for example, the time and material waste involved in carrying it out.

The limitations of this application involve that the correlations used individually do not lead to waste reduction at any time because it is a decision/support that is based on something that is not quantified because the proposal is only a guide. This matrix needs to be used in simulation models to validate quantifications and decision-making. Additionally, other limitations involve not having a validation directly with real construction projects. In the same way, it is necessary to provide a specific range or percentage of how much it is necessary to reduce or increase each parameter recommendation feedback. Moreover, it is also needed to provide the user with a percentage of how close they were to the KPI selected by following the visual tool's recommendations.

CONCLUSION

The construction industry is undergoing a slow transformation but with an interest that has been growing over the last decade related to technology adoption (Ofori-Kuragu & Osei-Kyei, 2021). The industry has an important challenge where one of the barriers that prevent it from adopting new technologies is not being clear about the benefits that they will obtain by doing so, which is why when proposing the visual tool, it is expected that have a clear, direct benefit that the construction project will obtain, will encourage the construction industry to start to migrate to this type of digital solutions to increase efficiency and reduce waste in their projects. The proposed interactive dashboard is a highly visual solution that works as a guide to easily evaluate or re-evaluate the construction project design.

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HOW TO CHOOSE THE BEST MEDIA TO IMPLEMENT THE CHOOSING BY ADVANTAGES (CBA) TABULAR METHOD

Annett Schöttle[1], Paz Arroyo[2], and Randi Christensen[3]

ABSTRACT

Choosing by Advantages (CBA) applications in the construction industry have been growing over time and teams need to decide which tools they will use to facilitate and document a CBA decision. This paper aims to determine which criteria should be considered when deciding on the tool/media to apply the CBA Tabular method? Researchers analyzed four different tools: (1) analog, (2) spreadsheet, (3) digital whiteboard, and (4) CBA decision-making software. These four tools were selected based on direct experience of the authors on four case studies. Researchers also conducted a survey to expand experiences, collect information on alternatives, and identify factors and define criteria to help users to select the tool. The conclusion is that there is no-one-size fits-all solution, and the authors therefore encourage teams to choose the best tool that suits their context. This paper aims to help teams be aware of multiple alternatives and of the consequences that come with each tool.

KEYWORDS

Analog, choosing by advantages, collaboration, digital tools, decision-making

INTRODUCTION

When implementing CBA, users must decide which tool will be used to support the decision-making process. It is often argued that the most effective way to collaborate is face-to-face. Nevertheless, there are phases in a project where team members are not able to co-locate, e.g., a design team where the different parties are located across the world. For a virtual team to perform at a high level, it is necessary to apply digital tools that are easy to use (Hildebrandt, Jehle, Meister, & Skoruppa, 2014), and that help the team to have a productive conversation to be able to agree on a decision. Over the last couple of years, digital ways of working have become popular. Before the COVID-19 pandemic, most teams had the analog alternative available, but now most teams have found ways to work remotely. This has also allowed for more alternatives when it comes to choosing a

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medium or tool to support the decision-making process. Reviewing the IGLC publications, there are no papers comparing different media for CBA application. Thus, this paper compares the four tools: (1) analog, (2) spreadsheet, (3) digital whiteboard, and (4) CBA decision-making software based on cases and a survey to better understand the users' need to identify factors and define criteria to help the teams decide on the tool.

CBA TABULAR METHOD

CBA is a multi-criteria decision-making system developed by Suhr (1999) that differentiates between alternatives based on their advantages. The decision is structured in a logical and transparent way and uses a clearly defined vocabulary so that a group can objectively formulate and discuss the different decision criteria with minimal emotional interference (Schöttle & Arroyo, 2017; Schöttle, Christensen, & Arroyo, 2019). CBA isn't yet widely applied, but documented cases show that CBA provides a high potential to better understand the different preferences existing in a group. This is an important aspect when a project team has to make decisions collaboratively (e.g., in IPD projects). The most used and best-known method is the CBA Tabular method. Figure 1 shows the different steps of the Tabular method.

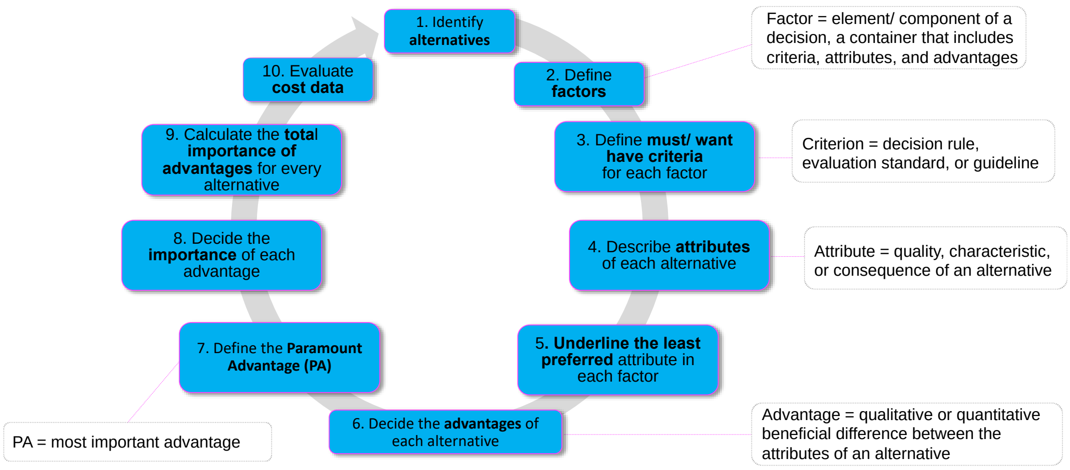

Figure 1: CBA Tabular method (Schöttle et al., 2019 based on Arroyo, 2014)

RESEARCH METHOD

This paper aims to determine which criteria should be considered when deciding on the tool/media to apply the CBA Tabular method. To differentiate between the alternatives, we identified factors and defined criteria to help users to select the tool. Therefore, a survey was carried out in February 2022 to collect data regarding the experience of CBA to a selected group. To ensure the level of experience with the correct implementation of the CBA Tabular method, the selection of participants was based on the following two factors: (1) participants were trained in the CBA Tabular method and (2) authors guided the participants in making a decision using the CBA Tabular method. After this, participants were asked to give feedback regarding their recommendation and were asked to specify which attributes a tool should have in order to make the use of the CBA Tabular method as easy as possible. The answers were reviewed based on content analysis (Mayring 2010). In total, 23 responses were submitted and analyzed. 29.2 % of the respondents were female and 70.8 % male. The number of moderators and participants was the same. The projects were located mostly in the USA, followed by Europe, South

America, and Canada (see Figure 2). The survey results are used to elaborate on the use and efficiency of the different tools.

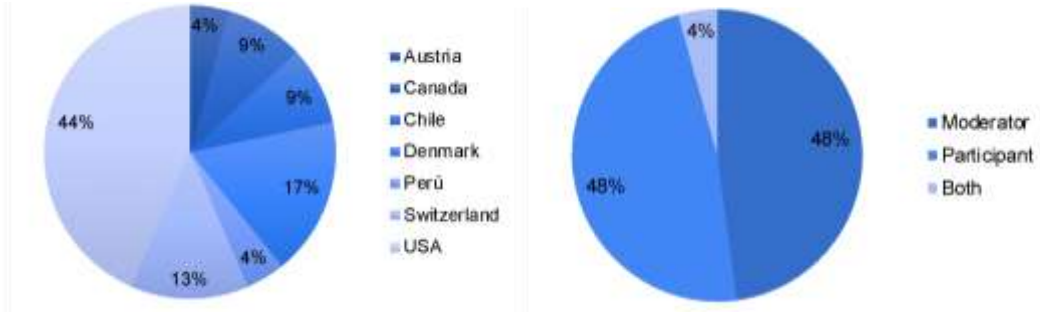

Figure 2: Background information of respondents

CASE STUDIES

The four case studies presented were cases where the author moderated different teams through a specific decision with the CBA Tabular method, and in all the first time for the teams. The cases give an overview of the four alternative tools used to support a CBA process: (1) analog (paper and sticky notes), (2) spreadsheet, (3) digital whiteboard, and (4) CBA decision-making software that the authors focused on in the questionnaire. The questionnaire was also sent to the participants of these cases.

CBA TABULAR ANALOG

The analog use of CBA with sticky notes on a white board or on paper has been documented in several case studies (e. g. Arroyo, Tommelein, & Ballard, 2013, Arroyo 2014). In this case, the team had to select acoustic ceiling tiles from a global and sustainability perspective. Figure 3 shows how the team was able to collaborate in the scoring of the importance of advantages. Here, the sticky notes are organized on a scale from 0 to 100. The team decided that the paramount advantage (PA) would be the acoustic difference of the ceiling tiles, since that impacted the acoustic isolation of the meetings rooms and would make the biggest difference in the usability of the space. Using this as the point of reference, each of the advantages were moved either up or down relative to the PA. The ability to physically move the sticky notes was appreciated by the facilitator and the team. Conversations about advantages were made openly face-to-face; assumptions of each team member were made explicit; and group conversations created a shared understanding of the importance of each advantage. Using sticky notes was an effective medium, as the team immediately understood the dynamic, and it was easy to learn how to use them.

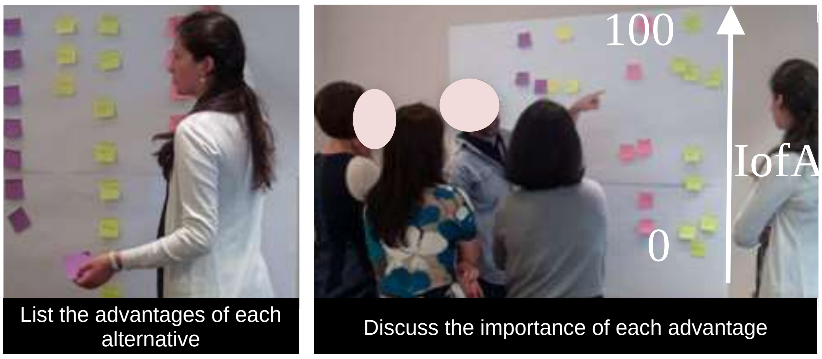

Figure 3: Image of working with the analog medium (Arroyo et al., 2013)

CBA Tabular Spreadsheet

In the following case, an Austrian General Contractor (GC) was selecting partners for a small Integrated Project Delivery (IPD) project in social housing in November 2020. The goal of the project was the development of a timber module that would fit the specific project and could also be used for future projects. The timber production line was the GC's own inhouse team. Regional small and medium-sized enterprises (SME) were interviewed to be partners during design development of the modules to optimize the production line and to produce the modules together not only for this project, but also for upcoming future projects. After explaining IPD to the different participants, interviews were conducted regarding the mindset of the potential team members. The information from the interviews were transmitted into the CBA Tabular format. The advantages where then determined, and the Importance of Advantages (IofA) assigned. Figure 4 shows the table and the scale of importance for the selection of the partner responsible for doors and windows. Using the Tabular method helped the GC to see the differences between trades in order to choose companies with a collaborative mindset. It also helped them to find solutions regarding capacity issues based on the size of the companies. For example, they brought two companies for the building equipment on board, which together developed the technical services.

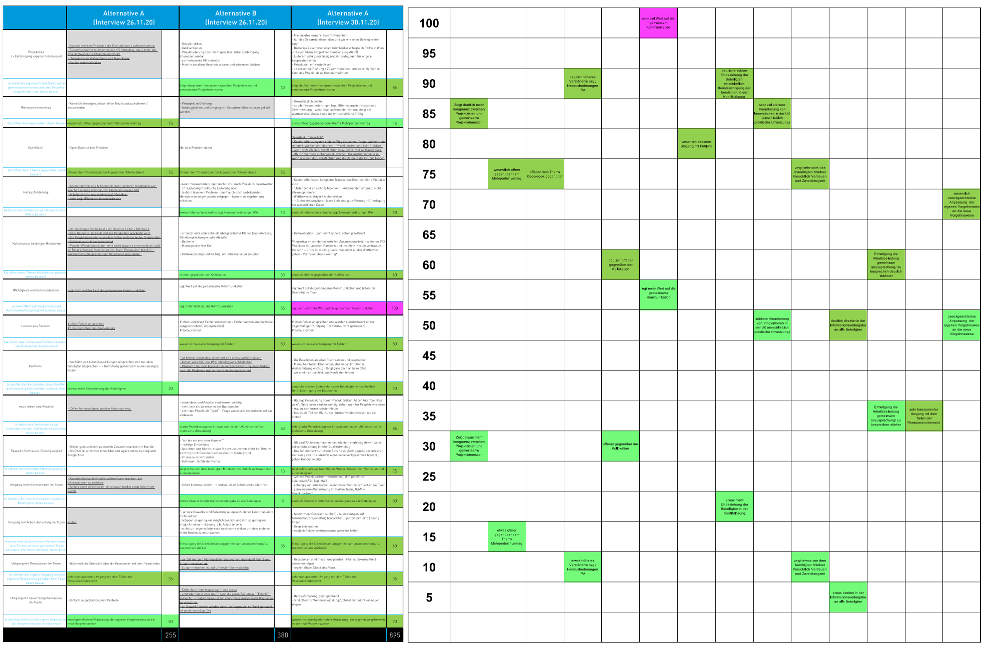

Figure 4: Image of the spreadsheet used to select the partner for doors and windows

CBA Tabular Digital Whiteboard

In this case study, a digital whiteboard was used to select the physicochemical process for a wastewater treatment plant. In separate sessions over a period of three months (January-April 2022), the Tabular was prepared with a small group of four people, including the Swiss public owner, and then discussed with a wider group. The decision initially consisted of eight alternatives, with 22 factors and 22 criteria. After defining the advantages and before assigning the importance through discussions and by seeing the differences, the team was able to reduce the number of factors and criteria to 13 (see Figure 5). The team was able to add and share information directly on the board, which helped them achieve a common understanding regarding attributes and advantages.

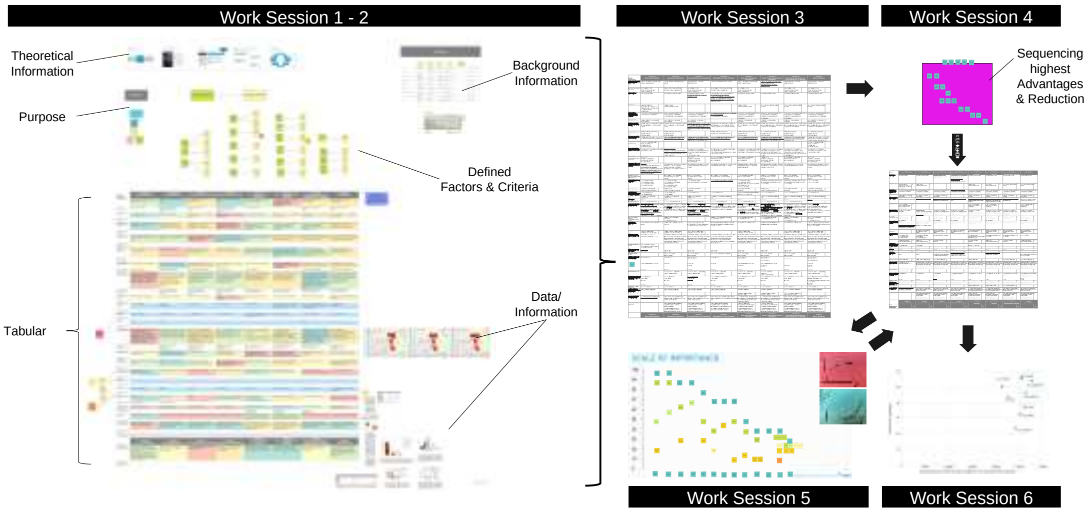

Figure 5: Image of the Digital Whiteboard for CBA Tabular use

CBA TABULAR SOFTWARE

Another way to document CBA decisions is through specialized software, such as Paramount Decisions. In this example the project team used software that helped them input CBA information step by step (see Figure 6). The inputs then are used to create graphics that summarize the decision. The decision was to choose a Demountable Glazing System for a partition wall in collaboration between the construction, design, and owner team. In this case, the GC team was introduced to CBA by an internal coach. One of the project engineers and the project estimator where particularly engaged, first understanding the CBA Tabular method and then learning how to use the software. The project engineer summarized the attributes of the alternatives, collecting four suppliers' information from a Request for Proposal (RFP). The GC team then asked the design team for additional factors to consider for aesthetics and functionality. Finally, the team met with the owner, presented an overview of CBA, and used the software scoring system to obtain the IofA from the owner's perspective. The last step was to make a decision by comparing the IofA with cost. The owner appreciated the team's preparation and transparency of the process, and the ability to separate cost vs. value. The software's reporting function was used to share this decision with the team.

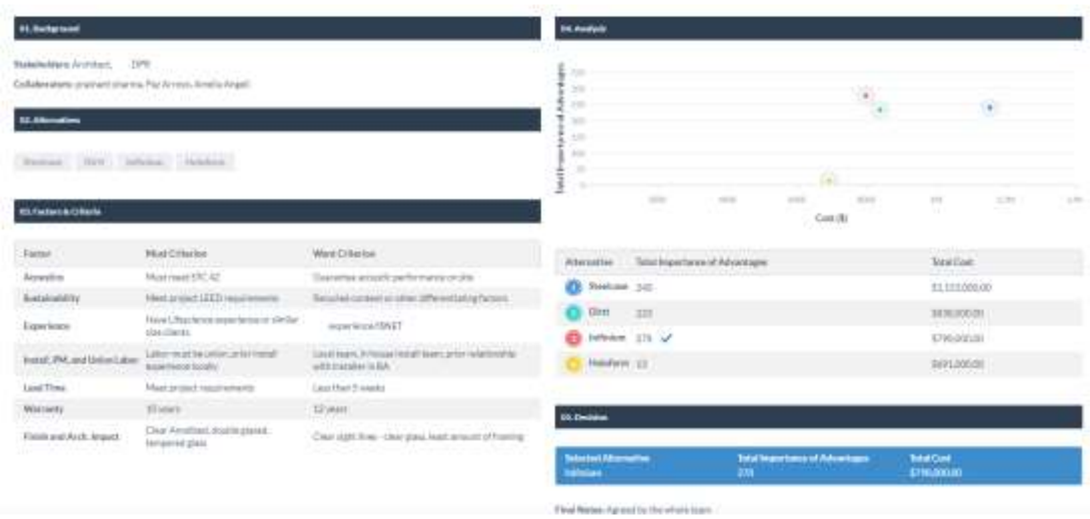

Figure 6: Image of choosing a demountable glazing system using CBA software

COMPARISON DATA ANALYSIS AND FINDINGS

USES AND RECOMMENDATIONS

Most of the respondents (61 %) used just one tool (see Table 1); a smaller number (26 %) used two, and even fewer used multiple tools. Overall, the spreadsheet was most frequently used (38 %) for the CBA Tabular method, followed by analog and the digital whiteboard. CBA-specific software was rarely used, so a clear conclusion cannot be drawn. Therefore, it is not surprising that the spreadsheet was recommended most frequently (52 %) (see Figure 7). Furthermore, it seems like fewer are likely to recommend the digital whiteboard as 27 % have tried it but only 19 % would recommend it. However, when an analog process is not possible due to remote working, a digital solution such as the digital whiteboard should be considered since it comes closest to the analog process. The preference regarding the spreadsheet can also be explained by the fact that it is a tool that people are familiar with, while the digital whiteboard is still a novel technology for many in the construction industry. PowerPoint was added as an experience by one respondent, but it wasn't recommended or named by other respondents. Thus, PowerPoint does not seem to be a preferred option and will not be further considered.

Table 1: Decision categories in which CBA Tabular was used (Abbreviation used in the table: P = Participant, M = Moderator, A = Analog, S = Spreadsheet, DW = Digital Whiteboard, SW = Software, PP = PowerPoint)

		Decision categories in which CBA Tabular was used						Experienced tools					
#	Role	Stakeholder/ Team member	Building Design	Building System	Materials	Formwork & scaffolding	Software	A	S	DW	SW	PP	Recommendation
1	P	x							x				S
2	P			x						x			DW
3	M		x						x	x			S
4	M	x	x	x				x	x				S
5	P		x		x			x					A
6	Both	x	x	x	x			x	x	x	x		S
7	M	x	x						x				S
8	M	x	x	x				x	x				A
9	P		x						x				S
10	M				x			x	x				S
11	P		x							x			S
12	M	x		x	x			x	x				A
13	M						x		x				S
14	M			x				x					A
15	M	x		x				x	x	x			DW
16	M	x				x		x		x			A
17	P		x		x					x			DW
18	P		x						x			x	S, can see DW
19	P			x						x			DW
20	P		x	x	x				x	x	x		DW
21	P			x					x				S
22	P			x						x			S
23	M				x						x		SW
		8	11	11	7	1	1	9	14	10	3	1	

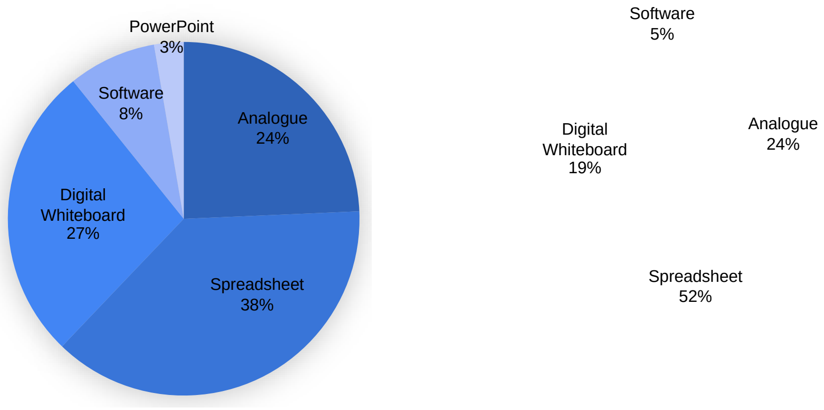

Figure 7: Tools used (left) and tools recommended (right)

INDICATION BASED ON FOCUS

Table 2 shows respondent feedback regarding their recommendations. Reducing the answers to the core of their statements gives an interesting overview of the focus of the respondents. It indicates that people prefer the spreadsheet focusing on this relatively easy and familiar process, whereas people recommending the digital whiteboard focused on the dynamics of the process with the flexibility and visualization of information to easily achieve a common understanding. People preferring the analog tool concentrated more on the social process within the group. For them, driving collaboration through interaction was key. It should be noted that most of the respondents experiencing the digital whiteboard did not experience the analog implementation. One respondent recommended the software, because of its automation. Based on the engineering and technical mindset of the construction industry, it is understandable that the spreadsheet is preferred, and that there is interest in using software. Nevertheless, it shows us that we need to educate people to focus on the social process that every group decision contains to overcome phenomena such as groupthink (Schöttle et al., 2019). Some of the respondents gave clear feedback and expressed the importance of interaction during the decision-making process. This could be an indicator that each group might make a different decision with the same data simply based on the medium. Thus, the analog way should be considered when the team members are new to each other, and the Tabular method is being used for the first time. This will also facilitate team building.

IDENTIFIED FACTORS

Based on the responses to the following three questions:

- Which attributes should a tool have to make the use of the CBA Tabular method as easy as possible for the team?
- Why do you recommend this tool?
- How did the tool/tools help with team collaboration?

17 factors were identified that can be considered when selecting a medium for the decision-making process. Figure 8 gives an overview of these factors based on how many respondents the factor named. This gives insights regarding their priorities in general. The most frequently identified factors were flexibility (43 %), visualization (39 %), and ease of use (39 %), followed by documentation (35 %).

Table 2: Focus behind the recommendation

Tool	Reason given for recommendation	Wording	Focus
Spread-sheet	• *It's familiar and it works for sharing* • *Automatic calculation, but flexible enough to jump around.* • *Simple, easy to adjust and customize.* • *Worked well for us.* • *A spreadsheet is easy to use, and it can be formatted as needed for visual sharing (on a screen, a PDF, or on paper).* • *Thorough and effective.*	Familiar, Sharing, Simple, Easy, Adjustable, Effective	Systematic framework of the process
Analog	• *All participants are seeing the big picture and have the opportunity to make a change. A digital whiteboard is a good idea for non-collocated decision makers.* • *Easy to use, facilitates team participation and collaboration* • *Because it allows a more direct interaction (face-to-face) between the people who participate in the decision, it also strengthens the feeling of commitment to the decision made.*	Big picture, Collaboration, Direct Interaction, Commitment, Easy	Social process
Digital Whiteboard	• *Easy to use. Editable. Great possibilities for visualization.* • *It is visual and collaborative and works within the constraints of hybrid or full virtual [workplaces].* • *High flexibility, interactive, easy to work with, team has full access anytime.* • *It gives the most freedom while still providing a framework to work within*	Flexibility, Visualization, Interactive, Discussion, Easy	Dynamic of process
Software	• *Automates the process*	Automation	Automation of process

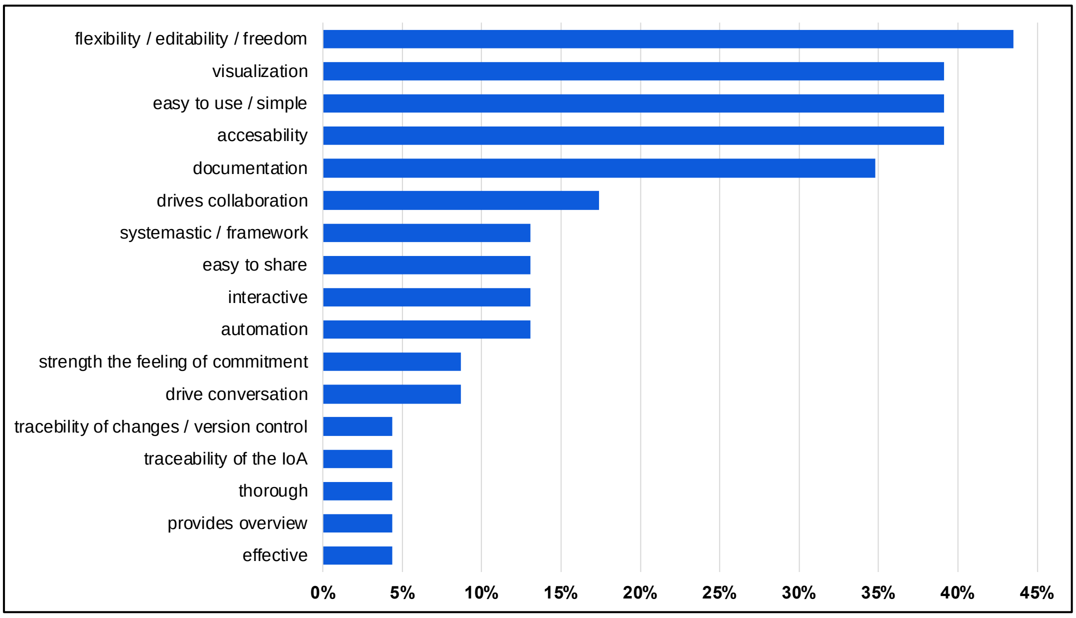

Figure 8: Identified factors (Based on % of respondents' input)

DISCUSSION

The medium used to implement the CBA Tabular method can have an impact on the team dynamic and understanding. It is therefore important to understand the specific context and the needs of the project team to better align on a decision. As most respondents had only experienced one tool to support the CBA this paper could serve as inspiration for future decision processes. To better select between the four alternatives, the following criteria (Table 3), can be defined using the identified factors. If a project team needs to decide which medium is best to use on a given project, the criteria pool can be used to quickly decide.

Table 3: Factors and criteria to choose the tool/media

Factors	Criteria
accessibility	Easier accessibility is better.
automation	Greater automation is better.
documentation	Clearer documentation is better.
drives collaboration	The more it drives collaboration, the better.
drives conversation	The more it drives an open conversation, the better.
easy to share	The easier it is to share, the better.
easy to use / simple	The easier it is in use, the better.
effective	The more effective it is, the better.
flexibility / editability / freedom	Higher flexibility/editability is better.
interactive	The more it is interactive, the better.
provides overview	The better it provides an overview, the better.
strengthen the feeling of commitment	The more it helps strengthen the feeling of commitment, the better.
systematic / framework	Higher systematic framework is better.
thorough	The more thorough, the better
traceability of the IofA	Easier traceability of the IofA is better.
traceability of changes / version control	Easier traceability of changes (version control) is better.
visualization	Greater visualization is better.

CONCLUSIONS

In this paper we have assessed the use of media or tools to support the CBA Tabular method. Four different tools were assessed: (1) analog, (2) spreadsheet, (3) digital whiteboard, and (4) CBA-specific software. This is not an extensive list, but it includes the most used. Four case studies are presented to exemplify the use of each tool and its advantages. Then, based on 23 international survey respondents, the use of the tools was analyzed in terms of what mattered for the participants. It became clear that most had experience with only one tool. It was also clear that no one solution was considered perfect in all cases. From the survey, 17 factors and criteria can be considered when making the decision of selecting a CBA tool. However, not all factors will be relevant for all contexts. Therefore, this paper offers a list of factors, criteria, and attributes to consider when selecting a tool for a decision process in its specific context. One important element in evaluating tools is whether the team can meet face-to-face or if the team must meet in a hybrid or remote environment. Thus, this paper presents a summary of tools that were used to facilitate and document CBA internationally and is a good starting point to decide which tool would be best for a team by using the identified factors and criteria. The authors caution readers to focus on preparation in advance to teach CBA concepts and allow time for practice, as well as choosing a facilitation and documentation tool.

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FRAMEWORK FOR USING LPS IN DESIGN ON IPD PROJECTS

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ABSTRACT

Design in nature is an iterative and interdependent process. Previous research shows that in some projects, 50% of this process contains waste. The Last Planner System (LPS) proved its efficiency in planning and controlling the execution phase. However, due to the nature of the design process, implementing LPS at this stage contains many constraints. Results show that the Integrated Project Delivery (IPD) and LPS together can significantly improve design workflow, still some issues remain that do not let the IPD project achieve the full potential of LPS in managing a design process. In this research the main constraints are studied and divided into five categories. Recently, many researchers studied the benefits of implementing LPS and how to optimize this method, especially in the execution phase, but there is no integrated framework that contains the available tools and techniques for overcoming constraints in using LPS at the design process. This study indicates that multiple strategies need to be adopted for increasing the applicability of LPS at the design process of a construction project. This paper proposes an integrated framework for addressing design constraints and optimizing the applicability of LPS in the design process on IPD projects.

KEYWORDS

Last Planner System, Integrated Project Delivery, design process, workflow, lean design

INTRODUCTION

In construction, design processes are dynamic and complex (Khalife et al., 2018). Hamzeh et al. (2009) stated that because of the high uncertainty in design tasks, this process is not easily predictable. Some sources of uncertainties include task duration, task sequence, task scope, task prerequisites, and constraints. Also, the design process may be responsible for a considerable amount of waste: design error is one of the primary sources of waste in the construction industry (Breit et al., 2008; Ko & Chung 2014). Moreover, the design process comprises positive and negative iterations that can significantly affect the quality of the

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product. Negative iterations are hard to predict and eliminate during the planning process because this process contains complex tasks that have mutual interdependencies and need sharing of incomplete information (Hamzeh et al., 2009). All these uncertainties together increase the difficulty of planning and controlling the design process.

The Last Planner System (LPS) is a production management system for improving workflow reliability (Ballard & Howell, 1994). LPS is one of the lean construction techniques that has been used in the construction industry since 1990 (Perez & Ghosh, 2018). The LPS has been used successfully on construction projects to improve reliability of planning, production performance, and creating a predictable workflow (Hamzeh et al., 2009). However, previous studies reveal some difficulties and constraints associated with applying LPS (Alarcón et al., 2008; Perez & Ghosh, 2018), especially at the design stage, which contains noticeable iteration process and interaction between different parties (Hamzeh et al., 2009).

LPS has been more successfully applied in the execution compared to design due to inherent differences between the two phases. The main factors that differentiate the production control during design process are 1) predictability reduction of the future tasks' sequence because of higher uncertainty of ends and means, 2) inappropriate constraints removal as a result of increasing the speed of design tasks' execution, and 3) increasing work complexity and planning process due to design tasks' interdependencies (Ballard et al., 2009, Hamzeh et al., 2009).

The mentioned differences between the design and production phase increase the difficulties in implementing LPS in the design compared with the execution. Simonsen et al. (2019) analyzed a case study that implemented LPS at the execution phase, however LPS in this project failed at the design stage and project participants preferred to continue with the traditional planning and control systems. The researchers concluded that implementing LPS requires enthusiasm and commitment, which take time to build in an organization.

Aside from design constraints, shifting from traditional planning methods to LPS is challenging, because most construction companies tend to use approaches that they are already familiar with. LPS requires a high level of communication and collaboration, which can be facilitated through Integrated Project Delivery (IPD). In an IPD project, the whole team works as a single unit and shares responsibility in risk and reward. The IPD approach tries reducing later conflicts such as extended schedule and cost overrun by improving the collaboration (Gomez et al, 2018).

In this research, after reviewing the previous studies, the main design-related constraints that lead to reduced efficiency of using LPS are divided into 5 categories: 1) changing priority and design task sequence, 2) negative iteration, 3) lack of communication and lean culture, 4) lack of proper training, and 5) time pressure. Moreover, regardless of the number of studies on implementing LPS in the construction industry, not many studies try to develop an integrated framework that contains the available tools and techniques for improving the efficiency of LPS in design and overcoming the related constraints. The objective of this paper is to propose a framework which contains the available approaches to address the challenges that reduce the efficiency of LPS during the design phase of IPD projects.

METHODOLOGY

In this study design science research (DSR) is used to achieve the aforementioned objectives. DSR is a research strategy driven by field problems. This approach tries to provide information to be used in the design and implement actions, processes, or systems in practice to reach the desired goals. (Simon, H. A, 1996; Van et al, 2016)

Hevner (2007), briefly analyzed the DSR within three relative cycles of activities;

Relevance Cycle: a good DSR starts with recognizing and displaying problems and opportunities in a real environment. Relevance cycle provides the research requirements as inputs as well as criteria for evaluating the results. In this research, the problems recognized from the literature review were discussed with experts to assure that these are real problems.

Rigor Cycle: in DSR, a foundation for rigorous design science is formed from a vast knowledge base of scientific theories and engineering methods. The knowledge base contains the experiences and expertise for defining the state-of-the-art as well as the existing artifacts and processes in the application domain of the research. In this study, previous research, the author's observations, and experts' opinions have been used.

Design Cycle: this is the internal and core cycle of the DSR. This cycle iterates between forming an artifact, evaluating it, and receiving feedback to better refine the design. Here, a set of interviews have been conducted to receive feedback and refine the proposed framework.

The data sources used in this paper are literature reviews, interviews with experts and the author's experience of using LPS on IPD projects. This research was conducted through four major steps to achieve the goals: 1) Investigate the previous research in implementing LPS in design, especially in IPD projects. Analyze and categorize the main constraints, solutions, and recommendations. 2) develop an artifact to reduce the design constraints during LPS implementation. 3) Interview with the experts in this field to achieve more realistic information and feedback about the developed framework. 4) refine and improve the developed framework.

DESIGN CONSTRAINTS IN IMPLEMENTING LPS

1) CHANGING PRIORITY AND DESIGN TASK SEQUENCING

Master scheduling is the first step in implementing LPS and contains recognizing milestones of the projects, in which deliverables are mapped and identified in order to determine the completion date (Hamzeh et al., 2009). Successful implementation of the master scheduling step is necessary to prevent the possibility of milestones' priority changing. Increasing the priority changes leads to failure in phase and pull planning and consequently, causes workflow interruption.

Although changing milestones sequence can lead to losing value in phase planning, in some cases prevention is not feasible due to complexity of the project. Nevertheless, precisely identifying the milestones and their deliverables in the master schedule can significantly increase the efficiency of LPS at the design stage by reducing unnecessary changes.

Besides changing sequence of milestones, inappropriate design task sequencing can create waste in the process. Design tasks contain interdependencies between different engaged parties, which can lead to workflow interruption (Khalife et al., 2018).

2) NEGATIVE ITERATION

Iteration is an inseparable component of the design process and can be divided into two parts: negative (non-value-adding) iteration and positive (value-adding) iteration. For generating value in the design process, positive iteration is an essential factor (Ballard, 2000). A positive iteration can lead to improve the project value through an innovative idea.

However, a negative iteration causes waste in time, cost, and failure in participant’s commitments.

Negative iteration can have different sources. One of the well-recognized causes is errors. When errors in design are discovered, then rework is mostly required (Lopez & Love, 2012). Informal surveys of design teams demonstrated that negative iteration dedicated 50% of design time to itself (Ballard, 2000). Erroneous actions are often identified as misinterpretations, miscalculations, and omissions (Lopez et al., 2010). Different reasons cause errors and many studies have been conducted in root cause analysis of error in the design process. For instance, Lopez et al. (2010) stated that human deficiency of cognitive ability to respond to cultural, social, and physical conditions can lead to inaccurate decisions and errors.

Notably, the other defect raised by wrong task sequencing, as mentioned in the previous subsection, is increasing the iterative loops and waste in the process.

3)LACK OF COMMUNICATION AND LEAN CULTURE

Right culture works as a foundation and builds up trust and efficient communication. Trust and communication have a two-way relationship. It is not possible to have clear and efficient communication without existing trust among participants and vice versa. Moreover, improving lean culture will reduce the resistance to change in an IPD project.

Lack of communication and solely design decision-making raises the project’s complexity and increases the difficulties in managing the workflow (Ballard & Koskela, 1998; Khalife et al., 2018). On the other hand, improving communication results in higher clarification in case any conflicts occur. The integrated project delivery method can create a well-functioning collaboration among contributors through positive thoughts about each other (Falch et al., 2020).

4)LACK OF PROPER TRAINING

Despite the approved advantages of using LPS, many developing countries have not executed LPS in their projects (Hamzeh et al., 2016).

In an IPD case study, Hamzeh et al. (2009) mentioned the necessity of training. The transition team recognized the importance of providing general training in lean methods and particular training in LPS for the staff. Many failures in applying LPS have been reported in different research due to the lack of training. Dave et al., (2015) explored a construction project that failed to implement LPS, they only used weekly work planning in this project, and lack of training was reported as one of the main reasons for LPS failure.

5)TIME PRESSURE

Even though LPS improves the reliability of scheduling through pull planning, some findings report time pressure trigger LPS failure.

The Tonsberg project, a case study on a large hospital, is an example of failing LPS in design because of time pressure (Simonsen et al., 2019). In this project, intensive planning was running out in the design process, and the short time between the design deadlines and the start of the execution phase induced additional challenges to the design team, which caused frustration and led to discontinuing the LPS in the design phase. Moreover, time pressure is stated as the reason for holding the participant back from the implementation of new methods in projects (Aslam et al., 2020).

Through analyzing previous research, mapping design processes, and authors observation of using LPS in IPD projects, we found that the design constraints are interdependent. Figure

1 tries to show how these constraints are linked and impact each other. Therefore, leaving one unsolved will cause emerging the other constraints and interrupt the whole process. The number on the top left corner of each box show the constraints group that they belong to. The yellow color demonstrates that usually at this stage the teams are not aware of the importance of these constraints. The negative impact becomes more and more obvious when the color is changed to orange and red and when the color turns to red, a workflow is interrupted and everyone becomes aware of the problem.

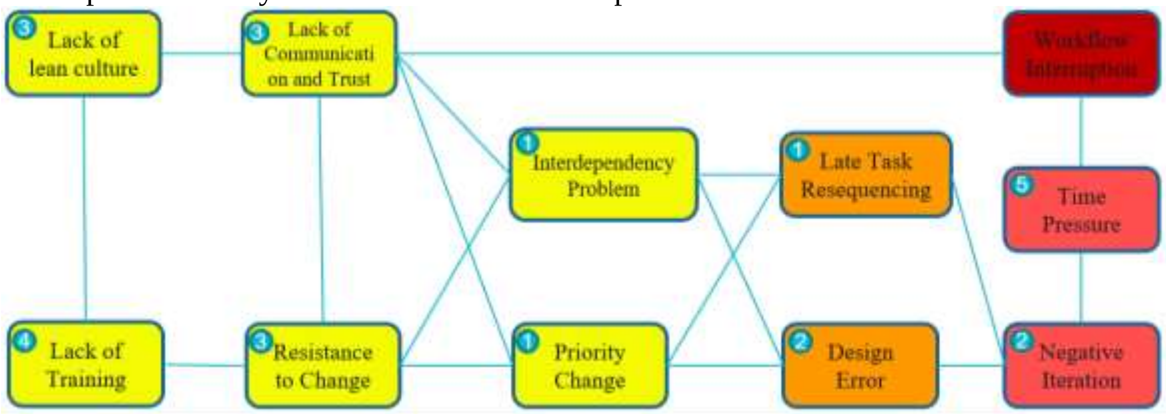

Figure 1: Design process constraints are interdependent.

RESULTS AND DISCUSSION

EXPERT INTERVIEWS

For assuring that the mentioned constraints are the reasons for making LPS challenging in the design stage of construction projects, a set of interviews with four experts in this field was conducted. The interviewees included four managers and all the participants have valuable experience in using LPS during different IPD projects. Participants answered questions related to each constraint's category. Also, from their answers, the magnitude of the negative impact of these constraints during the design process was analyzed.

Figure 2 depicts the negative impact of design constraints versus time for each constraint's categories based on average answers from the interviewees. The results from interviews show that the lack of communication and lean culture and lack of proper training have a significant impact during the whole design process.

Lack of communication shows its highest negative impact at the beginning of the process design. From the interviews, it is understood that mostly in the concept design stage, people try to show that they communicate well. However, when the process design starts, lack of proper communication and culture shows its negative effect when the design team needs to collaborate and decide together. Lack of proper training has a noticeable negative effect on the concept design, beginning and end of the process design. At the beginning of the project, enough training is required to build the right culture and to bring all the team members on the same page, and at the end of the process design due to overlapping the design and execution phase, training is required to improve the collaboration between different teams.

On the other hand, the highest negative impact of time pressure reveals at the beginning of process design. Negative iteration as well as changing priority and design task sequencing have a similar negative impact during the design process. They both have a low impact at first, and the further design goes, negative impact increases. It is mainly because of reducing the flexibility of changing the schedule and design close to the end of process design.

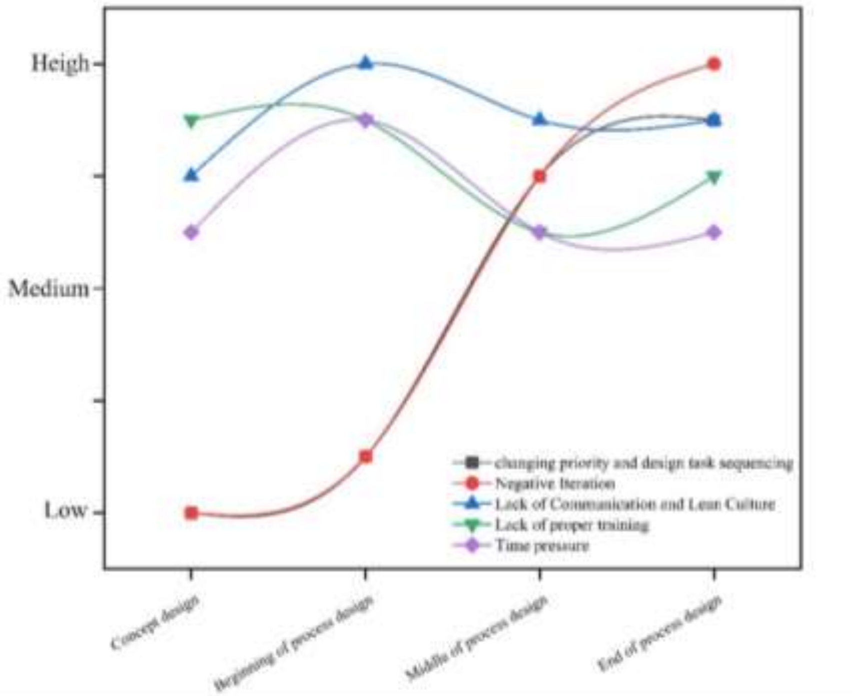

Figure 2: Negative impact of design constraints versus time.

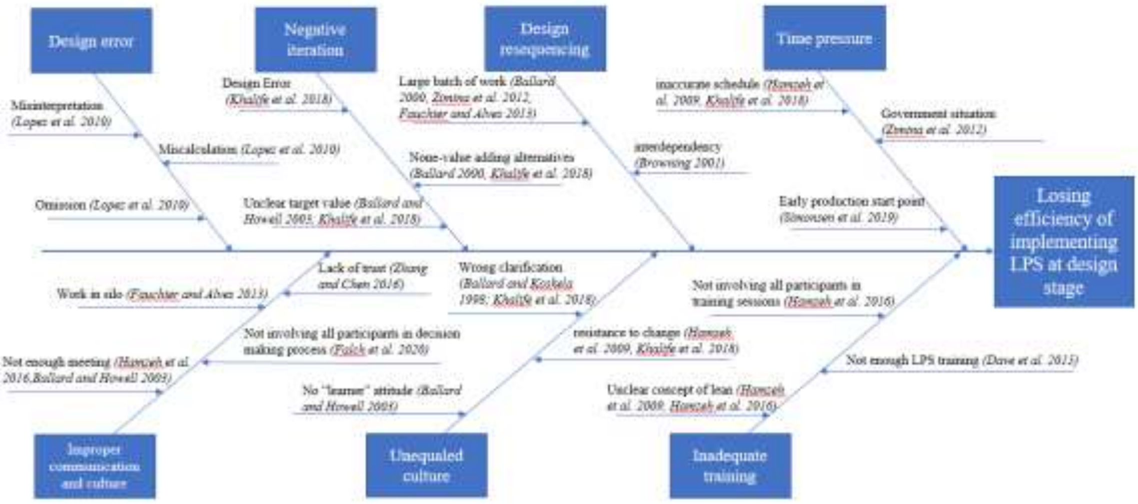

Figure 3: Cause-and-effect diagram.

After achieving data from reviewing previous research and conducting the interview, we mapped the whole design process for a better understanding of all the effective factors on the design process during implementing LPS. In this research, based on the data achieved from previous studies, the interview and process mapping, a cause-and-effect analysis is generated to better identify possible events that negatively impact the implementation of LPS, as shown in figure 3.

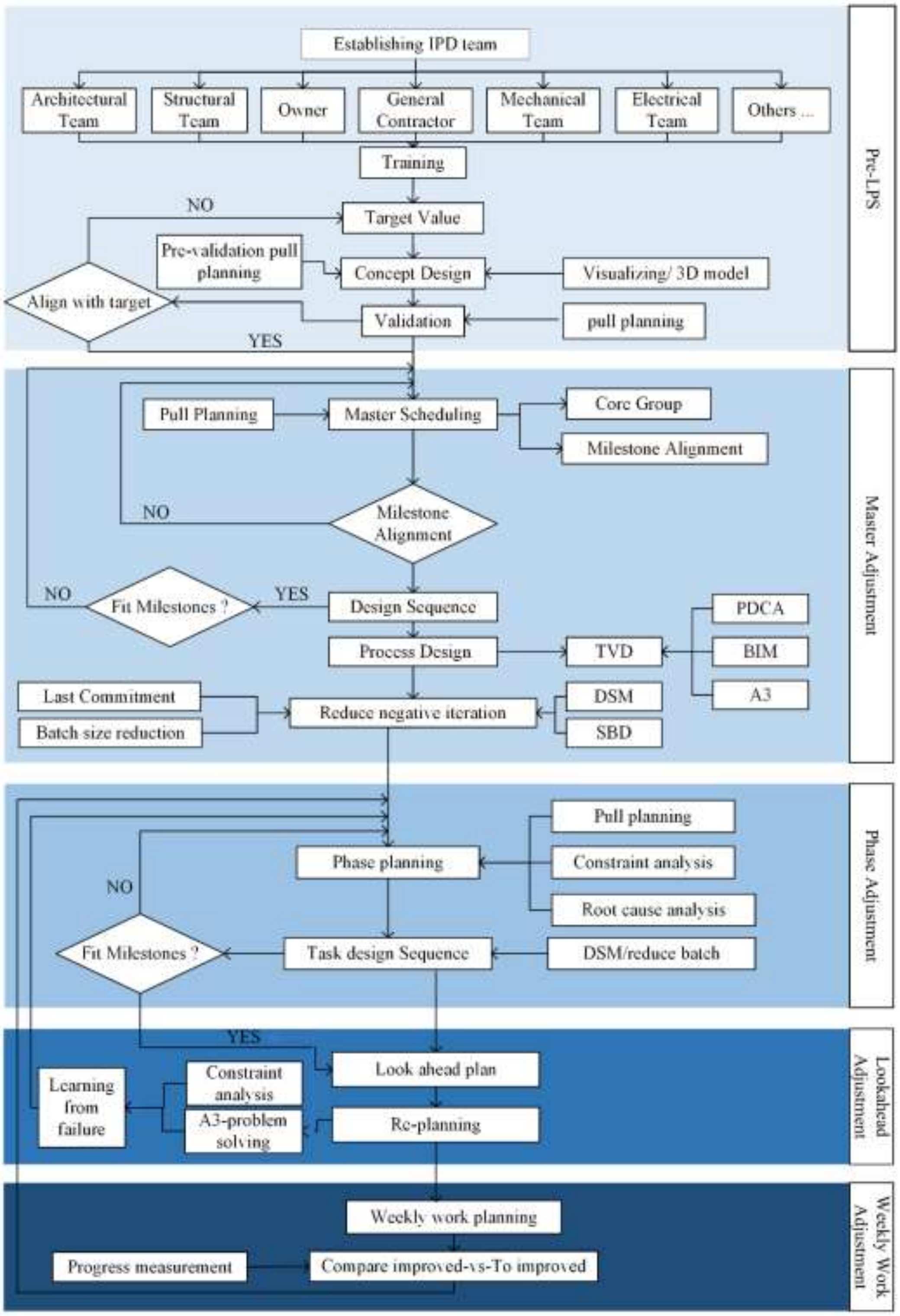

Figure 4: Five stages of the proposed framework.

PROPOSED FRAMEWORK

After gathering and analyzing the data from previous studies and interviews with experts, a framework consisting of five stages was developed to address the current problems of LPS at the design stage in IPD projects (Figure 4). The framework consists of the five stages explained below.

Pre-LPS

Setting up adequate training at the beginning of any IPD project is necessary to build lean culture and prevent creating new problems. Training was found to be useful for motivating project participants, who may tend to be resistant to shifting to a new system. Introducing LPS training and lean construction philosophy to all employees can help build a better lean culture (Hamzeh et al., 2016) and resolve cultural constraints in using LPS in design.

Therefore, in this framework, a pre-LPS stage is used, which is introduced immediately after forming the IPD team. After performing lean and LPS training and before initiating concept design, target value should be defined. Target value aims to make a client value a driver for design. These values can be significant design criteria, budget, schedule, or constructability (Tauriainen et al, 2016).

In developing concept design, 3D models and Building Information Modeling (BIM) can significantly improve the quality of communication and engagement level. Also, in early project stages, before master scheduling begins, pull planning needs to be implemented with rough design information. Pull planning session is another tool used in LPS that has been found to be very useful in improving communication and collaboration. Fosse and Ballard (2016) implemented the LPS method in a case study in the initial design phase and they achieved effective collaboration and transparency.

After developing the concept design, a validation process should be implemented to assure that the design concept is aligned with the target value. Likewise, a pull planning session should be conducted during the validation to improve the applicability of LPS. It will be very beneficial if a lean coach or champion works with the IPD team during the whole project.

Master Adjustment

at the master scheduling stage, milestones and their deliverables will be defined. This process should be done through ‘milestone alignment’ and considering participants' perspectives to minimize priority changes during the design process.

Milestone alignment, proposed by Hamzeh et al. (2009), is conducted during master scheduling and can help reduce changes in priorities. In milestone alignment, perspectives from different participants are considered and aligned for each milestone. Internal and end-users of each milestone are identified, and the output of each milestone is identified (Hamzeh et al., 2009). Milestone alignment is a crucial part of LPS, and correct implementation can significantly reduce the priority changing and increase the consistency of the workflow.

At this stage, pull planning also should be done by the core group containing the seniors of each team. After defining the milestones, the master schedule should be checked to ensure that all the milestones are aligned. After defining the milestones, the design sequence at the high level should be done by considering the alignment with the master schedule. Once the design sequence is determined, the design process will be started and be monitored through a Target Value Design (TVD) meeting. TVD meeting is a good approach in improving the communication and collaboration among the team. This method aims to satisfy or even exceed the client’s expectations by defining and considering all the client’s values such as design criteria, completion date, cost, and constructability (Zimina et al., 2012). Also, some different lean tools and techniques can be used in TVD and increase productivity such as; set-based and evidence-based design, A3 reports, Last Planner, PDCA (Zimina et al., 2012).

PDCA “Plan-DO-Checked-Act” is one of the useful quality management methods in lean construction and can be a good example of the importance of trust (Zhang & Chen, 2016). PDCA is linked with trust-building as it is; *Planning* by forming and maintaining reliable promises across a siloed organization, *Doing* in a predictable and transparent environment, *Checking* approaches and learning, and *Acting* together (Fauchier & Alves, 2013).

For reducing the none-value-adding design iteration, we suggest that from the beginning of the design process, the IPD team gets familiar with the available techniques for minimizing these negative iterations. Then based on the project situation, the most suitable approach can be selected and implemented.

In this regard, Ballard (2000) suggested first minimizing the iterative loops by Design Structure Matrix (DSM). DSM is one of the valuable methods for optimizing the design sequence. DSM visually represents the interaction and interdependency of different levels in a complex system and proposes innovative solutions (Browning, 2001).

After conducting DSM, Ballard (2000) recommended to select the suitable technique from the available options, which are: 1) team problem solving, 2) cross-functional teams, 3) shared range of acceptable solutions 4) share incomplete information 5) reduced batch size, 6) team pull scheduling, 7) concurrent design, 8) deferred commitment, 9) least commitment, 10) set-based vs point-based design, 11) overdesign.

Among the mentioned techniques, Set-based-design (SBD) as a Toyota design approach identifies the available design space and the functional requirements, then it adds input from different disciplines to narrow down the number of concepts to move towards a final design (Sobek et al., 1999). This method can help to keep the positive iteration and minimize the negative one through defining the boundaries for design suggestions, also SBD systematically shares information, which is a crucial feature in the design process (Busby, 2001). Conducting the appropriate techniques at the right time and including the right participants can be advantageous to remove the design constraints in LPS.

Phase Adjustment

after defining milestones, the next stage in LPS is Phase planning. Moreover, pull planning at this stage for each milestone, constraint recognition, and root cause analysis should be implemented to precisely complete this section and make it ready for the next step. These approaches in phase planning help to prevent workflow interruption during the design stage.

For reducing the negative impact of the interdependency in the design process, during design sequencing one of the available techniques or combination of them should be used based on the project situation. To minimize task resequencing, reducing the batch size and using DSM techniques can be very beneficial. This helps in reducing the need for resequencing the design task in the future.

After task sequencing at the phase planning stage, they should be checked to see if they are in line with milestones in master scheduling or not. To achieve a successful LPS in design, it is very important that the master scheduling and phase planning are connected. In case they are not aligned, it is required to go back to the beginning of phase planning and sequencing the task in a way that they fit milestones.

Lookahead Adjustment

After phase planning, the next stage in LPS is lookahead planning. All the related participants should involve in this phase, and they should share their perspectives to be sure everything will be ready for weekly work planning. Re-planning is an unavoidable part of Lookahead Planning. During re-planning, A3 problem solving, or constraints analysis should be conducted to analyze the failure, learn from it, and try to prevent it from happening again in the future. It is very important to consider the lesson learnt at the beginning of future phase planning to have a continuous improvement loop during the whole project.

Weekly Work Adjustment

The last stage of the LPS is weekly work planning, which involves all design team members. In this stage, participants know about their upcoming responsibilities and measurements of progress are taken and compared. Therefore, in weekly work planning, percent plan complete (PPC) and a comparison between *improved* versus *to be improved* should be executed and the achieved results should be considered in phase planning for the next step.

Identify failure and learn from the mistakes in the weekly work planning session can also improve communication by helping participants recognize failures and learn instead of focusing on blame (Ballard & Howell, 2003).

Understanding the constraints and predicting them before they occur plays a crucial role in implementing a possible solution to prevent or reduce them. Hence, learning from previous case studies and planning for failures and successes as part of the design process can be very beneficial.

This framework integrates most of the available techniques, tools, and approaches that can reduce the impact of the design constraints in implementing LPS during the IPD project. Although this is not an exhaustive framework, it can help practitioners to anticipate possible constraints that they might be faced during the design process and be aware of available solutions for them at each level.

CONCLUSIONS AND FUTURE RESEARCH

This research aims to investigate the challenges and constraints of the design process, which reduce the efficiency of implementing LPS in IPD projects and consequently propose an integrated framework for that. Data of this research has been gathered from studying and analyzing literature review and conducting a set of interviews with the experts in this field. In this study, relevant main constraints have been categorized into five different groups: 1) changing priority and design task resequencing, 2) error and negative iteration, 3) lack of communication and the right culture, 4) lack of proper training, and 5) time pressure. After analyzing the negative impact and available solutions for each category, it is found out that the design constraints are interdependent and leaving one constraint unsolved might cause creating other constraints. Therefore, an integrated framework in five phases has been formed to address the mentioned problems. These steps contain pre-LPS, master adjustment, phase adjustment, lookahead adjustment, and weekly work adjustment. The outcome of this research demonstrates that there is no single answer for addressing the design issues. Multiple strategies need to be implemented in an IPD project to optimize LPS at the design stage.

Further studies are required to investigate each category of design constraints in depth, as well as analyze the outcome of using available tools and techniques in preventing or reducing the design constraints.

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THE SILO GAME: A SIMULATION ON INTERDISCIPLINARY COLLABORATION

Thais da C. L. Alves[1]

ABSTRACT

Collaboration is a highly valued skill in construction, and it has become essential considering the advent of more collaborative delivery methods (e.g., design-build, integrated project delivery). This paper introduces the Silo Game which is a teaching simulation developed to mimic the trade-offs made during the design process to meet client's requirements while also meeting project goals. This simulation mimics the development of an environmentally conscious building using two phases: one illustrating disciplines isolated in teams mimicking silos and another with multi-disciplinary teams. The facilitator assumes the role of an owner and participants are assigned one of the four roles defined for the game: architect, civil engineer, mechanical engineer, and electrical engineer to meet the project's conditions of satisfaction defined early in the game. Initially, the professionals are grouped by role and later assigned to multi-disciplinary teams. The game has been played with three undergraduate classes and also with the Administering and Playing Lean Simulations Online (APLSO) community and the instructions are easy to relay. The lessons learned can be directly translated to construction settings sparking discussions about various Lean tenets and systems including integrated project delivery contracts, target value design, collaboration, and conditions of satisfaction.

KEYWORDS

Collaboration, sustainability, design, conditions of satisfaction, serious games, simulation

INTRODUCTION

This paper introduces the Silo Game as an additional teaching simulation to underscore the importance of collaboration in construction and how it is central to delivering value to environmentally conscious clients. In the early days of the International Group for Lean Construction (IGLC) community, topics related to waste reduction in construction projects were very prominent, and the focus was very much centered on reducing material waste and planning for more reliable flows of work, thus, reducing the waste of human effort (e.g., Alarcon 1997). The approaches used during the early days of the IGLC, expanded over the years as researchers and practitioners turned their attention to ways in which value is to be achieved for the clients, using only the resources necessary to achieve the clients' needs and considering broader solutions to achieve these goals from design, through production planning, supply chain initiatives, operations, and maintenance of projects (Alves and Tsao 2007). As this shift took place over the years, increased attention

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was placed on a Lean Project Delivery System (Ballard 2008) which considers multiple disciplines working in different areas from design, through production planning and control, work structuring, and supply chain management to name a few.

In this scenario, calls to promote interdisciplinary work, while addressing value maximization for the client and promoting a smooth flow of work, gained more popularity and contracts also became a relevant element in the discussion. Contracts incorporating more collaborative forms of work (e.g., design-build, integrated project delivery) became a necessity to promote environments where interdisciplinary work across trades and specialties was not only required but also rewarded (Alves et al. 2021). Comparisons between project performance using the traditional design-bid-build (DBB) delivery method versus design-build (DB), and integrated project delivery (IPD) methods showed the marked differences between these approaches (ElAsmar et al. 2015). Markedly, the development of projects using DBB in a siloed fashion revealed shortcomings that were addressed by the collaborative nature of DB and IPD projects.

In order to illustrate how traditional versus collaborative delivery methods play out in delivering projects and satisfying the client's conditions of satisfaction, the author developed a simulation to mimic the design process in both methods in a classroom setting. This simulation was developed to support activities related to an undergraduate course on environmentally conscious construction in California, where building codes are markedly progressive and unique (e.g., Calgreen 2022) and tend to push environmental standards much higher than other codes in the United States. In many cases, California building codes are stricter than requirements defined by rating systems like Leadership in Energy and Environmental Design (LEED), and this puts projects in California on a more streamlined path to certification, considering that many prerequisites and credits are standard practice in the state (USGBC 2022a, b). Considering these factors, the simulation was developed to mimic the design process and underscore the importance of collaboration in the development of environmentally conscious buildings.

SIMULATIONS TO TEACH LEAN CONSTRUCTION

This simulation builds on a long-standing tradition of teaching Lean Construction principles using simulations shared with the IGLC community and beyond (Tsao et al. 2012). The author is also part of a group of Professor Iris Tommelein's former graduate students at UC Berkeley, who have spearheaded the development and use of lean simulations (Rybkowski et al. 2020). From a production planning standpoint, these simulations have illustrated the effects of production system design using pull techniques to plan assembly (Tommelein 1998), the effects of uncertainty in production performance (Tommelein et al. 1999), how customization can be managed using lean principles (Sacks et al. 2007), and how site organization and communication using 5S can support better performance (Pollesch et al. 2017) to name a few. Additionally, simulations illustrating the importance of collaboration in general (Bavelas 1973) and use of lean principles in design to achieve targets (Rybkowski et al. 2016) and support architectural programing (Solhjou Khah et al. 2019) have also been used in the IGLC community to underscore the dynamics of the design process and trade-offs involved.

While most simulations developed until 2019 relied mostly on in-person interaction, with some exceptions including those using computer simulations (e.g., Tommelein et al.'s (1999) parade game), during 2020 and beyond, academics and practitioners had to pivot and translate face-to-face simulations to online environments to continue teaching during the Covid-19 pandemic. This effort is well documented in the description of the

Administering and Playing Lean Simulations Online (APLSO) community by Rybkowski et al. (2021). The APLSO is a virtual community of academics and practitioners, which started in March of 2020 during the Covid-19 pandemic, and was led by Dr. Zofia Rybkowski. The community, which was still active at the time this paper was written, meets once a month to play a simulation developed by one of its members or invited guests illustrating lean concepts. It was in this environment that the Silo Game was developed: virtual instruction using Zoom, breakout rooms, and Google Drive documents to support instruction. The author was involved with the early days of the APLSO and at the time the community started, she had already adapted the Architectural Programing (AP) simulation (Solhjou Khah et al. 2019) to the virtual environment and worked on a version of the Silent Squares simulation (Bavelas 1973) to teach a graduate course and, finally, the development of the Silo Game to support the teaching of design of an environmentally conscious building in an upper division undergraduate course. The common thread in simulations used in the APLSO community is the simplicity of the play and the clarity of instructions and concepts involved, which are relayed on an environment that needs to be inclusive and free of jargons, or regional expressions, to facilitate understanding (Rybkowski et al. 2021).

INTERDISCIPLINARY TEAMS, SUSTAINABLE DESIGN, AND LEED

Sustainable and high-performance buildings rely on the work of interdisciplinary teams to come to life (Kibert 2016). Solving problems from a multi-disciplinary standpoint helps teams reap synergistic benefits that cannot be achieved by any single specialization. For instance, addressing water consumption reduction and/or recycling in a building relies on the work of architects, landscape architects, civil engineers, and mechanical engineers, to name a few, so that the building and its systems are designed to use the minimum amount of water possible and recycle it whenever possible, in addition to capturing rainwater. An example of this extraordinary effort can be seen in net zero buildings, those that produce what they consume, in which water, energy, and/or trash are reduced, recycled, and reused. The Kendeda Building is an example of a high-performing building where the design approach allows the building not only to be net zero, but also give back to the environment and regenerate it (Georgia Institute of Technology 2022).

Environmentally conscious buildings can be attained by meeting and exceeding existing codes like the California Green Building Standards (Calgreen 2022), a recognized leading code in the United States (USGBC 2022a). However, the Leadership in Energy and Environmental Design (LEED) is arguably one of the most recognizable rating systems in the world (USGBC 2022b) and very educational in how it defines areas of concern and focuses the attention of teams on its main categories: Location and Transportation (LT), Sustainable Sites (SS), Water Efficiency (WE), Energy Efficiency (EE), Materials and Resources (MR), Indoor Environmental Quality (EQ), and additional areas of interest in Regional Priority (RP) and Innovation (IN) (USGBC 2022b). Considering the widespread popularity of LEED and its implementation in over 100,000 projects around the world (USGBC 2022c), this rating system was used to inform the development of the different categories used in the Silo Game.

THE SILO GAME SIMULATION

This section describes the process to develop the Silo Game. It starts by introducing why the simulation was developed and the approach taken to design its different elements.

Designing the Simulation

This simulation was developed with the intention of illustrating the importance of interdisciplinary collaboration in the design of sustainable buildings. The author teaches a course on environmentally conscious construction to students in civil and construction engineering majors and had the goal of showing that the traditional way of designing buildings, where specialty designers in different fields work separately, is not an appropriate option to design sustainable buildings.

For this game to effectively mimic the traditional versus a more collaborative approach to design buildings, and solve problems in general, the simulation was designed considering a few areas of interest (e.g., siloed vs. interdisciplinary discussions; trade-offs related to solutions; synergies between environmentally conscious solutions), which are discussed in the following sections.

The Problem: Design an Environmentally Conscious Project

Considering the main topic of the course for which this simulation was developed, the focus of the design would have to be related to the design of environmentally conscious buildings. A fictitious project also had to be defined so that participants could be held to the value proposition that they would need to deliver.

In this simulation, the project's vision comprises "*an environmentally conscious building that appeals to the market and has a low maintenance cost over the long run*" (Figure 1). The owner has a budget of “10 units of currency” (target value) to spend on the project. Please notice that a fictitious currency was used to remove the focus on the real cost of such a project, given that other characteristics are not precisely defined. Considering where the game was developed, the project was loosely defined as a multi-family development in Northern California. The target market was defined as environmentally conscious, young professionals living by themselves or sharing a unit, couples with one or two children. The allowed cost was set as medium to high for these small units, and because of the small square footage of the units, there should be open areas and amenities to provide additional space beyond the small private unit. Additionally, parking should also be provided. Finally, the units need to have individual meters for water and energy (sub-metering).

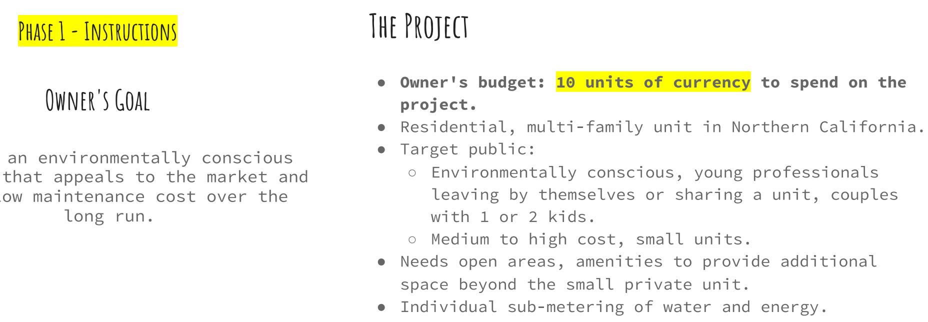


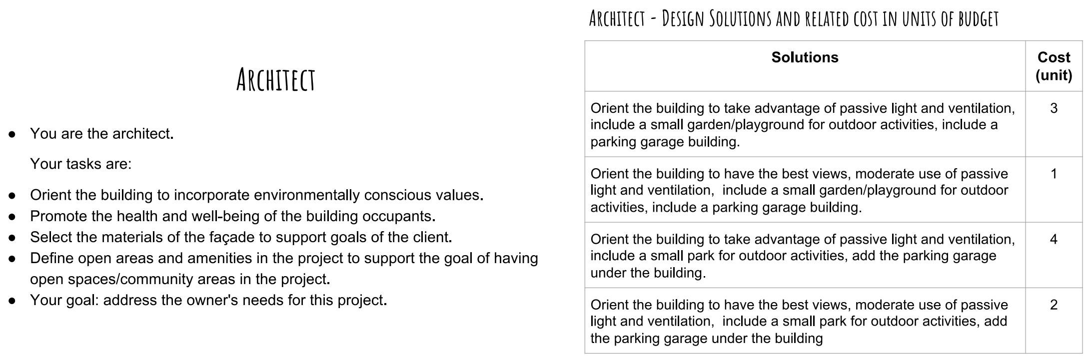
Figure 1: Examples of slides used to share information about the project and the owner.

Stakeholders/Roles

The definition of stakeholders for this simulation should also mimic those involved in the design process and how they would interact or not during the simulation, and help in the evaluation of how the conditions of satisfaction for the design were met. Participants were assigned one of the four different roles, namely: Architects, Civil Engineers, Electrical Engineers, and Mechanical Engineers, whose specific responsibilities are outlined in Table 1. An example of the slides shared with participants representing one of the roles (e.g., Architect) is shown in Figure 2.

Table 1: Roles and responsibilities (each participant receives instructions for their role only)

Professional Role	**Responsibilities**
Architect (A)	• Orient the building to incorporate environmentally conscious values. • Promote the health and well-being of the building occupants. • Select the materials of the façade to support the goals of the client. • Define open areas and amenities in the project to support the goal of having open spaces/community areas in the project. • Your goal: address the owner's needs for this project.
Civil Engineer (CE)	• Address site water runoff. • Propose alternatives to support water conservation and reuse. • Promote the health and well-being of the building occupants. • Advise on solutions related to the parking lot.
Electrical Engineer (EE)	• Design the electrical system to be environmentally friendly. • Promote the health and well-being of the building occupants. • Propose alternatives to support energy conservation/generation. • Reduce maintenance costs for the owner of the building over the long run.
Mechanical Engineer (ME)	• Design the HVAC and plumbing systems to be environmentally friendly. • Promote the health and well-being of the building occupants. • Propose alternatives to support water conservation and reuse. • Propose alternatives to support energy conservation/generation. • Reduce maintenance costs for the owner of the building over the long run.



Solutions	Cost (unit)
Orient the building to take advantage of passive light and ventilation, include a small garden/playground for outdoor activities, include a parking garage building.	3
Orient the building to have the best views, moderate use of passive light and ventilation, include a small garden/playground for outdoor activities, include a parking garage building.	1
Orient the building to take advantage of passive light and ventilation, include a small park for outdoor activities, add the parking garage under the building.	4
Orient the building to have the best views, moderate use of passive light and ventilation, include a small park for outdoor activities, add the parking garage under the building	2

Figure 2: Examples of slides showing the roles and responsibilities of the Architect as well as the design solutions

The slides repeat the combined information shown in Tables 1 and 2 for each of the roles. These slides can be printed and shared with participants in face-to-face settings or shared via Google Slides in a virtual setting. For example, in a virtual setting, all architects receive the same link to a Google Slide deck with their roles and responsibilities and the solutions available to them. Other links are generated for additional slide decks for each of the roles as each participant receives information about their role only.

CATEGORIES TO FOCUS DURING THE DESIGN EXERCISE

Predefined solutions for each professional role (Table 2) were developed as part of the simulation to meet the owner's conditions of satisfaction.

Table 2: Predefined solutions (each participant receives the solutions for their role only)

Professional Role	Design Solutions	Cost (unit)
Architect (A)	Orient the building to have the best views, moderate use of passive light and ventilation, include a small garden/playground for outdoor activities, include a parking garage building.	1
	Orient the building to have the best views, moderate use of passive light and ventilation, include a small park for outdoor activities, add the parking garage under the building.	2
	Orient the building to take advantage of passive light and ventilation, include a small garden/playground for outdoor activities, include a parking garage building.	3
	Orient the building to take advantage of passive light and ventilation, include a small park for outdoor activities, add the parking garage under the building.	4
Civil Engineer (CE)	Parking lot under the building + BMPs for site water runoff.	1
	Parking garage building next to the building + best management practices (BMPs) for site water runoff and conservation on the surrounding landscape.	2
	Parking lot under the building + Retention basin in a small park + BMPs.	3
	Parking garage building + coordinated system to catch and recycle water as part of a small park + BMPs throughout the project.	4
Electrical Engineer (EE)	Use sensors to turn off lights when areas are not used and adjust light intensity depending on the incidence of natural light in different areas. Use efficient lighting systems.	1
	Use sensors to turn off lights when areas are not used and adjust light intensity depending on the incidence of natural light in different areas. Add photovoltaic panels to the project.	2
	Use sensors to turn off lights when areas are not used and adjust light intensity depending on the incidence of natural light in different areas. Use efficient lighting systems. Add photovoltaic panels to the project.	3
	Use sensors to turn off lights when areas are not used and adjust light intensity depending on the incidence of natural light in different areas. Use sensors to communicate with the HVAC system to open/close windows to achieve desired temperature. Use efficient lighting systems. Add photovoltaic panels to the project.	4
Mechanical Engineer (ME)	No HVAC system or individual heaters, design only the plumbing system.	1
	Use of individual heaters in each unit, design the plumbing system.	2
	Fully mechanically ventilated system with controls/sensors in individual units + design the plumbing system.	3
	Mixed: partial use of a HVAC system + operable windows with sensors to communicate changes to the operating system of the building + design the plumbing system	4

Considering that the course for which the simulation was originally developed addresses environmentally conscious construction, the LEED scorecard (USGBC 2022b) was used as a guideline to define the main categories addressed in the game and the main characteristics considered during the design exercise. Participants are led to discuss elements of passive design to save energy by orienting the building for best light and ventilation, open spaces for recreational use, parking location, use of best management practices (BMPs) to address the Civil side of the project and the need to retain and slowly release water out of the site per California code, and use of sensors in combination with windows and the heating, ventilation, and air-conditioning (HVAC) system to address occupant comfort and energy consumption. While decisions are made by each professional during the simulation, they have to remember that the owner has defined a budget of "10 units of currency" for this project. The cost of each predefined solution is defined in Table 2, which attempts to mimic costs associated with each solution. The cost for each solution increases as they become more encompassing and start having synergistic relationships with solutions presented by other professionals. Later in the description of the phases, the reader will notice that the best solution is not necessarily the most expensive when considered from an interdisciplinary standpoint.

LOGISTICS AND APPROACH TO RUNNING THE SIMULATION

Considering that this simulation was developed during the Covid-19 pandemic, when classes were still online, the simulation was initially played via Zoom and later in-person. In order to accommodate multiple participants in different teams, while the simulation was played on Zoom, breakout rooms were used. Finally, in the virtual environment, documents were shared with participants online via Google Drive links, with different links defined for each of the four professional roles previously described. When the game is played in person, paper copies of the roles and the design solutions are distributed to participants. Each participant only receives information about their role in Phase 1.

PHASES

Figure 3 gives an overview of how participants are assigned to groups in two phases to help the reader visualize how the phases are structured.

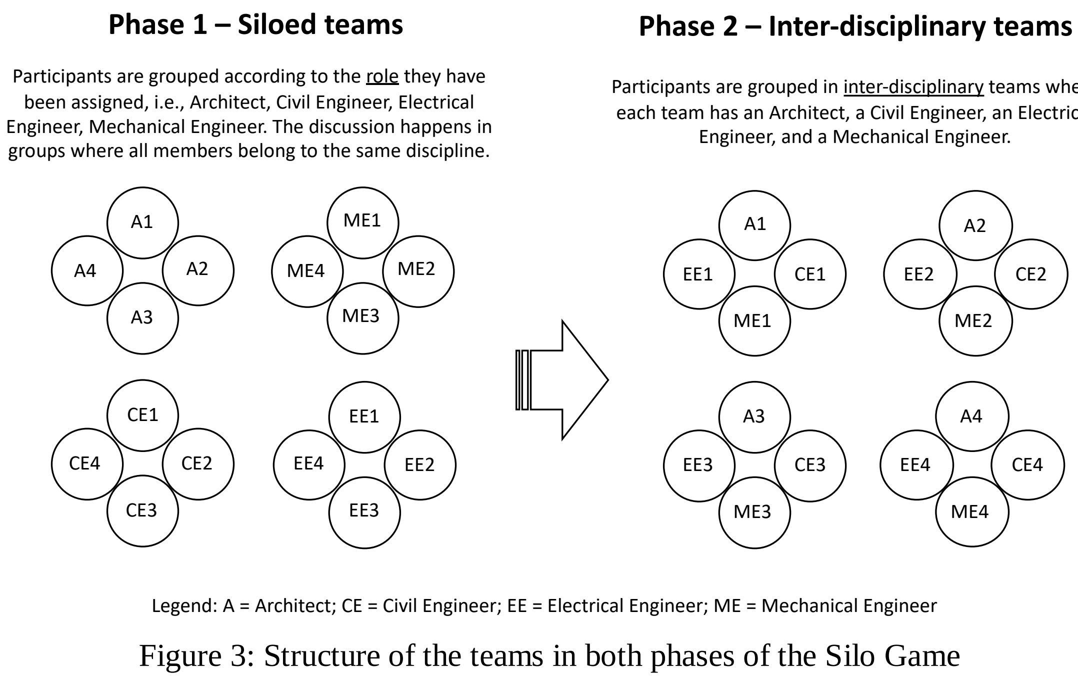


Figure 3: Structure of the teams in both phases of the Silo Game

The two phases to deliver the project previously described were defined illustrating different approaches used in this simulation. Each phase lasts for eight minutes and is described as follows.

Phase 1 – Siloed teams

Similar to the Design-Bid-Build (DBB) environment, the first phase illustrates isolation, lack of interaction and information exchange between participants of a project. During the first phase, participants are assigned a project team number (e.g., 1, 2, 3, etc.) and a specific professional role (e.g., Architect, Civil Engineer, Mechanical Engineer, or Electrical Engineer), and are put into groups with professionals with their same assigned role (e.g., EE1, EE2, EE3, EE4) to define which of the four predefined solutions indicated for their role in Table 2 will be chosen to address the owner's needs. The four professional roles should be equally split among participants to four project teams, in the case presented in Figure 3, which are separated as described in the first phase, but will be together later during the simulation.

For instance, all architects (e.g., A1, A2, A3, A4) are put into a group with other architects to mimic their interaction with peers from the same company, with whom they can exchange ideas for this particular project. The same is done for the other three professional roles. However, professionals with different roles can only communicate with their own group of professionals, as shown in Figure 3, but cannot communicate with peers assigned different professional roles and placed into separate groups. This phase also illustrates the lack of interaction with professionals from other disciplines and the lack of knowledge about what other professionals might be selecting to meet the conditions of satisfaction defined by the owner for a single project team. The professionals in Phase 1 select solutions without much, or any, regard to the cost of their own solutions and how this will impact the final project cost or how the solutions could benefit from synergistic effects obtained if solutions were coordinated among disciplines. In a real project, this would also impact the conditions of satisfaction (COS) defined by the owner and how well trade-offs could be made considering the value of each solution and their associated cost.

Phase 2 – Interdisciplinary teams:

The second phase illustrates a collaborative and interdisciplinary environment where different professionals work together to achieve the project's COS. This is similar to the environment in Design-Build (DB) and Integrated Project Delivery (IPD) projects where value is maximized through collaborative work and exchange of ideas. During this phase, participants are put together with their respective teams (e.g., 1, 2, 3, etc. as shown in Figure 3), and each team has a representative of all four professional roles to represent an interdisciplinary team. For instance, team 1 will have one Architect (A1), one Civil Engineer (CE1), one Mechanical Engineer (ME1), and one Electrical Engineer (EE1), who will all work together to meet the client's goals. Participants are instructed to discuss how their solutions help achieve the goals of the project and meet the cost defined by the owner.

Moreover, considering that some of the solutions have synergistic relationships, participants are rewarded for that with cost reductions for their design. For instance, the facilitator might remind participants that if the architect properly orients the building to take advantage of passive light and ventilation, less energy will be consumed; this is one example that can be shared during the simulation. During this phase, participants should have some basic understanding of how the categories considered in all four professional roles are related to one another. The author also played this simulation with freshmen students in an introductory seminar to the field of Construction Management and all students were well aware of these relationships.

For each solution selected by the project team that addresses an additional category (i.e., by displaying synergistic relationships as previously described) the cost of the solution is reduced by 2 units. For example, if a design solution selected by the electrical engineer (EE) helps the mechanical engineer (ME), the solution from the EE and the ME each get a 1 unit cost reduction lowering the cost of the combined solution. This aims to illustrate the fact that sustainable solutions are not more expensive than traditional solutions when they are considered from an interdisciplinary standpoint. This activity also mimics the work of cross-functional design teams, or clusters, tasked with developing solutions for specific systems in a project considering interdisciplinarity (Lostuvali et al. 2014).

Report out and debrief

The time limit was defined for this task considering the time allocated for the entire simulation which ideally should fit within a class period of 50 minutes. Ultimately, the time given to the teams was eight minutes in each phase, followed by 10-15 minutes of discussion after each phase so that participants can share lessons learned and observations. During the reporting breaks, after each phase, participants are asked to share:

- What is the final cost of their project?
- Each breakout room enters the cost of the solution adopted by their respective discipline either in a spreadsheet shared online or report to the facilitator who enters the cost of each solution defined for each group on a board or shared computer screen.
- What are your impressions of the phase being discussed (1 or 2)?
- Could the team meet the budget and the client's requirements?
    - Yes/No?
    - What happened?
    - What worked and what didn't work?

DISCUSSION

So far, the Silo Game has been played with freshmen, junior, and senior students at San Diego State University and also with the APLSO community. Feedback has been gathered but the simulation has not been changed from its original version by the author. However, those interested in playing this simulation are free to make adaptations while making proper attributions to the author considering the Creative Commons attribution CC BY-NC-SA 4.0 (Creative Commons 2022).

During the game plays, feedback gathered so far indicates that participants learn during Phase 1 (siloed) that they are prone to fail as decisions are made based on the information from a single discipline who might choose what is best for their specialty area but might not meet the budget requirements defined for the project. Results have been tabulated live during the simulation, however, they have not been kept for reporting purposes after each play. In Phase 1, participants invariably do not meet the cost defined by the client as each siloed group picks the best option for their discipline without much regard to the solutions and related costs chosen by other disciplines. After this phase, participants share their frustration regarding not knowing what other disciplines have selected.

During Phase 2, participants meet the conditions of satisfaction rather quickly after having become familiar with the design solutions they have. During the APLSO play, participants (who were in general more experienced in the construction industry) noted that while synergies can be taken advantage of, the trade-offs made regarding each design solution selection do not have the same cost, and that the focus should be on value for the client not on cost. Participants also pointed out to the need to have teams develop their own conclusions about the lessons learned within their group, and later share them with the broader group to avoid groupthink. During the discussion in each phase, special attention can be given to topics related to collaborative versus siloed delivery methods and construction contracts, the level of understanding achieved by the teams during the collaborative phase, and the definition and achievement of a target value and conditions of satisfaction for the project as illustrated by what the owner wants given the project monetary constraints. Finally, thanks to the suggestion of one of the anonymous reviewers of this paper, this simulation could also address the role of rework that happens between Phases 1 and 2. Participants could be asked to document if and how their solutions changed between phases and a rework cost could be added to that change. Questions could be asked about who pays for the rework and how that impacts the final cost of the project, the time to resolve changes, and the potential impact on client satisfaction.

CONCLUSIONS

This paper described the development and related rules of the Silo Game, which was originally developed to mimic the development of an environmentally conscious project and teach important concepts related to interdisciplinary work, design synergies, collaboration, and sustainability. Participants with various levels of construction experience from undergraduate freshmen to academics and professionals played this simulation. The game has proven to be simple and easy to grasp and play, potentially adaptable to teach different subjects using its basic design, and to promote a rich discussion about the impacts of siloed decisions (e.g., in DBB projects) versus collaborative ones (e.g., DB and IPD projects). Various Lean tenets and systems including integrated project delivery contracts, target value design, collaboration, and conditions of satisfaction can be discussed during the game play and any or all of these topics can be illustrated by the process mimicked in this game.

ACKNOWLEDGMENTS

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EVALUATING BLOCKCHAIN IN CONSTRUCTION SUPPLY CHAIN MANAGEMENT

Danial Gholinezhad Dazmiri[1], Ramin Aliasgari[2], and Farook Hamzeh[3]

ABSTRACT

The supply chain in the Architecture, Engineering, and Construction industry is often perceived as inefficient due to a lack of data and traceability links. This study investigates the practitioners' understanding and acceptance of blockchain to address this inefficiency. A survey is conducted to glean expert opinions concerning implementing blockchain technology in the Construction Supply Chain Management (CSCM) domain. The research hypothesizes that professionals are open to blockchain technology adoption and that this adoption positively impacts four variables that represent the primary factors that can be implemented using blockchain technology. The One-Sample Test of Means is then used to evaluate the four identified variables against the hypotheses. Survey findings reveal that CSCM experts are knowledgeable about innovative technologies such as blockchain and believe that all characteristics of blockchain should be considered during implementation. Findings also show that most experts acknowledge that their current CSCM systems disregard blockchain entirely.

KEYWORDS

Blockchain, Supply chain, Smart contract, Lean construction, Trust.

INTRODUCTION

The Architecture, Engineering, and Construction (AEC) industry confronts various difficulties, including supply chain fragmentation, insufficient information and manufacturing traceability integration, and lack of innovation (Koskela, 2000; Hamzeh, 2021). Construction Supply Chain Management (CSCM) regulates managing the movement of information, money, and materials throughout the lifecycle of a project (Vaidyanathan & Howell, 2007). Modern Supply Chain Management (SCM) practices advocate executing the supply chain as a continuous value creation stream rather than a collection of discrete processes (Vrijhoef et al., 2001). SCM suffers from insufficient standardization and process integration, resulting in an inability to meet industry requirements (Atiq et al., 2021). Papadopoulos et al. (2016) highlighted further shortcomings in existing CSCM practices, including lengthy design processes, document modifications, and frequent misunderstandings. Finally, a lack of trust and transparency,

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combined with the current payment methods, contributes to the current CSCM's inadequate performance, which blockchain technology (BCT) might assist in addressing (Shemov et al., 2020).

With the dawn of Lean construction 4.0, the urge to integrate smart technologies and digitalization to boost performance and production while eliminating waste is more crucial than ever. While there are multiple ways to increase the "Leanness" of CSCM, one of the most promising means is the use of blockchain technology to decrease waste and increase value (Tezel et al., 2020). Although blockchain is a relatively novel technology that has not been widely embraced in the construction sector, it can help improve the business considerably, particularly in the CSCM domain (Tezel et al., 2020). A blockchain is a decentralized system that stores and manages information and transactions (Dakhli et al., 2019). Blockchain technology saves data in blocks that build a chain of blocks that records each piece of data (Mason, 2017). Once added, records can only be modified by impacting all the primary data, which exceptionally can be used for corporate processes or developing decentralized currencies (Baumers & Holweg, 2019). Nawari and Ravindran (2019) provided an overview of blockchain technology and its uses in the AEC industry and possible inclusion in the Building Information Modeling (BIM) procedure. Their research examines how blockchain technology may benefit the BIM process by focusing on network security, offering more reliable data storage and traceability, using Smart Contract technology, and verifying data ownership (Nawari & Ravindran, 2019).

According to the emerging literature, the most common application of blockchain that is increasingly being used in supply chain processes is digitalization, transparency, visibility, and smart contracts (Nabipour & Ülkü, 2021). Perera et al. (2021) investigated the principles of blockchain technology and its advantages. They regarded Decentralisation, Immutability, Transparency, Security, Auditability, and Trust are features of blockchain-based procurement procedures in the AEC sector. Wang et al. (2019) indicated that blockchain applications in construction management might be used to authenticate documents, automate payment and processes, and increase transparency and traceability. CSCM involves many documents, such as design documents, blueprints, terms and conditions, contracts, and agreements. Blockchain technology may help reduce the time and effort necessary to verify them and increase transparency. This may be performed by adding a unique identifier to the blockchain (Cresitello-dittmar, 2016).

Trust among participants and stakeholders is essential for a free flow of information and resources throughout a project, which is difficult to achieve amidst the current methodologies. As a result, third parties are virtually always involved to ensure that transactions run smoothly (Dakhli et al., 2019). Professionals such as lawyers and financial organizations serve as intermediaries, and these transactions take a substantial amount of non-value-added time and effort to complete. Smart contracts are one solution that satisfies traditional contractual limitations while simultaneously lowering expectations and eliminating the requirement for trustworthy intermediates. One type of smart contract is an automated contract to purchase and pay for goods and services. Smart contracts may begin the payment after all prerequisites have been met and completed (Hughes, 2017).

Data about the supply chain is not necessarily visible, accessible, or trustworthy. Quality control is simplified by quality traceability and an open information flow that enhances transparency in the supply chain. Traceability may act as reliable quality control by highlighting any possible defects. As a result, the requirement for traceability across the supply chain is critical (Zhang et al., 2020). However, the most critical aspect of traceability is identifying and collecting relevant information that may be used in the future (Olsen & Borit, 2013). Although some promising new technologies, such as the blockchain, have been established, the AEC industry has usually been one of the slowest industries to accept new technologies (Foroozanfar et al., 2017). The unwillingness of stakeholders to provide information due to potential conflicts of interest is another factor slowing blockchain adoption in the AEC industry (Longo et al., 2019).

Implementing new and smart technologies requires all aspects and components of the industry to accept the improvement culture. A Lean culture that seeks continuous improvement within the industry requires transparency, the value offered to customers, and proactive input may all be improved (Hamzeh et al., 2021).

Also, as blockchain provides a high level of openness, companies may be less likely to use it. Zhang et al. (2020) developed a framework to help with traceability and quality control. Their study used three smart contacts to accomplish a set degree of traceability via blockchain. The study found that conservatives' adoption resistance and stakeholders' reluctance to reveal private information were among blockchain's challenges (Zhang et al., 2020). Also, because of the blockchain's novelty, organizations claim to have limited information about smart technologies (Longo et al., 2019).

Additionally, the AEC industry is likely to lack innovative technology and digitization facilitated by blockchain. This is due to the AEC industry's ineffective organizational transformation management (Maali et al., 2020). The question that is thus raised is regarding CSCM's expertise in blockchain technology and its adoption as a novel and smart technology. Therefore, this study wants to determine how blockchain is understood and accepted in CSCM by analyzing responses from industry professionals. This will aid in the development of future blockchain concepts and applications within CSCM.

METHODOLOGY

The AEC industry is concerned about the effectiveness of the operations in the projects since there is a lack of expertise and perspective in the industry (Hamzeh et al., 2021). One of the obstacles facing blockchain implementation is a lack of knowledge and acceptability. Therefore, this research evaluates the industry professionals' opinions on new and smart technologies and their knowledge of blockchain technology and its execution in the construction supply chain. The study hypothesizes that professionals are willing to adopt blockchain technology and that this adoption has a beneficial impact on four variables that represent the primary factors that can be implemented using blockchain technology. In this regard, following a literature review, data collection was conducted. The covid-19 outbreak and its related limitations restricted the methodological approach. Due to the difficulty of visiting construction projects and companies, the most secure data collection method was via a web-based questionnaire. The survey was made available by contacting several companies and emailing them a link to the survey.

The survey is developed based on blockchain characteristics and distributed among respondents. The questionnaire includes 17 questions divided into two sets. The first set contains two questions and analyzes respondents' frequency distribution according to their socioeconomic characteristics. The second section includes 15 questions categorized into the four variables addressed through the survey. The variables for the research are chosen through the literature review. According to the reviewed literature, the factors that can be implemented using blockchain technology in the construction sector include visibility, smart contracts, transparency, and digitalization. The methodology diagram is shown in Figure 1.

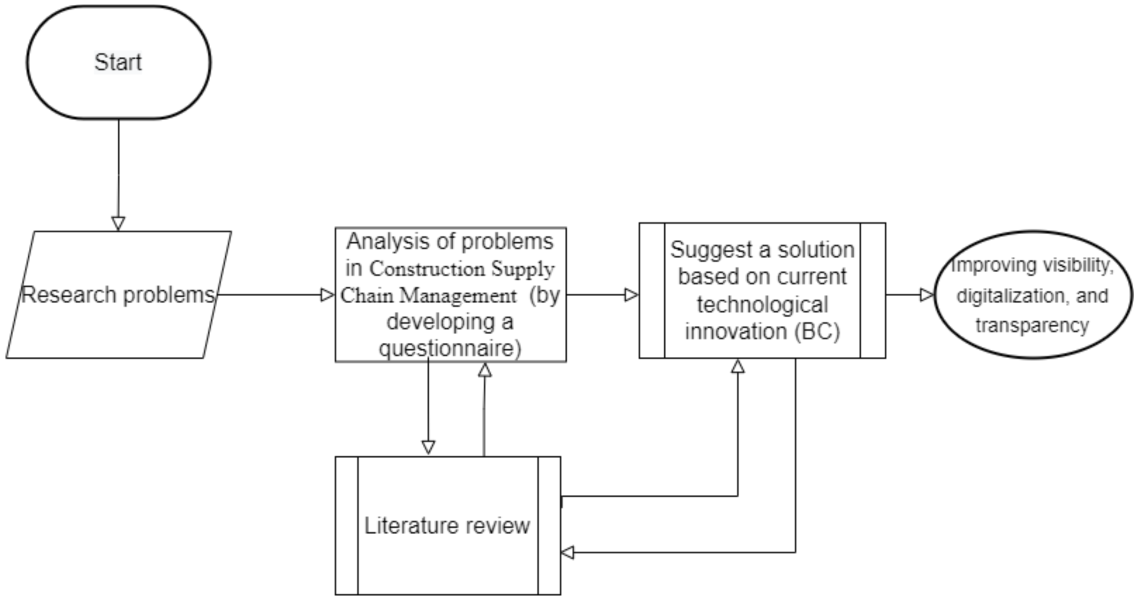

Figure1: Methodology diagram

Each answer is rated on a five-point scale derived from the Likert model. The participants use this scale to determine their agreement with the variables based on predetermined levels. These levels are sequential and indicate the degree of understanding from lowest to highest. The five-point Likert scale, in this case, is one as “totally disagree,” three as “disagree,” five as “neutral,” seven as “agree,” and nine as “totally agree.” As a result, the mean result of comparing the respondents’ opinions is five.

In statistics, the One-Sample Test of Means can compare two sets of data containing a single value. This test is available in two parametric and non-parametric modes: the One-Sample T-test is used in the parametric model, while the non-parametric model employs the One-Sample Wilcoxon Signed Rank Test.

To choose the appropriate mode of analysis for the questionnaire, two conditions must be considered: questionnaire reliability and data normality (Gotama & Simamora, 2022). Reliability is one of the measurement tools’ technical characteristics. This concept refers to how a measurement tool produces identical results under conditions. The accuracy of its results primarily determines a measurement tool’s reliability. In general, reliability is a term that can be used interchangeably with accuracy. A reliable tool is capable of reproducibility and obtaining consistent results.

The next thing to consider is the normality of the data as an assumption of parametric testing (Mishra et al., 2019). The Kolmogorov–Smirnov (K–S) test is done to evaluate the normality of data. The null hypothesis is that the variables are normal in a normality test. A null hypothesis asserts no statistical significance difference between the two possibilities.

RESULTS

In order to carry out the survey, a web-based survey was used. The email was sent out to around one hundred fifty employees working for CSC. One hundred twelve responses were received, and the following section provides the results. The survey commenced with the question about the respondent's job experience. Work experience is one of the respondents' characteristics. The participants in this study are classified into four broad categories based on their work experience. Not having worked for more than ten years, this group accounts for 75% of the total sample. The work experience groups of 10 to 20 years and over 30 years, which accounted for approximately 7% of the total sample, had the lowest frequency. Finally, 20 to 30-year-olds accounted for 13% of the total sample. Finally, 20 to 30-year-olds represented 13% of the whole piece. Figure 2 presents the frequency of this characteristic among respondents.

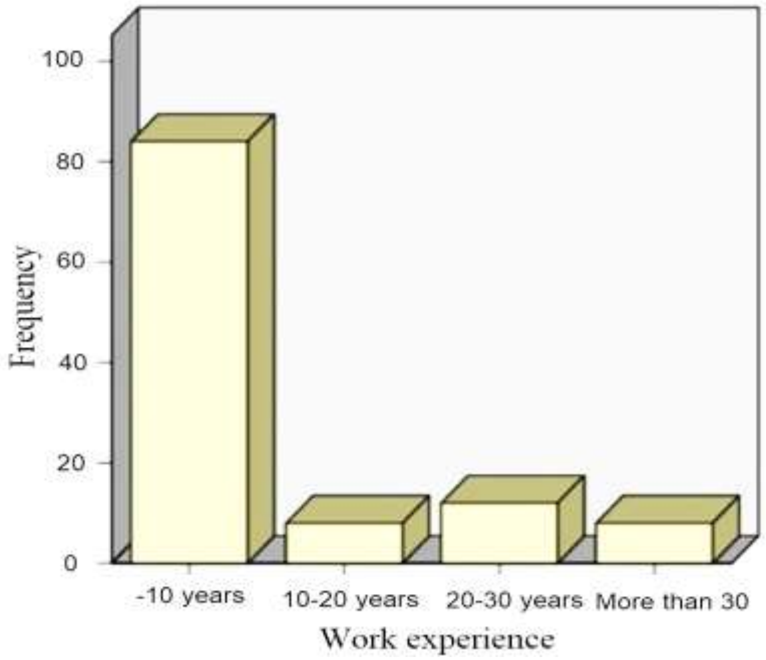

Figure 2: Three-dimensional bar chart of respondents' work experience

Moreover, the participants were asked about four majors of experience as the procurement specialist, construction engineer, project manager, and other disciplines for the experience. The result shows that the highest frequency is related to the procurement specialist group, with more than 38% of the sample volume. Moreover, the circular diagram of the respondents' field of experience is in Figure 3.

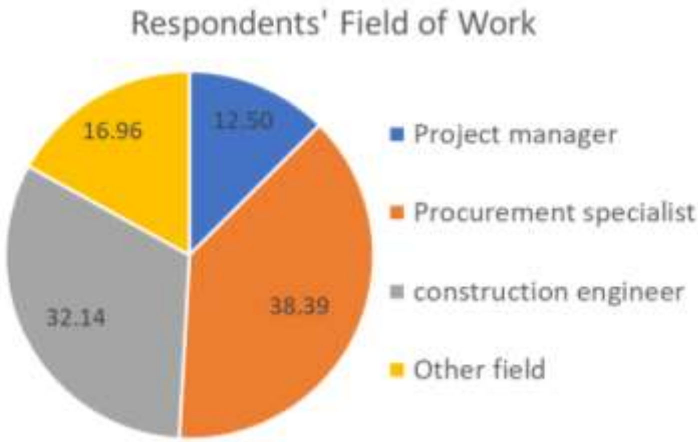

Figure 3: Circular diagram of the respondents' field of work

As previously stated, this research applies the 5-point Likert scale. The average score for the research variables is greater than the median, indicating that the variables have an above-average success rate. Table 1 summarizes the findings for the research variables, and Table 2 shows the variable's average for different work experiences.

Table 1: Descriptive Statistics

Variables	Median	Average	Standard deviation
Visibility	5	5.539	1.5241
Transparency	5	7.310	1.9066
Smart contract	5	6.457	1.6302
Digitalization	5	7.32	1.992

Table 2: Variable's average for different work experiences

Work experience	Frequency	Average			
		Visibility	Transparency	Smart contract	Digitalization
-10 years	84	5.66	7.12	6.43	7.14
10-20 Years	8	5.75	7.92	6.20	8.00
20-30 Years	12	4.96	7.89	7.00	7.67
+ 30 Years	8	4.90	7.83	6.20	8.00

Figure 4 shows the histogram charts for the research variables, including the average and standard deviation.

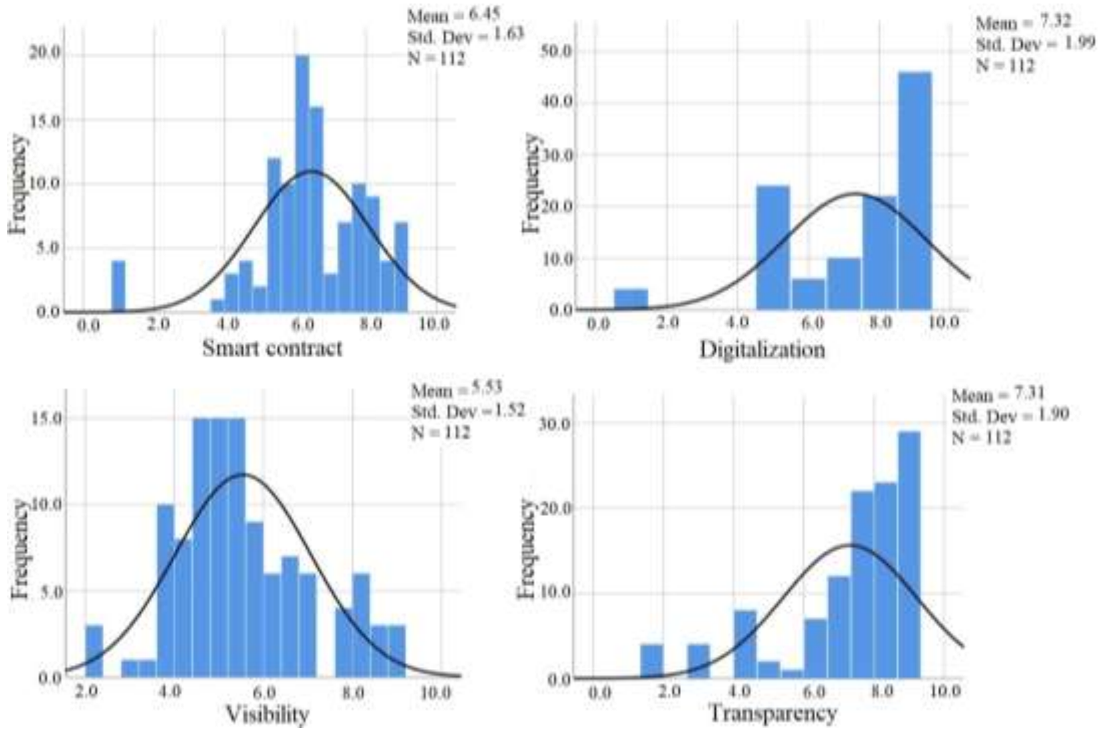

Figure 4: Histogram charts for the research variables

The reliability of a questionnaire could be evaluated using Cronbach's alpha coefficient. Values above 0.7 for this coefficient indicate high reliability, while values between 0.5 and 0.7 indicate acceptable reliability. Table 3 examines the reliability of the questions.

Table 3: Cronbach's Alpha Coefficient for Variables

Variables	Questions	Cronbach's Alpha Coefficient
Visibility	5	0.707
Transparency	3	0.778
Smart contract	5	0.785
Digitalization	2	0.882

According to Table 3, it can be concluded that the reliability assumption of the questionnaire is confirmed. The Kolmogorov–Smirnov (K–S) test for normalcy is reported in Table 4.

Table 4: K-S Test Coefficient for Variables

Variables	Static	Sig. (2-tailed)
Visibility	0.144	0.001
Transparency	0.235	0.001
Smart contract	0.133	0.001
Digitalization	2.109	0.001

If the null hypothesis is not banned at the level of 0.05 (when the significant rate is greater than 0.05), it would be concluded that the data related to the tested variable follow the normal distribution, and they do not reject the normality hypothesis. However, if the null hypothesis is rejected at the level of 0.05 (a significant value is less than 0.05), the data relating to the tested variable would not have a normal distribution. As shown in Table 4, the assumption that the data is normal for all research variables is rejected. Therefore, the non-parametric method, One-Sample Wilcoxon Signed Rank Test, should test the research hypotheses. The following is the result for testing each hypothesis.

The first one is about the effect of increasing visibility in implementing blockchain in the construction supply chain. The null hypothesis for this test is that there is no statistically considerable difference between the mean of the respondents' answers and the score's mean value, which is five.

According to Table 5, this assumption is rejected (the significance level is less than 0.05). Therefore, there are significant differences between the mean of the answers given to all variables, and the mean value and differences are in a positive direction. This means that increasing all aspects effectively implements blockchain and new technology systems in CSCM. Therefore, the hypothesis of the study is confirmed.

Table 5: One-Sample Wilcoxon Signed Rank Test

Variables	Static	Sig. (2-tailed)
Visibility	3.213	0.001
Transparency	7.925	0.001
Smart contract	7.440	0.001
Digitalization	7.272	0.001

DISCUSSION

The average score for all factors is greater than the median, and the differences are positive. Therefore, increasing transparency, visibility, digitalization, and implementing the smart contract effectively facilitate implementing blockchain and new technology systems in the construction supply chain. As our hypothesis, we hypothesized that adding blockchain technology will lead factors to have positive effects on enhancing AEC. As a result, the study hypothesis has been validated.

Each variable had a mean score greater than the median, indicating that each variable was significant in the opinion of experts. According to Table 1, digitalization and transparency scored higher than the other two variables, indicating that these two variables have a more significant impact.

Moreover, the average visibility score is 5.5, while the average smart contract score is 6.4. This demonstrates that these two have not been well-introduced compared to other variables. It could also imply that they did not demonstrate an urging need in the industry. Smart contracts and visibility contribute to the CSCM with the assistance of a third party, like a bank or a lawyer. This may explain why experts in the CSCM place a premium on matters directly related to them.

Comparing each variable's average across different work experience classes in Table 2 shows that digitalization scored the highest in -10 years, 10-20 years, and more than 30 years of work experience. Consequently, this variable has a more significant effect than the other factors. However, transparency has the highest average in 20-30 years of work experience class. Figure 5 shows the Hypothetical Median and the Observed Median of each variable.

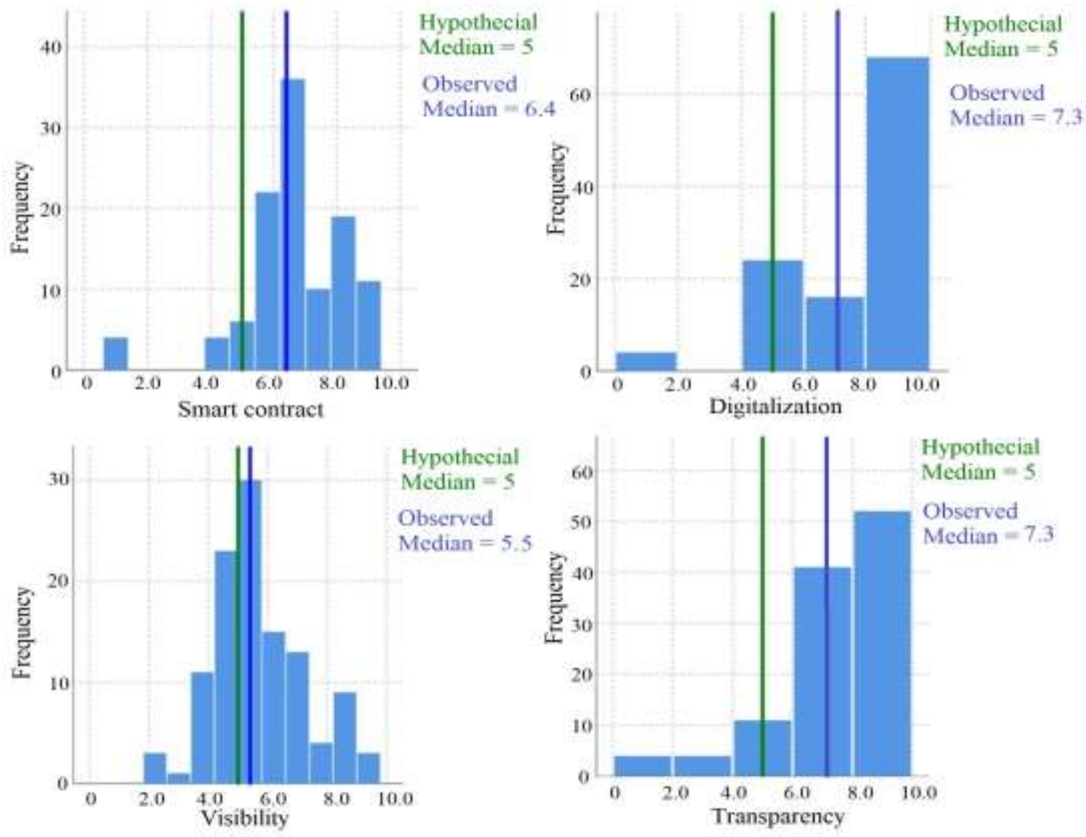

Figure 5: the Hypothetical Median and the Observed Median of each variable

Transparency may increase mutual trust and risk sharing, as all parties have access to the data preserved in CSCM. According to participants' responses, it is clear that all experts understand the critical nature of trust and transparency in completing a project, as traceability, which comes with digitalization, contributes more to quality control during the CSCM. RFID, sensors, software, and other tools or artificial intelligence techniques that enable tracking and tracing a product throughout CSC may help improve quality.

CONCLUSIONS

This study examines the adoption of blockchain technology in CSCM and the significant differences among the respondents' assessments of blockchain benefits on visibility, transparency, smart contracts, and digitalization in implementing blockchain systems.

As a result of this research, it is concluded that implementing blockchain technology in the construction industry would benefit industry professionals. However, due to the recorded survey questions' average scores ranging from 5.4 to 7.3, there is still a long road to adopting this technology. To further address the limitations of the research and the obtained results, future research can investigate additional hypotheses and variables to evaluate their effect on implementing blockchain in the construction industry generally and construction supply chain specifically.

Integrating blockchain into CSCM allows for the following benefits:

- Redesigning the process to achieve a high value-added and continuous flow. This may be achieved by eliminating idle or waiting for a third party to perform on a project. Blockchain allows for automating this procedure and thus facilitates the flow.
- Eliminating unnecessary burden on people and equipment as avoiding inconsistency in the supply chain schedule is just as critical as avoiding waste.
- Utilizing blockchain as a reliable and thoroughly tested technology to assist people.
- Creating operations that need very little inventory. This will make a waste of time and resources readily apparent to everybody. Once the waste is identified, staff could be encouraged to reduce it through a continuous improvement approach (Kaizen).

Other researchers could conduct future research on examining the result of blockchain technology deployment in enhancing productivity in the CSCM. Data collection methodologies were constrained due to the covid-19 epidemic. However, we encourage other researchers to employ different methodological methods (e.g. interviews) for comparable studies.

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DEVELOPMENT OF SIMULATIONS & PULL PLANNING FOR LEAN CONSTRUCTION LEARNING AND IMPLEMENTATION

Cynthia C.Y. Tsao[1] and Gregory A. Howell[2]

ABSTRACT

To manage projects based on Lean principles including global optimization, transparency, reliability, and flow, Lean learners need to learn an alternative approach that includes different language and techniques that better support production system management. By helping us model what happens in the real world while focusing on a few key concepts, simulations help Lean learners focus on how they would diagnose problems and determine how to deliver the project better. While Lean learners may think they are learning *something* during simulations, instructors are really getting them to reflect on *how things happen and why*. In essence, simulations help with "learning to see" waste and other problems on projects (Rother and Shook 1999) so Lean learners can develop strategies for waste removal and problem solving to generate value better.

How did the Lean Construction community adopt this training approach for Lean learners? This paper explores the Lean Construction community's use of simulations (particularly the Airplane Game and Parade of Trades®) and creation of the Pull Planning technique. This reflection provides a foundation for instructors to share training practices and collaboratively refine their teaching approaches to accelerate the rate of Lean learning and implementation.

KEYWORDS

Simulations, Pull Planning, facilitation, action learning/research, learning

RESEARCH MOTIVATION

Simulations help Lean learners evaluate from a flow- and efficiency- perspective how project team members are managing production system design and control on Architecture-Engineering-Construction (AEC) projects. By practicing this method of inquiry, Lean learners start learning to see the root causes (e.g., behaviors, contractual frameworks, resource availability, and traditional practices) behind the roadblocks to workflow found on AEC projects. Through simulations, Lean learners develop hands-on experience in measurement-based continuous improvement. This is important because managing continuous improvement and respect for people should not only be a business goal but rather a fundamental way of being that helps companies improve not only their competitive edge but also the quality of their employees' work lives (Spear 2010).

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2 Retired, Lean Construction Institute; Greg developed this paper with Cynthia starting in 2014. He passed away on June 15, 2020.

Accordingly, this paper seeks to document the development and evolution of simulations and Pull Planning to provide a foundation for future researchers to: (1) share their theoretical frameworks and best practices regarding Lean training and implementation and (2) work collaboratively to improve and refine their teaching approaches to help accelerate the rate of Lean learning and implementation in the AEC industry. This paper also seeks to help researchers recognize that effective simulations take time to develop, so rapid prototyping and sharing simulation improvements is critical in advancing Lean learning and implementation (Rybkowski et al. 2021).

RESEARCH METHODOLOGY

The authors developed this research through interviews with primary sources and supplemented the study with a literature review. The first author shared drafts of the study with the primary sources, followed up with them to confirm that their experiences were accurately portrayed, and made revisions based on their feedback whenever needed.

ALL PARTIES FORUM & USE OF SIMULATIONS

In 1979, Greg Howell and Glenn Ballard started collaborating in a productivity improvement initiative on the construction of an ethylene plant near Alvin, Texas. On the project, they found that they had a common interest in systems thinking and began investigating how to represent a systems-based approach on the meeting room wall for project teams as well as how to intervene in ways to improve project performance.

By the early 1980s, Greg Howell started assisting companies with improving construction productivity through Timelapse Inc. and amassed a collection of movies that illustrated construction productivity problems. At one point, he considered, "Is there only one solution for each problem, or is there actually a solution space that contains multiple solutions? Before you could implement any solution to the productivity problem, could you get everybody to agree on the change?" With help from Clark Oglesby and Hank Parker of Stanford University, Greg organized an All Parties Forum in the mid-1980s in Palo Alto to explore these questions with representatives from different AEC project stakeholders (e.g., business agents, contractors, and designers).

In the initial meeting, attendees formed mixed groups, watched the time-lapse movies, studied the relevant data, and proposed improvements acceptable to all parties. After taking about an hour to develop the group solutions, the attendees gathered as a large group to review the various proposed solutions and implications for AEC industry practice. Many attendees enjoyed the exercise and suggested that they meet again with the same meeting format. As a result, Greg and Glenn started organizing a series of these forum meetings every six to nine months over the next 10 years.

During earlier All Parties Forum meetings, one attendee shared the simulation "Win as Much as You Can," and another attendee, organizational development consultant Jerry L. Talley, introduced the group to the simulation "Build as Many Roads as You Can" (Howell 2011). Attendees enjoyed these simulations because they allowed the group to explore the advantages of competition versus cooperation. Competition/cooperation simulations are designed to make participants consider the larger opportunity to behave badly, as they decide whether they will work with or fight against others in the situation created by the simulation. The All Parties Forum meetings that featured simulations often generated deep, value-adding discussion for the attendees. As a result, attendees willingly tried different simulations whenever they were introduced at the meetings.

Greg noted, “I like to use simulations because I learn best by doing. Others don’t so you can’t rely on them entirely… I prefer exercises that isolate on a single issue or principle and make it very apparent at least by the end. This type of simulation is realistic in that it illustrates some bit of theory in action… or it puts people in a dilemma much like they experience in life… More ‘realistic’ simulations are just too complex and have too much going on to allow careful focus when processing… Running simulations is always manipulative because unlike lecture, the test comes first… Simulations put people in the middle of a dilemma or reveal some fundamental relationships operating but hidden in practice” (Howell 2009).

Following World War II, the Associated General Contractors’ (AGC) New Mexico Building Branch endowed the construction management and engineering chairs at the University of New Mexico (UNM). Then, the AGC-New Mexico committee and board members were involved in soliciting, reviewing, and hiring candidates for these positions every five years (Graystone 2022). As a result, in 1987, UNM appointed Greg as the AGC Visiting Professor. Meanwhile, his wife Dana worked on a leadership team that was restructuring public education in New Mexico. Through her work, Dana attended an Institute of Cultural Affairs’ course in facilitation taught by Tim Karpoff. Tim works with business, government, and non-profit organizations on strategic and project planning. Dana introduced Tim to Greg, and they began facilitating partnering and leadership development programs together. In these sessions, Greg continued to test and use simulations to help attendees develop common project goals.

These programs featured not only the simulations that emerged from the All Parties Forum but other simulations as well that explored team building and organizational issues. These simulations were very similar thematically as they tested groups in establishing who was in charge of the project and how to get to a group solution. Greg gained many personal lessons and insights from administering and participating in the simulations, so he became passionate in using, developing, and refining simulations. Since simulations could appeal to different learning styles of workshop attendees (Hawk and Shah 2007), he found them to be more effective (in comparison to presentations) in helping project team members consider different principles to guide their efforts and behaviors on projects. Greg also began exploring more Lego® simulations to study production system design challenges, including a partially developed Lego® Hotel simulation (Howell 2009).

Meanwhile, although attendees enjoyed the intense discussions about the state of AEC practice at the All Parties Forum meetings, they came up short in terms of developing a solution for organizational learning. As a result, the All Parties Forum attendees eventually decided to stop meeting. However, during the last meeting in a Northern California restaurant in the mid-1990s, Jerry Talley was exuberant because he noted that the lack of a common organizational learning solution indicated that there might also be a lack of a learning language for how work happens. He convinced Greg and Glenn to meet with him the next day to develop that language (Howell 2011).

FOUNDATIONS OF LPS, INTRODUCTION OF AIRPLANE GAME, AND CREATION OF PULL PLANNING

Led by Jerry, Greg and Glenn developed “Work Mapping” as a graphical tool. When they realized that “Work Mapping” was similar to the IDEF0 method for modeling decisions, actions, and activities (Grover and Kettinger 2000), they refined “Work Mapping” further and “called [it] Activity Definition Process, consisting of a process box with circles entering from [the] top, left, and bottom, representing directives, information and materials, and resources, respectively (P2SL 2022). An arrow coming out of the left side of the box pointed at Output. There was also a check loop to answer the question if the Output matched what was expected in the Directives" (Ballard 2019). The Activity Definition Process then provided the graphical framework for the Last Planner® System (LPS). With this basic LPS framework in place, Greg left UNM and started the Lean Construction Institute (LCI) with Glenn, Iris Tommelein, and Todd Zabelle in August 1997. Greg and Glenn adopted the term "Last Planner® System" (Ballard 1994) because "the participants [in planning meetings] have been the 'last planners'; i.e., the front line supervisors who speak for the direct workers that are members of their work group" (Ballard and Howell 2003). Through LCI, they met with companies that were interested in improving project management and changing the status quo on AEC projects. Through those meetings, Greg and Glenn recruited projects to gather data to test and improve the LPS framework. Meanwhile, Iris provided the first operations science-based explanation about how pull-based Lean Construction processes were more "responsive to customer needs and therefore superior in performance" (Tommelein 1997, 1998, & 2015). This provided an initial justification for introducing Pull Planning into the LPS framework.

Meanwhile, David Neenan, founder of the Neenan Company (TNC) in Fort Collins, Colorado, had been organizing 2-day learning symposiums each year for their clients, consultants, employees, and trade partners. After assisting TNC with a symposium based on innovation, Hal Macomber started consulting with TNC in the mid-1990s and challenged TNC's Design Manager, Mike Daley, to "do something more than just be a foot soldier" (Daley 2022a and 2022b). With that challenge, Hal gave Mike a copy of *The Machine that Changed the World* (Womack et al. 1990) and instructed him to read it in terms of: (1) What are the authors' claims, and are they grounded? (2) What can you see in this book that is like the AEC industry? (3) What are our opportunities based on what you read in this book? Inspired by the book's Chapter 4 about "Running the Factory," TNC began a study-action effort in November 1996 to get through the first 15% of design within one day in-person with their clients and called this effort "Schematic Design in a Day" (SDIAD) (Miles 1998; Daley 2022b and 2022c).

Mike then read *Lean Thinking* (Womack and Jones 1996) and reached out to Jim Womack to learn more. Jim helped Mike contact Doyle Wilson, the homebuilder in Austin, Texas, that was featured in *Lean Thinking*. Mike, David Neenan, and Hal Macomber visited Doyle and saw him use "Lean Zone® Production Methodologies" to train the trade partners on his projects. Lean Zone® is a cellular manufacturing simulation developed by Michael Deese of Visionary Products for Santech Industries (Visionary Products 2014). Known colloquially by the Lean Construction community as "the Airplane Game," the Game helps workshop attendees learn about the value of managing work in smaller batches, introducing pull into a production system, and balancing workflow to increase productivity while achieving better quality.

Doyle also shared how his company was working under a standard process for building houses within 60 days using a one-day takt, and they were working on achieving a faster delivery by using a half-day takt (Macomber 2022 and Daley 2022b). This process resembled Pull Planning in some ways, but it was still a work in progress because it was hard for Doyle to get his trade partners organized like a manufacturing line, and weather delays further hampered their efforts (Daley 2022b). As a result, it was not yet fully developed and working during TNC's visit.

Around this time, Mike reached out to LCI after reviewing an LCI flyer shared by a coworker because LCI's goals resonated with TNC's learning and continuous improvement efforts. Then, guided by the principles outlined in *Lean Thinking* and influenced by their visit with Doyle, Mike and Hal started working with Greg and Glenn at TNC's offices to test how the Activity Definition Process could improve the LPS framework. At this time, the early design of the LPS "did not have a macro level Pull scheduling for the overall schedule method, as I remember it, more at the task level from the lookahead to the two week" (Daley 2022c).

Given TNC's preference to work as a Design-Builder, Mike suggested that they start with value for the client, that is, to determine the Conditions of Satisfaction (CoS) for the client and start working backwards from there (Daley 2022a). Daley (2022c) clarified, "we started using the big sheet to begin at the end and work backwards, since computer scheduling (the present system at the time) could not work backwards." As a result, they first clarified what generated value for the client, and then mapped the value stream starting from the end – thus creating the technique of "Pull Planning."

Once they refined this approach, TNC integrated Pull Planning into SDIAD and later renamed it the Collaborative Design Process (CDP) when "they realized they had a solid way to have the 'customer define value' which was the first principle [identified] in *Lean Thinking"* (Daley 2022b). Daley (2022b) noted that "the third principle, 'Make it Flow,' seemed easy to understand [within the AEC industry] as it was every superintendent and subcontractors dream that never actually occurred on the jobsite or within design. The fourth principle was 'Pull,' and it was easy to see how this was 180-degrees from what was done in the design and construction industry as all we did was push. Womack says to start at the end and Pull backwards. Traditional scheduling software did not allow this to occur. Per other companies adopting lean, TNC went simple" and hung a 7' tall x 40' long (2 m x 12 m) sheet of ripstop nylon on the wall (Daley 2022a) and attached small pieces of paper with tasks handwritten on them to it by spraying the ripstop nylon with 3M repositionable adhesive spray. Then, the CDP process began with "client move in" and worked back to the beginning of design (Daley 2022b). Meanwhile, inspired by their visit with Doyle Wilson, TNC started facilitating the Airplane Game during their projects and learning symposiums *(ibid).* After attending TNC's leaning symposiums as a keynote speaker, Jim Womack invited Mike to start participating in Lean Enterprise Institute (LEI) conferences to share TNC's experience with other companies and industries.

In December 1997, LCI invited TNC to attend a quarterly LCI meeting hosted by Bob Miles and John Strickland of Industrial Design Corporation (IDC) in Portland, Oregon (Miles 1998). IDC was incorporated in 1985 as a subsidiary of CH2M HILL Companies, Ltd. (CH2M Hill AA 2021), and then CH2M Hill was acquired by Jacobs in 2017 (Chuang 2017). Mike attended that meeting and met others in the LCI community, including Ed Beck of the Linbeck Group and Todd Zabelle of Pacific Contracting. At the meeting, Hal gave an impromptu presentation about TNC's approach to planning based on a project's Conditions of Satisfaction, and Greg tested an early prototype of the Parade of Trades® (Macomber 2022 and Strickland 2022). A common sentiment among attendees was that they were all aspiring to improve flow during design and construction on their projects. Mike noted it was encouraging to meet others who were also striving to improve project delivery like TNC. Todd remarked that it was like "we were all at the [Mos Eisley] cantina in Star Wars… all the freaky animals from outer space focused on flow" (Daley 2022a). In a similar vein, Greg remarked that meeting attendees were "a tribe of like-minded malcontents" (Strickland 2022).

After Mike presented about TNC's Lean journey during the LCI meeting, TNC started working with IDC in February 1998 to deliver Lean Design & Construction to a design/build client (Miles 1998). Meanwhile, Linbeck also invited TNC to come to Houston in May 1998 to help train one of their project teams. Mike agreed and helped set up 7-8 games of the Airplane Game for around 50 people. They hung up a light green ripstop sheet on the wall, and TNC helped Linbeck pull plan that project with their partners. According to Ballard (2019), “the first use of stickies on a wall, at least for doing Pull Planning, happened in 1998 in planning Linbeck Construction’s Next Stage Project. An all-star team from around the country had been selected to design and build this 7,000-seat enclosed theater for performing arts. Mike Daley, an architect with the Neenan Company (an early LCI member company) suggested that we do it backwards. He overcame our hesitations, thank goodness. Incidentally, this project was the first on which the LPS was used to manage design” (Ballard 2000, 2019).

After the Linbeck meeting, Greg and Glenn started using the Airplane Game in LCI’s “Introduction to Lean Construction” workshops. They also used sticky walls with index cards to help with early collaborative planning sessions and developing the LPS further in Lean implementation experiments. In the meantime, TNC often attended early LCI meetings, shared how they adapted the use of the LPS on their projects, and experimented with how to achieve ideas proposed by Greg and Glenn. For example, when Glenn suggested embedding buffers into the work week, TNC experimented with not scheduling anything on Fridays to better manage the variation and challenges that emerged during the work week (Daley 2022a).

Subsequently, Ballard and Howell (2003) described using sticky walls for what they then called “Pull Planning.” At that time, “Pull Planning” referred to introducing pull into the planning process, especially for Phase Planning to determine the work sequence and key work handoffs between project milestones. According to Ballard (2019), “When we introduced Pull Planning as a new component in the Last Planner System, we used ‘Phase Pull Planning’ to emphasize that we were extending the territory where Last Planner was to be used, for the first time proposing to specify SHOULD, at least in part. The [next] Process Benchmark for the Last Planner System will extend that territory further, to take on Project Execution Planning” (Ballard et al. 2019) (Ballard and Tommelein 2021). Furthermore, Ballard (2019) “stopped using the term ‘Phase Pull Plans’ unless it refers specifically to phase scheduling since it long since became evident that the method is appropriate as the first step in any kind of planning because it reveals dependencies and clarifies CoS for making handoffs.”

As project teams started using Post-it® sticky notes for Pull Planning, they found that they had difficulty keeping the sticky notes attached to the walls because of the rigors of Pull Planning – meeting attendees attached, removed, and then reattached sticky notes frequently as they considered different ways of managing work handoffs and structuring workflows (Tsao et al. 2004). When the 3M company introduced Post-it® Super Sticky notes in 2003 (Green 2007), the use of sticky walls with 3M repositionable spray adhesive fell out of favor as project teams became more capable of using 3M’s Super Sticky Post-it® notes on walls to develop, refine, and preserve Pull Plans.

Even with the development of software options to assist with LPS implementation, the use of sticky notes on walls for Pull Planning remains a popular Lean implementation practice as they provide a tangible and accessible means for first-line planners/foremen in design and construction to interact “hands-on.” Sticky notes allow project teams to quickly sort out options for organizing workflows through planning modules (aka “work zones” or “work locations”) and clarifying the handoffs of work between specialties/trades. Furthermore, the tangible nature of sticky notes is an effective means to help first-line planners/foremen develop ownership of the identified work tasks and subsequent work sequence. This is critical because it helps first-line planners/foremen develop better buy-in into the collaboratively developed work plan. Consequently, many project teams continue to use sticky notes on walls for the initial Pull Planning effort. Then, they may decide to transfer that information into LPS-based software for managing the refinement and implementation of the Pull Plans, especially if the project site does not have enough space to support wall-based Lean implementation.

Nevertheless, Pull Planning has emerged as a popular first step for many companies that begin to implement Lean on AEC projects (McGraw-Hill 2013). However, the McGraw-Hill report had a surprising finding – amongst the 193 survey respondents, 36% reported implementing Pull Planning while only 30% reported implementing the Last Planner® System (LPS). As a result, Lean instructors should help companies understand that Pull Planning is only one of five planning levels of the LPS, so the other levels (i.e., Milestone Planning, Make Ready Planning, Weekly Commitment Planning, and Daily Learning) can provide additional possibilities for value generation and waste reduction.

PULL PLAN TECHNIQUES, CONCEPTS, + TERMINOLOGY

Ballard (1997) and Ballard and Howell (2003) describe 'Phase Scheduling" as a component of the LPS and recommended Pull Planning as the method for developing phase schedules. When Greg and Glenn introduced Pull Planning to help project teams with structuring work to achieve a milestone as a part of Phase Planning, they called their efforts "Pull Planning" to reinforce the concept that customers should request work handoffs from suppliers to introduce "pull" into the planning process.

As project teams experimented with Pull Planning, Pull Planning etiquette started emerging as well. For example, Pull Planning etiquette and procedure suggests that meeting attendees only place their sticky notes on the wall when a customer invites them to do so. This is how "pull" is introduced into the planning process. Then, meeting facilitators may ask attendees to move only their own sticky notes and ask permission to move the sticky notes of others. This not only fosters a culture of respect amongst meeting attendees, it ensures that everyone is not only aware of but approves any sequencing changes to their work tasks. However, if there are meeting space or time constraints, facilitators can help the team move sticky notes to sort out proper sequencing if all attendees pay close attention and regularly make suggestions for improvement.

Planning backwards is a challenging process that forces meeting attendees to start at the end milestone and determine what work must be put into place to achieve it. This step helps "shake out the waste" that is deeply embedded in past work plans, and project teams start developing more customer-focused work plans that improve transparency of how work is handed off between companies to generate value for the end customer. After this initial "backwards-pass" in Pull Planning, project teams may conduct (Tsao et al. 2014):

- **"Forwards-passes"** to confirm the logic, add forgotten "value-adding" tasks, and add "required but non-value-adding" tasks.
- **"Tightening-passes"** to find opportunities for improving the overall duration between the start and end milestones through a combination of strategies, including (1) managing work in parallel, (2) reducing tasks durations by increasing crew sizes or decreasing the size of work zones, (3) introducing time or space buffers to improve workflow, (4) using prefabrication or modularity to

minimize on-site work in congested work zones by moving work to less-crowded work zones or off-site, and (5) takt planning (Frandson et al. 2013).

- Additional **"Backwards-passes"** to refocus the work plan and shake out additional waste from the work plan so it is more customer-focused and subsequently, more efficient at value generation.

Then, by managing a combination of these three types of "passes" during Pull Planning, project teams can improve the quality of the Pull Plan before starting work plan implementation (i.e., extracting and developing Make Ready Plans and Weekly Commitment Plans from the Phase Pull Plan, tracking their statuses, and refining the work plans when needed in response to changing on-site conditions and project circumstances).

It is critical to note – while it is preferred to start a Pull Planning meeting with a backwards-pass, sometimes project teams have difficulty doing so. When that happens, facilitators can start with a forwards-pass to get *some* planning started, but at one point, it is still helpful to double-check with a backwards-pass to ensure that team members have truly "pulled" the work tasks from the end milestone. Also, based on the difficulty of the work scope being planned, project teams may take anywhere from one to several meetings to complete the backwards-, forwards-, and tightening-passes. Then, while it is better to complete all three passes before starting implementation of the Pull Plan, many projects may not have the luxury to do so. In those circumstances, team members may decide to proceed with implementation with only one backwards- or forwards-pass complete.

Furthermore, as "[Pull Planning] is appropriate as the first step in any kind of planning" (Ballard 2019), project teams can use Pull Planning to manage different levels of the LPS, that is, project teams can "pull plan" the Milestone Plan, the Phase Plan, the Make Ready Plan (Tommelein and Ballard 1997), or even the Daily Plan, depending on project needs. For example, project teams may "pull plan":

- A Milestone Plan to establish the overall project execution strategy
- A Phase Plan to get from a "Weathertight" milestone to a "Ready for Rough Inspection" milestone 2-3 months later
- A Daily Work Plan in hourly detail to coordinate a single-day equipment shutdown process

Meanwhile, members of the Lean Construction community have given various names to collaborative planning between key milestones, including "Pull Planning," "Reverse Phase Scheduling," "Reverse Phase Planning," "Phase Scheduling," and "Phase Planning." Although "Phase Planning" can continue to be used to indicate collaborative planning sessions between key milestones and "Pull Planning" can represent the "backwards-pass" technique of collaborative planning at different levels of the LPS, LCI has been encouraging its members to use the term "Phase Pull Planning" to distinctly indicate "Pull Planning" at the "Phase Planning" level between key milestones. Doing so introduces consistency in language and improves the quality of Phase Pull Planning practice by making it easier for project teams to recognize, share with, learn with, and continuously improve with each other because they are aligned not only in Pull Planning techniques but concepts and terminology as well.

DEVELOPMENT OF THE PARADE OF TRADES®

By the early 1990s, Greg Howell had many simulations at hand as he worked with Tim Karpoff to facilitate partnering and leadership development sessions. Around the same time, Greg and Glenn's solicitation to AEC companies for project data to test and improve the LPS framework started yielding results. Projects provided data on planning reliability, so Greg began searching for simulations to help explain the importance of plan reliability.

During a camping trip in New Mexico, Greg read *The Goal* (Goldratt and Cox 1984) and had difficulty understanding the description of the dice simulation that the main character, Alex Rogo, played at lunch during a hike with his son's boy scout troop. The next morning, Greg attempted to make sense of *The Goal's* simulation by working with his daughter Emily to make a spinner with a popsicle stick and using pine nuts on a picnic table. Through their efforts, Greg concluded that *The Goal's* simulation got him closer to a simulation that showed the impact of dependence and variation on group performance, but it was still not quite right and he continued to search for a better simulation.

Greg then started exploring ways to use dice by purchasing every kind of dice that he could buy (e.g., different-sided dice and different-numbered dice). At one point, he realized that the problem with the dice he purchased so far was that they all had different distributions that yielded different averages. Finally, while visiting an educational supply store with his wife Dana, Greg found blank dice and discovered that he wanted dice with different distributions but the same average. Then, a dice simulation could illustrate that dependence and variation really matters.

As mentioned earlier, Greg and Glenn played an early form of the Parade of Trades® simulation at the 1997 LCI meeting in Portland, Oregon. At that time, they used 100 chips, and the dice and chips moved in the same direction. Play lasted a long time due to the use of 100 chips and the scoring method. On acetate sheets, each trade tracked their rolls on the horizontal axis and the chips moved on the vertical axis. Then, after drawing a status line for each trade, they would line up the acetate sheets on an overhead projector and see how work was tied up by the gap in the lines. After improving the simulation through additional workshops, the Parade of Trades® became an effective simulation for use during LCI Introduction to Lean Construction workshops. At one point, a superintendent attendee suggested naming the simulation the "Parade of Trades" due to inspiration from the closing parade sequence at the end of the movie Animal House.

Meanwhile, Tommelein et al. (1999) explained how "the Parade Game illustrates the impact workflow variability has on the performance of construction trades and their successors." Then, by the early 2000s, Sven Bertelsen of LCI Denmark helped Greg realize that the dice were moving in the wrong direction – they needed to move in the opposite direction of the chips. This change enabled instructors to more closely simulate how construction work begins on AEC projects when using the Parade of Trades®.

After learning about the change of dice direction and inspired by Greg's initial attempts in LCI workshops to line up acetate sheets to illustrate the performance of the different trades as well as the charts included in Tommelein et al. (1999), Cynthia Tsao developed an Excel spreadsheet in 2005 that generated cumulative charts that illustrated trade productivity as students played during an undergraduate Lean Construction course (Tsao et al. 2012; Tsao et al. 2014). While it may be cumbersome to manage such a spreadsheet during practitioner trainings, utilizing such a spreadsheet during trainings in academia would help illustrate the impact of variation on continuous workflow.

By the early 2010s, after much searching, Greg finally found a manufacturer who was willing to custom fabricate dice with blue pips (containing 1,2,2,5,5,6), dice with red pips (containing 2,3,3,4,4,5), dice with green pips (containing 3,3,3,4,4,4), and dice with black pips (containing 1,2,3,4,5,6). However, it should be noted that the dice manufacturer was concerned about the intention of the use of these "loaded" dice. Nevertheless, this innovation enabled Lean instructors to become more capable of preventing the discovery that the dice were different during play. However, if Lean learners discovered the dice difference during play, facilitators could congratulate the students in noticing the difference and encourage them to continue playing to minimize play distraction.

AIRPLANE GAME + PARADE OF TRADES® REFINEMENT

To eliminate the challenge of transporting heavy materials for the Airplane Game, Will Lichtig and Greg Howell adapted the "Make-a-Card" simulation "to demonstrate the advantages of Kanban and Pull over traditional Push and Batch" for LCI based on "The original manufacturing version of [the] simulation… developed by Mike Studley for ACT in England, and… modified by HP and Lockheed, by Kevin Meyer and John Vermillion at Abbott in Salt Lake" (LCI 2021). As Ballard (2019) noted, "The last straw for me was pulling a muscle in my back when I took Legos® for 60 people to play in Buenos Aires. We tried other approaches, for example, using only words, but they were not as effective [as Make-a-Card] because they lacked the 'moving material around' aspect."

Meanwhile, while the Visionary Products version of the Airplane Game featured four rounds of play (Visionary Products 2007), LCI found that three rounds of play were sufficient for providing key takeaways for project teams:

- **"Batch" Round 1** – players remained silent, built in batches of 5, set up workstations out of sequence, placed materials far from convenient reach of workstations, and allowed only the last workstation to work on quality control
- **"Pull" Round 2** – players remained silent, built with one-piece flow (to introduce pull into the system), organized workstations in sequence, placed materials within easy reach, and still only allowed the last workstation to work on quality control
- **"Balance" Round 3** – players communicated, built with one-piece flow, organized workstations in sequence, placed materials within easy reach, added quality control at any workstation, and balanced work between the workstations

In 2005, Cynthia Tsao introduced using different colored Legos® when facilitating the Airplane Game during instruction at the University of Cincinnati (Tsao et al. 2012). Shortly afterwards, she shared this improvement with Greg Howell while co-facilitating a training session at Baker Concrete Construction, Inc., headquarters in Monroe, Ohio.

Due to concerns from some Airplane Game facilitators and attendees that part of the productivity gains from Round 1 to Rounds 2 and 3 could be attributed more to a learning curve, Rybkowski et al. (2012) investigated this question and found that "[70% of] productivity improvements can primarily be attributed to the mechanistic benefits of lean principles themselves and less significantly to non-mechanistic phenomena."

In March 2020, the Covid-19 pandemic introduced a new challenge to the Lean community – how do we continue training to support project implementation while keeping attendees safe? As a result, Lean instructors started exploring how to facilitate typical Lean training workshops within a virtual environment. Future research can help document the development and improvement of these virtual simulations and their effectiveness in Lean learning. However, two simulations in particular have emerged to support the lessons typically provided by the Airplane Game and Parade of Trades® in-person simulations – "Batch, Pull, and Balance" and "The Online Parade of Trades®."

As one of the leading AGC Lean Construction certification instructors, Colin Milberg of ASKM & Associates initiated the development of these virtual trainings and tested them in Administering and Playing Lean Simulations On-Line (APLSO) virtual meetings hosted by Texas A&M (Rybkowski et al. 2021). Then, after adding cumulative production charts to improve “The Online Parade of Trades®,” Cynthia Tsao initiated and coordinated the decision at the end of 2020 to share these virtual simulations with others for free through a Creative Commons Usage Agreement in exchange for improvement feedback and facilitation data (*ibid*). As a result of this decision, for example, over 70 instructors from 10 countries have downloaded a copy of “The Online Parade of Trades®.”

FUTURE RESEARCH AND CONCLUSIONS

Future research could explore: (1) the perspective of the pre-Lean period for other researchers who have contributed to the IGLC and LCI communities, (2) the development, adoption, or customization of other key simulations that help with Lean learning [e.g., Silent Squares (LCI 2022), DPR Pull Planning Game (DPR 2022), and Villego® (BOB bv et al. 2012)], and (3) the appropriate timing and usage of various simulations for Lean learning based on project phases, project team moods, etc. (Tsao and Alves 2021).

This paper provided insight into the motivations and drivers that inspired early Lean Construction community members to develop better methods for training Lean learners on how to start thinking and behaving differently to achieve better AEC project outcomes. Documenting the evolution of simulations usage in Lean learning helps all instructors work within a better foundation and theoretical framework as they facilitate and improve the training workshops that support Lean learning and project implementation.

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REDUCING BIAS IN THE HIRING PROCESS THROUGH CHOOSING BY ADVANTAGES: A CASE STUDY

Anthony F. Paucar-Espinoza[1], Andrews A. Erazo-Rondinel[2], Paz Arroyo[3] and Luis A. Salazar[4]

ABSTRACT

Construction projects rely on the people in the project team; people are selected to perform their role satisfactorily in the project and contribute to its success. However, the selection in the hiring process has different biases that are often not perceived by those who decide to hire people. This research aims to present a study applying the Choosing By Advantages (CBA) Tabular method for the hiring process of a new team member, aligning the structure of the selection process with the five phases of the CBA system. The selection process is divided into two parts to reduce bias in decision-making: the first preliminary part uses information associated with objective data from the applicants' CVs without knowing their identities. The second part complements information knowing their identities obtained from personal interviews. In this research, we use a practical approach called the SEEDS Model®, represented in five categories of biases present in everyday thinking (similarity, expedience, experience, distance, and safety). Furthermore, the results demonstrate that CBA and SEEDS Model® help reduce bias in the selection process and choose people for their attributes representing their capacities, avoiding bias in the selection.

Keywords

Choosing By Advantages, multi-criteria decision analysis, CBA Tabular Method, SEEDS Model®, hiring process, bias.

INTRODUCTION

Different methods can support decision-making in the Construction sector, where the decisions made are of great importance to increase the value in the different stages of the projects. Thus, in the construction sector, different methods have been applied for decision makings, such as WRC (Weighting, rating, and calculating), AHP (Analytic Hierarchy Process), and CBA (Arroyo 2014). Arroyo et al. (2019) indicate that CBA has gained more attention in the construction industry in recent years. This increase has been driven by demands for more collaborative project organizations and transparent decision-

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making processes due to the synergy of CBA with other agendas such as improving sustainability and safety and by a growing need to incorporate multiple factors into the decision-making process. Although CBA has been applied in several types of decisions; it has focused on design (Arroyo & Long, 2018; Perez & Arroyo, 2019; Sahadevan & Varghese, 2019; Schöttle et al., 2019, 2018), with only one study in the literature on its application in personnel selection for a new member of a construction team (Paucar-Espinoza et al., 2021).

One of the most critical decisions made in construction projects is the team's formation, and many times they are fraught with different types of biases. In addition, there is no standard in practice for selecting project team members, and each company develops its way of choosing its human resources. Therefore, there is no emphasis on avoiding bias. Also, the research on this topic is scarce in Lean Construction. That is why the following article focuses on the application of Choosing by Advantages in the hiring process. The paper presents a case study where project team members select a new team member using the Tabular CBA method to reduce decision-making biases.

BACKGROUND

In this section, the authors initially discuss Choosing by Advantages (CBA), cognitive biases, and hiring biases, as they are relevant to understanding the challenges of the construction recruitment process.

CHOOSING BY ADVANTAGES

CBA is a multi-criteria decision-making method that helps build group consensus more transparently than traditional methods, such as WRC and AHP, because CBA bases value judgments on factual and agreed differences between the alternatives (Arroyo 2014). Suhr (1999) developed CBA, and it has been adopted in the Lean Construction community mainly for design and construction decisions. For example, Paucar-Espinoza et al. (2021) used CBA for selecting a new team member; however, their study did not consider bias mitigation strategies.

COGNITIVE BIASES

By definition, a bias is a deviation from normal, defined by social norms. Cognitive biases, which occur unconsciously, have been studied in psychology; Kahneman (2011) presents multiple types and examples, summarizing decades of research. In this research we used a practical approach developed by the Neuroscience Institute called the SEEDS Model® (Lieberman et al., 2015) to help people identify, interrupt, and mitigate unconscious biased thinking. The SEEDS Model ® represents five different categories of biases present in everyday thinking: Similarity, Expedience, Experience, Distance, and Safety Bias. Lieberman et al. (2015) describe them as follows.

1. Similarity bias: Arises from our innate motivation to distinguish between in-group and out-group biases. We feel more comfortable with people with similar experiences than us. We believe that people similar to us are better than others.
2. Expedience bias: Arises when we try to save mental energy by recalling recent information. This bias includes confirmation and availability bias. We believe that our first feeling should be correct.

3. Experience bias: This draws from the unconscious belief that we see things as they are (blind-spot bias) and know all there is to know (fundamental attribution error). We believe that our subjective perceptions are objectively true.
4. Distance bias: Our tendency to value people, events, and things based on their proximity to us in time and space. We unconsciously assign less value to psychologically distant things (temporal discounting bias), and we overvalue short-term concerts while undervaluing long-term concerns (affective forecasting bias). We believe that the people closest to us are better than those far away.
5. Safety bias: Arises from the brain's threat detection network, continuously scanning the environment for danger. Since undetected threats can be fatal, so we assign more value to potential losses than to potential gains (loss aversion bias). We believe that bad results are much more relevant than good results.

HIRING BIASES

The impact of gender bias on career development was studied by Arroyo et al (2018); the findings suggest that gender biases negatively affect hiring and career development for women in AEC Industry. However, other biases may be present in the hiring process, such as age and race biases. This research documents some of the biases present in the hiring process and explores how to mitigate them using strategies from the SEEDS Model® and applying CBA.

RESEARCH METHODOLOGY

CASE STUDY

We selected the case study methodology because the researchers had little control over the events, and the phenomenon is contemporary (Yin, 2003). A controlled experiment was discouraged because the study does not represent a "sample", as an experiment does. We established a longitudinal-holistic case study since the main objective of this research is to extend and conceptualize theories by means of an analytical generalization of causal relationships (simple, complex, and enigmatic), performing a second-level analysis, verifying whether or not the case study supports the proposed theory (Yin, 2003) and not a statistical generalization, the two being epistemologically independent (Yacuzzi, 2005; Yin, 2003).

We used "information-based selection" because of the research feasibility with the construction company. It indicates that the company belongs to a specific economic sector and is located in a specific sector (Lima, Perú).

The unit of analysis consists of a construction project for a hospital building located in an interior sector of the country (Huánuco, Peru) due to the magnitude of the project. It will have a team of 40 people from different support areas; one of these areas is Project Controls specifically; the position analyzed is a Planning Assistant for the architectural works of the project. To select a Planning Assistant, the project team applies CBA, which is explained in the following section.

CHOOSING BY ADVANTAGES

For the CBA application in selecting the new member of the project team, steps were structured through the five phases of the CBA system, shown below in Figure 1.

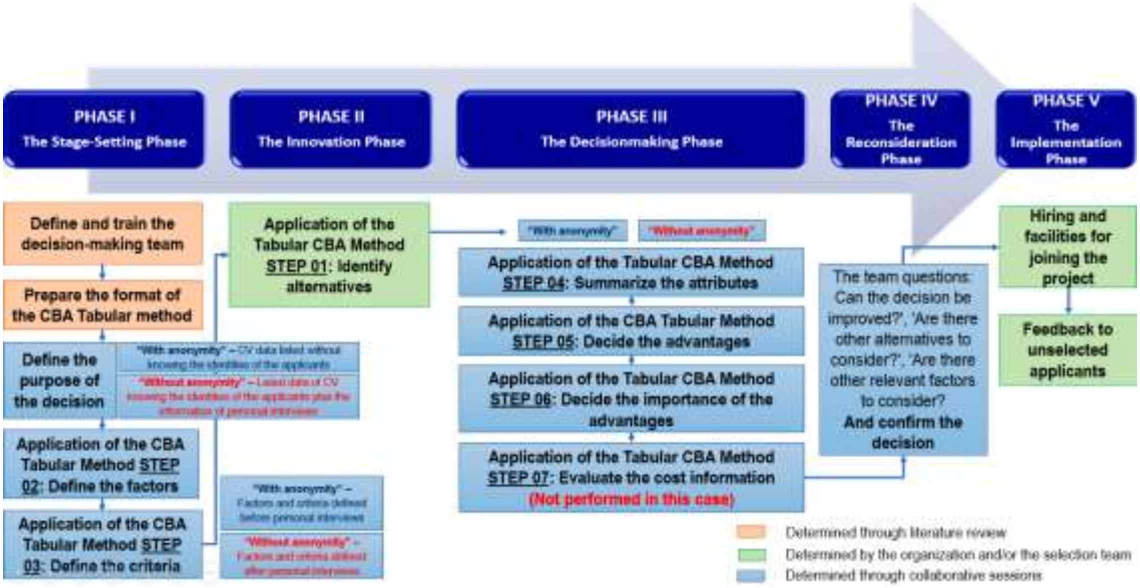


Figure 1: Selection process structured through the phases of the CBA system

As an initial part of the selection, the selection team is defined and trained in the basic concepts of the CBA system, the steps of the Tabular CBA method (with examples from the bibliography), and the typification of the most common biases in selection processes. In addition, the team prepares formats to be used for the adequate development of the method.

The next step is to define the decision's purpose; the project controls team describes the new member's role and functions. Also, the team decided on how to carry out the selection to reduce as much bias as possible, taking at this point the initiative to carry out the development of the selection in two parts.

- The first part of the selection was called "with anonymity," where only the information collected from the curriculum vitae (CV) of each applicant was used (assigning a number to each applicant) without knowing their identities
- The second part of the selection was called "without anonymity." In this stage, the identity of each applicant was revealed to proceed with the interviews. It permits to complement of the information of the previous iteration.

FIRST PART: SELECTION OF CANDIDATES ANONYMOUSLY

The application of the steps of the CBA Tabular are explained below:

Step 01: Identify the alternatives

One person from the work team was assigned to collect the information of all the CVs into a single list without consigning names and providing a number to each applicant. In this step, the project team identified ten participants to select the new member of the project team.

Step 02: Define the factors

The team conducted a brainstorming session to define the factors for the selection, considering the Lean Construction Professional Profile (LCPP) (Pavez & Alarcon, 2007 and Paucar-Espinoza et al., 2021) and the context of the project, listing 11 factors.

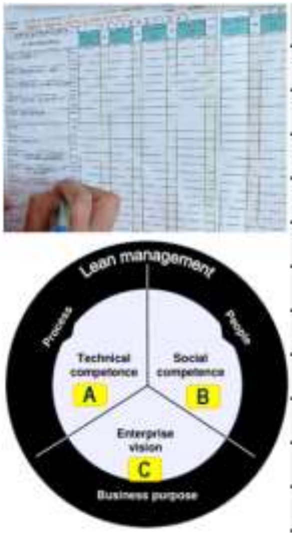
For this first part of the selection, the team divided factors into two categories (Figure 2):

- The factors whose attributes could be extracted directly from the list with information from the CVs were assigned the label "with anonymity" (6 factors).
- The factors whose attributes could be obtained due to the interaction in the interviews were assigned the label "without anonymity" (5 factors).

Step 03: Define the criteria

The team agreed on the respective criteria associated with each factor (Figure 2).

For this first part of the selection, we proceeded with the following steps using only the factors labeled “with anonymity”.



LCPP	Label	Factor Number	Factor (Criterion)
A (Technical Competence)	"With anonymity"	1	ACHIEVEMENTS The more achievements, the better
A (Technical Competence)	"With anonymity"	2	KNOWLEDGE IN REVIT If he/she is proficient in REVIT, better
A (Technical Competence)	"With anonymity"	3	EXPERIENCE IN THE FIELD/WORKS The more months of work experience, the better
A (Technical Competence)	"With anonymity"	4	KNOWLEDGE IN PROJECT CONTROL The more knowledge in Project Control, the better
A (Technical Competence)	"Without anonymity"	5	REFERENCES If he/she has project references, better
C (Enterprise Vision)	"Without anonymity"	6	AFFINITY FOR PROJECT CONTROL The more security of his/her targets in the area, the better
–	"With anonymity"	7	LOCATION The closer to Lima, the better
B (Social Competence)	"Without anonymity"	8	CREATION OF A GOOD WORK ENVIRONMENT The more development in his/her answers, the better
C (Enterprise Vision)	"Without anonymity"	9	ATTITUDE AND PREDISPOSITION TO WORK The better his/her attitude in the cases raised, the better
B (Social Competence)	"With anonymity"	10	CONTINUOUS LEARNING The more recent training, the better
C (Enterprise Vision)	"Without anonymity"	11	COMMUNICATION SKILLS The better his/her response to the cases raised, the better

Figure 2: Factors and respective criteria obtained by the selection team

Step 04: Summarize the attributes

The attributes inherent to each alternative were transferred to the Tabular Format, obtained from the consolidated list with information from the CVs.

Step 05: Decide on the advantages

For this step, the team first identified the least preferred attribute and then objectively compared each attribute versus the least preferred attribute on each factor, the differences being the advantages of the alternatives.

Step 06: Decide the importance of the advantages

In this step, the discussion was generated within the team with all the information centralized in the Tabular Format. First, the most favorable advantages were highlighted, then a scale from 0 to 100 was used to assign the Importance of Advantage (IoA). Next, collaboratively, the team reviewed all of the most favorable advantages, selecting the paramount advantage (100 IoA score) "high knowledge in Project Control." Then weighted the IoA of the other most favorable advantages against the paramount advantage and finally weighted the IoA of all remaining advantages, comparing them to the most favorable advantages. Once the IoA score was assigned to all the advantages, the final IoA score representing the value of each of the alternatives was calculated, taking into account only the factors labeled as "with anonymity."

Step 07: Evaluate the cost information

In this decision, the project team did not evaluate costs because the salary of this position is similar for the participants.

Tables 1, 2, and 3 describe the first part of the decision. Then, half of the applicants with the highest IoA were selected. In this stage, the project team revealed the identity of the participants to schedule personal interviews and send e-mails with acknowledgments to the people who did not pass this part of the selection.

Table 1: First part of the selection process (referred to as “with anonymity”)

FACTOR (Criterion)		Postulant 01	IoA	Postulant 02	IoA	Postulant 03	IoA	Postulant 04	IoA	Postulant 05	IoA
ACHIEVEMENTS	Att.:	1 achievement		**Did not document achievements**		1 achievement		3 achievements		**Did not document achievements**	
The more achievements, the better	Adv.:	1 more achievement	**7**		**-**	1 more achievement	**7**	3 more achievements	**20**		**-**
KNOWLEDGE IN REVIT	Att.:	Yes		Yes		**No**		Yes		**No**	
If he/she is proficient in REVIT, better	Adv.:	He/She is proficient in REVIT	**70**	He/She is proficient in REVIT	**70**		**-**	He/She is proficient in REVIT	**70**		**-**
EXPERIENCE IN THE FIELD/WORKS	Att.:	29 months		33 months		36 months		18 months		**Did not work on site**	
The more months of work experience, the better.	Adv.:	29 more months of work experience	**48**	33 more months of work experience	**55**	36 more months of work experience	**60**	18 more months of work experience	**30**		**-**
KNOWLEDGE IN PROJECT CONTROL	Att.:	**Little knowledge in Project Control**		**Little knowledge in Project Control**		High knowledge in Project Control		Medium knowledge in Project Control		**Little knowledge in Project Control**	
The more knowledge in Project Control, the better	Adv.:		**-**		**-**	More knowledge in Project Control	**66**	Little more knowledge in Project Control	**33**		**-**
CONTINUOUS LEARNING	Att.:	2 recent trainings		2 recent trainings		5 recent trainings		**0 recent trainings**		3 recent trainings	
The more recent training, the better	Adv.:	2 recent trainings more	**28**	2 recent trainings more	**28**	5 recent trainings more	**70**		**-**	3 recent trainings more	**42**
IoA Total			**153**		**153**		**203**		**153**		**42**

Table 2: First part of the selection process (continuation)

FACTOR (Criterion)		Postulant 06	IoA	Postulant 07	IoA	Postulant 08	IoA	Postulant 09	IoA	Postulant 10	IoA
ACHIEVEMENTS	Att.:	**Did not document achieve-ments**		3 achieve-ments		3 achieve-ments		3 achieve-ments		**Did not document achieve-ments**	
The more achievements, the better	Adv.:		**-**	3 more achieve-ments	**20**	3 more achieve-ments	**20**	3 more achieve-ments	**20**		**-**
KNOWLEDGE IN REVIT	Att.:	**No**		Yes		Yes		Yes		**No**	
If he/she is proficient in REVIT, better	Adv.:		**-**	He/She is proficient in REVIT	**70**	He/She is proficient in REVIT	**70**	He/She is proficient in REVIT	**70**		**-**
EXPERIENCE IN THE FIELD/WORKS	Att.:	**Did not work on site**		29 months		**Did not work on site**		**Did not work on site**		8 months	
The more months of work experience, the better.	Adv.:		**-**	29 more months of work experience	**48**		**-**		**-**	8 more months of work experience	**13**
KNOWLEDGE IN PROJECT CONTROL	Att.:	**Little knowledge in Project Control**		Very high knowledge in Project Control		Medium knowledge in Project Control		**Little knowledge in Project Control**		**Little knowledge in Project Control**	
The more knowledge in Project Control, the better	Adv.:		**-**	Much more knowledge in Project Control	**100**	Little more knowledge in Project Control	**33**		**-**		**-**
CONTINUOUS LEARNING	Att.:	4 recent trainings		2 recent trainings		**0 recent trainings**		2 recent trainings		**0 recent trainings**	
The more recent training, the better	Adv.:	4 recent trainings more	**56**	2 recent trainings more	**28**		**-**	2 recent trainings more	**28**		**-**
IoA Total			**56**		**266**		**123**		**118**		**13**

Table 3: Results of the first part of the selection process

Alternative	Applicant name	IoA Total	Comment
Postulant 07	AAA AAA	266	Continue with the second part of selection
Postulant 03	BBB BBB	203	Continue with the second part of selection
Postulant 01	CCC CCC	153	Continue with the second part of selection
Postulant 02	DDD DDD	153	Continue with the second part of selection
Postulant 04	EEE EEE	153	Continue with the second part of selection
Postulant 08	FFF FFF	123	Does not continue selection process
Postulant 09	GGG GGG	118	Does not continue selection process
Postulant 05	HHH HHH	42	Does not continue selection process
Postulant 06	III III	56	Does not continue selection process
Postulant 10	JJJ JJJ	13	Does not continue selection process

SECOND PART: SELECTION OF CANDIDATES WITHOUT ANONYMITY

The team selected and interviewed Applicants 07, 03, 01, 02, and 04 for the second part of the selection. Again, the questions were structured according to the factors "without anonymity" to obtain information on their attributes. After the interviews section, the steps of the CBA Tabular method are restarted from step 04, completing the information in the remaining factors and criteria.

Step 04: Summarize the attributes

The team completed the Tabular Format with the attributes inherent to each alternative obtained from the interviews with each participant.

Step 05: Decide on the advantages

For this step, the team first identified the least preferred attribute and then objectively compared each attribute versus the least preferred attribute on each factor.

Step 06: Decide the importance of the advantages

In this step, the team discusses if it is convenient to weigh all the advantages together again or not. Because the team observed that one of the applicants grouped a greater number of more favorable advantages of the factors "without anonymity." Agree that it was no longer necessary to weigh the advantages since this applicant would have the highest IoA. Therefore, and ignoring step 07, the decision was made to select applicant 07 as the new member of the project team. Table 4 describes the results of the second part of the selection.

The reconsideration of the decision was carried out throughout the process. The team questioned whether other factors or even alternatives could be considered and even if the decision could be improved, concluding to reaffirm the decision made.

Finally, the last step of the selection process consisted of providing a formal response from the project for hiring through the company's headquarters and making arrangements to provide the selected person with the necessary facilities for their immediate incorporation into the project. Like the first part of the selection, the team sent e-mails with acknowledgments to the participants not selected.

Table 4: Second part of the selection process

FACTOR (Criterion)		Postulant 01 CCC CCC	IoA	Postulant 02 DDD DDD	IoA	Postulant 03 BBB BBB	IoA	Postulant 04 EEE EEE	IoA	Postulant 07 AAA AAA	IoA
ACHIEVEMENTS	Att.:	1 achievement		**Did not document achievements**		1 achieve-ment		3 achieve-ments		3 achieve-ments	
The more achievements, the better	Adv.:	1 more achievement	**7**		**-**	1 more achieve-ment	**7**	3 more achieve-ments	**20**	3 more achieve-ments	**20**
KNOWLEDGE IN REVIT	Att.:	Yes		Yes		**No**		Yes		Yes	
If he/she is proficient in REVIT, better	Adv.:	He/She is proficient in REVIT	**70**	He/She is proficient in REVIT	**70**		**-**	He/She is proficient in REVIT	**70**	He/She is proficient in REVIT	**70**
EXPERIENCE IN THE FIELD/WORKS	Att.:	29 months		33 months		36 months		18 months		29 months	
The more months of work experience, the better.	Adv.:	29 more months of work experience	**48**	33 more months of work experience	**55**	36 more months of work experience	**60**	18 more months of work experience	**30**	29 more months of work experience	**48**
KNOWLEDGE IN PROJECT CONTROL	Att.:	**Little knowledge in Project Control**		**Little knowledge in Project Control**		High knowledge in Project Control		Medium knowledge in Project Control		Very high knowledge in Project Control	

The more knowledge in Project Control, the better	Adv.:		-		-	More knowledge in Project Control	**66**	Little more knowledge in Project Control	**33**	Much more knowledge in Project Control	**100**
AFFINITY FOR PROJECT CONTROL	Att.:	**Medium affinity for Project Control**		High affinity for Project Control		High affinity for Project Control		High affinity for Project Control		Very high affinity for Project Control	
The more security of his/her targets in the area, the better.	Adv.:		-	Higher affinity for Project Control		Higher affinity for Project Control		Higher affinity for Project Control		Much higher affinity for Project Control	
CREATION OF A GOOD WORK ENVIRONMENT	Att.:	**Regular performance in dynamic team**		Good performance in Dynamic team		Good performance in Dynamic team		**Regular performance in Dynamic team**		Very good performance in dynamics	
The more development in his/her answers, the better.	Adv.:		-	Better performance in creating good working environment		Better performance in creating good working environment			-	Much better performance in creating good working environment	
ATTITUDE AND PREDISPOSITION TO WORK	Att.:	**Good attitude and predisposition to work**		Very good attitude and predisposition to work		Very good attitude and predisposition to work		Very good attitude and predisposition to work		Very good attitude and predisposition to work	
The better his/her attitude in the cases raised, the better	Adv.:		-	Better attitude and predisposition to work		Better attitude and predisposition to work		Better attitude and predisposition to work		Better attitude and predisposition to work	
CONTINUOUS LEARNING	Att.:	2 recent trainings		2 recent trainings		5 recent trainings		**0 recent trainings**		2 recent trainings	
The more recent training, the better	Adv.:	2 recent trainings more	**28**	2 recent trainings more	**28**	5 recent trainings more	**70**		-	2 recent trainings more	**28**
COMMUNICATION SKILLS	Att.:	**Good communication skills**		Very good communication skills		Very good communication skills		**Good communication skills**		Very good communication skills	
The better his/her response to the cases raised, the better	Adv.:			Better communication skills		Better communication skills				Better communication skills	
IoA Total			**153**		**153**		**203**		**153**		**266**

DISCUSSION

In the first stage, 10 participants were considered, and the selection focused on identifying the participants with the best attributes, which were participants 01, 02, 03, 04, and 07. In this first stage, participant 07 (Table 02) obtained a higher IoA (266) mainly due to their affinity for project management. This information could be obtained by reviewing their CV anonymously. In the second stage, 05 participants were considered, and the project control team sought to know them in greater depth through an interview. From the interview, we could obtain that participant 07 (Table 04) had a more significant number of advantages in the attributes: affinity for project control, good working environment, attitude, and predisposition to work and communication skills. Because participant 07 had higher scores in stage 01 and more advantages, the team decided not to weigh the advantages and proceeded to choose participant 07. These results could change for future applications if, during the interview phase, the selection team considers that the participant with the highest score in the initial phase has fewer advantages in this second stage.

Due to the team's awareness of potential bias throughout the selection process, the discussion and rhetoric focused on this topic were important.

After the selection, a brief positive and introspective discussion was held in the team regarding possible biases incurred. As a result of that conversation, some were detected that are listed below:

- Similarity bias: This bias was incurred when determining that the candidates should have similar technical capabilities to the members of the selection team, evidencing this point when determining the supreme advantage associated with the "Knowledge in Project Control" factor. [*"The person we select must know about topics related to our area"*].
- Expedience bias: It was identified that this bias was incurred when considering the first feeling caused by the answers provided by the applicants to summarize the attributes associated with the factor "Creation of a good work environment," presenting them with a case situation. [*"His/Her response gave me a good insight into how she would handle that situation."*].
- Experience bias: This bias was minimized when supporting the identification of selection factors with the LCPP. Factors related only to the technical part would traditionally have been considered. The selection team indicated they were all the factors they knew and believed to be sufficient to select the new team member based on their previous experiences.
- Distance bias: This bias was minimized by taking the initiative to identify alternatives for external applicants since the team pointed out that generally, in previous selections, the only alternatives they had were close referrals indicated by the company's recruitment area.
- Safety bias: It was identified that prior to the interviews, the applicants' answers when answering the telephone calls to set the interview schedule influenced them to think about possible threats that would prevent the development of the interviews and the success of the selection. [*"I hope he/she participates in the interview..., I perceived a lack of interest"*].

In addition, taking as a reference a previous documented experience (Paucar-Espinoza et al., 2021), it was shown that the face-to-face use of the CBA method was more beneficial than its virtual use. Social aspects play an important role in the decision-making process (Martínez et al., 2016), even more so if the objective is to minimize bias. In this case, they became more dynamic and transparent, generating trust to talk constructively about biases.

CONCLUSIONS

Training in the CBA system and the CBA Tabular Method for the selection team was essential; it allowed them to become familiar with the vocabulary, the principles, and the steps of applying the method. Adding to this training, the concept, and typification of biases, using the SEEDS Model®, allowed to create a reflection in the selection team to mitigate biases as the main objective when selecting a new member of the project team.

The selection team concluded that knowing the biases before starting the selection process allowed them to design a better way to minimize biases influencing the selection. This application proved to be effective in allowing the selection team to recognize and reduce bias throughout the selection process. The use of the CBA Tabular Method allowed the decision to be made transparent, dynamic, and collaborative, reaching a consensus on the decision made. After this selection, selectors are aware of the biases they may have before making a decision.

This work contributes to the body of knowledge of CBA applications, raising awareness of the influence of biases in a hiring process and suggesting a way to reduce them. Also, this research helps construction companies and construction teams to select team members in a better way and reduces bias in the hiring process.

Finally, the authors suggest replicating the selection using CBA in other positions, such as heads of projects and project managers, and studying the influence of biases in decision-making.

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DIGITALIZING COLLABORATIVE PLANNING IN DESIGN – A CASE STUDY

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ABSTRACT

Collaborative Planning in Design (CPD) has been used in Norway by the contractor Veidekke since 2009. One of the main principles, collaboration, has previously taken place through co-location of the various actors that take part in the design phase. The COVID-19 pandemic placed restrictions such as social distancing, which led to the digitalization of certain elements in CPD. This paper, based on a construction case in Norway, looks at the effects of the digitalization of CPD. This is done using three research questions: How is digitalized CPD achieved, what strengths and weaknesses arise when CPD is digitalized, and how can the digitalization of CPD improve?

The research was done through a literature study and qualitative interviews of eight design participants from the research case.

Findings show that the digital start-up session should not be used further, as it has negative ripple effects later in design in the form of less collaboration. Fully digital ICE sessions are effective and worth continuing in the future but are dependent on what type of work is scheduled. Phase scheduling should try to use physical post-it notes during a physical meeting, and later convert the schedule to a digital format.

KEYWORDS

Design Management, Last Planner® System (LPS), collaboration, phase scheduling, digital

INTRODUCTION

Design management problems are major contributors to the failure of construction projects (Uusitalo et al., 2019). How to best manage the design phase effectively and efficiently is not so clear either (El. Reifi & Emmitt, 2013). Even though the Last Planner® System (LPS) mostly is applied to the production phase, projects benefit from using an adapted version of this lean methodology in the design phase (Fosse & Ballard, 2016). This indicates that development and adaptation of lean construction in design is worth continuing in the future.

Collaborative Planning in Design (CPD) is a lean construction methodology developed by the Norwegian contractor Veidekke to make the design process more efficient (Veidekke, 2013). The most important aspect of CPD is to involve everyone

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participating in the design process (Fundli & Drevland, 2014; Veidekke, 2013). All design participants should be involved in planning their own work. This part is, as the name suggests, done through collaboration.

The collaboration was mainly conducted through co-location before the COVID-19 pandemic surfaced in 2020. The pandemic led to several restrictions which influenced the use of existing lean construction methods. One of the restrictions was social distancing. CPD, which heavily relies on physical meetings among the participants, had to switch over to digital alternatives to compensate.

This paper will look at how digitalization affected CPD. Three research questions have been prepared with the intention of looking closer at the digitalization of the CPD methodology:

- *How is digitalized Collaborative Planning in Design achieved?*
- *What strengths and weaknesses arise when Collaborative Planning in Design is digitalized?*
- *How can the digitalization of Collaborative Planning in Design improve?*

There were several thematic limitations to this case study. It was decided to only dive deeper into three of the elements in CPD, namely the start-up session, ICE sessions, and phase scheduling through the post-it note technique. The research connected to the case will only be angled towards the digitalization of CPD.

Methodical limitations such as time have constricted the case study. This is because the research is a part of a master thesis, and time to work is limited. It would have been preferable to analyze more than one project, and over a longer timespan to observe which parts of the digitalized CPD endured over time, and which parts are opted out.

THEORETICAL BACKGROUND

LAST PLANNER® SYSTEM (LPS) AND COLLABORATIVE PLANNING IN DESIGN (CPD)

Last Planner® System (LPS) is a lean construction methodology developed by Glenn Ballard (Ballard, 2000). LPS was initially designed to improve the controlling and planning of production in projects (Ballard & Tommelein, 2021). Fuemana et al. (2013) point out that LPS should be implemented completely from design to utilize the methodology's full potential. Implementing LPS in design shows significant benefits (Fosse & Ballard, 2016; Mota et al., 2019). Some of the benefits were increased transparency of the process, better team alignment, and a clearer task description (Fosse & Ballard, 2016).

Veidekke, a Norwegian contractor, adapted a version of LPS named Collaborative Construction management, which has been in use since 2006 (Veidekke, 2008). This methodology was further developed to fit the design phase and was named Collaborative Planning in Design (CPD) (Veidekke, 2013). The work on improving and adapting CPD to better suit design has been in progress since 2009 and is still ongoing (Aslesen & Bølviken, 2017). The methodology is used to manage the progress of the design process (Veidekke, 2013). This is done by creating flow and optimizing the process. The literature study revealed there are only a few papers that are written about CPD.

A paper by McHugh et al. (2021) looks at how the COVID-19 pandemic has affected LPS in production. It is a case study that shows how a digital version of LPS can increase productivity while maintaining the health and safety of the workforce. Salhab et al. (2021)

also look at a similar topic. Here, a framework used to introduce LPS in a virtual environment is presented. Both papers look at the digitalization of LPS in production. The literature study revealed that there is close to no literature which looks at the digitalization of CPD.

START-UP SESSION

The start-up process of a CPD project begins with a start-up session (Knotten & Svalestuen, 2016). The start-up session is held before the detailed design phase and consists of one or more meetings (Veidekke, 2017). The participants in the meetings are the client, project manager and design team, construction manager, foremen, and the primary subcontractors (Fundli & Drevland, 2014). The purpose is to create a mutual understanding of the tasks, goals, and to provide insight into how CPD is used as a methodology (Veidekke, 2017). Another aspect of the start-up session is getting to know the other design participants (Veidekke, 2013). Getting to know each other through these meetings will promote cooperation and trust between the participants.

INTEGRATED CONCURRENT ENGINEERING (ICE)

For the meeting structure in CPD, it is strongly proposed to use Integrated Concurrent Engineering (ICE)-sessions, and special meetings when there is an additional need for it (Veidekke, 2013). This is because the activities in design have interdependencies with other disciplines, decisions, or activities (Knotten, 2018). The design participants are more mutually dependent compared to participants in the production process (Veidekke, 2013).

ICE sessions are collaborative work that involves the various actors required in the design (Eastman et al., 2008). It is used to solve interdisciplinary problems (Veidekke, 2017). ICE sessions are often used during Building information modeling (BIM) work or phase scheduling. ICE puts everyone involved in the same room, which creates an opportunity for discussion (Eastman et al., 2008). This technique helps search for faster solutions from all the participants present in the room. Including ICE sessions when important decisions are made makes it possible to speed up assessments of various alternatives. A large part of the design manager's task is to find out which parties are needed in the ICE sessions (Veidekke, 2013).

PHASE SCHEDULING PROCESS USING POST-IT NOTES

CPD uses a post-it note technique that is widely used in Veidekke's projects during phase scheduling. The phase schedule divides the design process into phases which contain the most important activities in the design work, with time indications (Bølviken et al., 2010; Veidekke, 2013). The plan describes requirements for, and when design documentation, decisions, and drawing deliveries are needed (Veidekke, 2017).

Together with the client, architect, designer, and the relevant subcontractors, the phase schedule is made using the post-it note technique (Veidekke, 2017). All design activities are written on post-it notes and are attached to a physical grid on a wall where columns are divided by week number. Each row on the grid corresponds to each discipline, and each discipline will be assigned its own post-it note color. This makes it easy to create an overview of what each discipline needs from the others, and from whom they need it. The post-it note technique ensures everyone involved in design gets involved in the plans and increases the ownership they have to these plans (Lillestøl, 2016).

METHODOLOGY

The work on the paper started with a literature study. Then, after being assigned the research case, the interview guide was prepared.

LITERATURE STUDY

A literature study was the chosen method to gain insight into the topic. The literature study started in the fall of 2021 and has been a continuous work in progress. Since Collaborative Planning in Design (CPD) is further developed from the Last Planner® System (LPS) literature about CPD and LPS in design was systematically reviewed.

Most of the literature that covers CPD is based on the Norwegian contractor Veidekke's guides, and papers written by the creators of the methodology. This is since CPD is a lean methodology developed and adapted by Veidekke. Other international sources were used to supplement where necessary.

The reviewed literature consisted of peer-reviewed publications, as well as Veidekke's websites related to the topic. To cover the topic in the best possible way, a combination of different databases were used. These databases were selected based on credibility, the relevance of the hits, and the possibility of filtering and delimitation during searches. The selected databases were thus *Web of Science*, *Oria (NTNU University Library), Science Direct,* and *Scopus*. In addition to these databases, it was also decided to supplement with searches for relevant literature on *The International Group for Lean Construction (IGLC)* website.

RESEARCH CASE

The case is one of Veidekke's construction projects. The project is in Trondheim and has a turnkey contract of 300 million NOK (ca 34 million USD). At the time of writing, the project is at the end of the detailed design phase. The finished product is a large office building, with great environmental ambitions both during construction and in operation (Veidekke, 2020). The total size of the project will be a total of 15 000 sqm spread over seven floors. The contract also involves the redevelopment and demolition of an existing building, the construction of a parking basement of approximately 2 000 sqm, and an outdoor facility that will safeguard biological diversity and urban ecology.

The design takes place with the help of BIM, and the detailed design phase started in January 2021. The detailed design phase is planned to last until March 2022. The detailed design phase was divided into two phases due to the lack of details in the early stages. Each phase lasted approximately half a year. The construction started at the same time as the detailed design phase, i.e., January 2021, and will be concluded in March 2023.

As can be seen, the planning started during the COVID-19 pandemic. This means the design phase had to be in accordance with regional guidelines that had been introduced. Thus, it was a necessity to have an increased focus on using digital collaborative tools. Most notably the meeting structure changed to virtual meetings, and the physical post-it note technique was carried over to a digitalized version.

QUALITATIVE INTERVIEWS

The data from the case was collected through qualitative individual interviews in a span of five months. A combination of face-to-face interviews and digital interviews were used. The structure of the interview guide was decided after the initial literature study. It was found how to structure the paper, and in which order the different elements should be presented. The interviews further confirmed that the structure was sensible.

A total of eight interviews were conducted. There were three representatives from Veidekke, the turnkey contractor in the project, four representatives from their subcontractors, and one from the architect. The roles of the interviewees were as follows:

- Design manager (Newly graduated) – turnkey contractor
- Design manager (Experienced) – turnkey contractor
- Construction manager – turnkey contractor
- Consulting Engineer (Plumbing) - subcontractor
- 2 x Consulting Engineer (Construction) - subcontractor
- Consulting Engineer (Fire) - subcontractor
- Architect

The reasoning for choosing interview candidates from both the contractor and subcontractors was to triangulate their answers. This helps create a more objective picture of how CPD works in practice. Candidates from the contractor's side had the responsibility for the execution of digital CPD, and the subcontractors experienced their execution first-hand.

FINDINGS

The findings from the case are presented below. Every research question is reviewed under each headline. The findings follow the same structure as the interview guide.

START-UP SESSION

How Digitalization of the Start-up Session Is Achieved

The digital start-up session was held on the business communication platform Microsoft Teams. The session was fully digital, and all participants attended on their own electronic devices. Everyone needed in the design phase attended the meetings which spanned two workdays. The design manager took responsibility for convening all relevant parties to the meeting. Day one was focused on the participants introducing themselves and introducing Collaborative Planning in Design (CPD). All meeting participants prepared a PowerPoint slide with brief information about themselves in advance of the first day. This allowed the various meeting participants to learn about each other. The turnkey contractor used day two of the start-up session to present all necessary information about the tasks, goals, and expectations for the project.

Strengths and Weaknesses of a Digital Start-up Session

According to the interview candidates, there were only a few strengths in having a digital start-up session. It was found that a digital start-up session is better than not having one at all. The biggest strength was timesaving in the form of traveling. In addition, the turnkey contractor did not have to find a location, which can be both time and cost-saving.

There were several weaknesses in having the start-up session digitally. The greatest weakness was the disappearance of the social aspect that accompanies a start-up session like this. The participants missed the personal contact with those they collaborated with, so it took longer to get to know each other. This thus influenced how well the collaboration was perceived by the participants at later stages in design. Another weakness was that some of the meeting participants found it more difficult to stay focused during the meeting since it was digital. It was taxing to look at a screen for long periods of time. This led to them missing information during the meetings. It was mentioned that not so many breaks were taken. This could be because the threshold to interrupt an ongoing presentation and ask for a break was higher when meeting the other participants digitally for the first time. Time usage on the start-up session was longer than it would normally have taken if it had been held physically. Mainly because of the great number of participants and the conversation limitations that accompanies digital meeting platforms.

How Digitalization of the Start-up Session Can Improve

One of the improvements to a digitalized start-up session was the introduction of teambuilding activities that are not related to the project. This could contribute to getting to know each other better and increases cooperation and trust. Such activities would have helped further when working together at later stages. Another aspect is that everyone should spend more time on the presentation slide about oneself so that others could get a better impression of who that person is. It was suggested that the turnkey contractor use more time on making sure the participants get to know each other.

DIGITAL ICE-SESSIONS

How Digitalization of the ICE Sessions Is Achieved

Only digital meetings were used during the ICE sessions. Both fully digital and semi-digital meetings were used. Semi-digital meetings means that some people joined a digital meeting on one common electronic device, while others joined on their individual devices. ICE sessions were held every Thursday at the start of the detailed design phase and were later reduced to every other Thursday. It was mandatory to have the camera on during the ICE sessions. This was to make sure everyone could see each other and counter some of the barriers that come with having digital meetings. The meeting plan was set up by the design manager in relation to a meeting agenda. Special meetings were sometimes needed. These were often held parallel to other special meetings during the ICE sessions. The design manager had to set up several different digital meeting notices when special meetings were needed. Towards the end of the ICE-days, a joint gathering was held where everyone who had participated gathered and summed up in plenary. An experience from the digital ICE sessions was that the participants now had the opportunity to work on other things if they were not immediately needed during the session. Those who physically sat in the office and participated in digital ICE sessions had better experiences than those who participated from home. The participants who sat in their offices were often surrounded by colleagues from the same subject area or field. This made it easier to discuss with colleagues and ask for help. Another aspect was that the home is often not an ideal setting as a workplace, and more distractions were therefore experienced. Meetings with fewer participants were preferred since fewer participants made it easier to communicate digitally. At these meetings, the differences between a physical meeting and a digital meeting were minimal, especially if the participants knew each other. It was easier to speak up, notice body language and facial cues, and small talk was possible.

Strengths and Weaknesses of Digital ICE-sessions

Clear strengths could be seen by having digitalized ICE sessions. All the meeting participants saved time since they did not have to travel. This further led to more meetings being held during one ICE session. It turned out that digitalization was streamlining the efficiency of the ICE sessions. The ability to share the screen with everyone else who participated in the meeting proved to be greatly beneficial. Especially when working with

BIM. The attendees had the possibility to get in and out of the meetings sensibly, based on the need for competence. This would ensure that only the most relevant disciplines were present during the meetings. The disciplines that were not needed for the task were thus on "stand-by" and could work on other things. In digital ICE sessions, it was easier to split up into smaller groups if needed. Digitalization made it easier to document everything that was done throughout the ICE sessions.

One weakness was that the major disciplines, which most often had to sit in digital ICE sessions throughout the entire day, felt it was demanding. It was taxing to sit in front of a screen the entire day and be focused. Another weakness due to digitalization is to invite disciplines who are thought to be relevant to the meeting, and not just those who were relevant. This is because the invitation when scheduling a meeting was just a click away, which led to less thought being put into planning which disciplines to invite. As a result, too many people participated in the ICE sessions, and the meetings got cluttered. It ended up with disciplines that were not needed just sitting and observing, or they worked on something else. They had the possibility to leave the session and come back when needed, but this was rarely done due to social norms. Where special meetings were used, it was experienced that the decision-maker was not present. Even during the joint summary at the end, it was not possible to go through all the decisions that were to be made, which led to important decisions being delayed until the next meeting. Using semi-digital meetings worked very poorly. One consequence was that those who sat physically together had the session between them, and there was a high threshold for those who sat digitally to be able to join the discussions. One aspect that was mentioned is that the lack of small talk decreased the number of impromptu solutions that could have been discussed over lunch, or on the way to the car. The major disciplines (such as consulting engineering construction, consulting engineering plumbing, and the architect) believed that digital ICE sessions were demanding. They had to sit through entire days of digital meetings, which were heavy because they missed out on a dynamic workday and the social aspects.

How Digitalization of the ICE Sessions Can Improve

A possible solution to the lack of a decision-maker during digital ICE sessions was to include more representatives from the client. This ensures that a decision-maker will always be present when needed. Another solution was to schedule more time for the joint summary, so decisions could be made in plenary. Better planning of which disciplines actually are needed in the meetings was also suggested.

PHASE SCHEDULING PROCESS USING VIRTUAL POST-IT NOTES

How Digitalization of the Phase Scheduling Process Is Achieved

The alternative to the physical post-it note technique is a software named Miro. Digital ICE sessions was the meeting structure used to work on the phase schedule in Miro. The ICE sessions using this post-it note technique were held prior to each of the two phases in detailed design. The sessions often started with a joint introduction. All design participants were present during this introduction. After the introduction, the participants were split into smaller groups, based on what was on the meeting agenda. Those who were not needed were on "stand-by" so that they could participate in the discussions when needed. The virtual post-it notes were created by each discipline on their own. The placements of the virtual notes on the timeline was jointly done by everyone attending the ICE session. A prerequisite for using Miro in the best possible way is to have access to two screens. This gave a better overview of the different dependencies.

Strengths and Weaknesses of a Digital Phase Scheduling Process

A strength of Miro is that the turnkey contractor saves time on further handling of the phase schedule. When the post-it note technique was physical, part of the work was to transfer the plan to a digital form. This step was avoided by using a digital form of the post-it note technique. Another strength is that the software is relatively easy to learn. The design participants did not have to spend a lot of time learning the software. A major advantage of using Miro was that the updated post-it note plan was digitally available regardless of location or time. If you were to discuss a specific note during a meeting, it was relatively easy to share the screen and point out exactly which note you are talking about.

When it comes to weaknesses of the virtual post-it note technique, it could be seen that it was harder to get the desired interaction between the disciplines. The discussions did not flow as well digitally, and therefore it was difficult to find out the needs the different disciplines had. The discussions became more static when digitalized since only one person could speak at a time. The interdisciplinary aspect of using the post-it note technique was reduced because of this. The digital ICE meeting with phase scheduling using virtual notes also suffered the problem of inviting too many irrelevant participants. Miro does not provide as good opportunities for making changes in the plan, in the form that a small change could be time-consuming. This was something that affected the efficiency. It was difficult to keep track of the digital post-it notes since one had to zoom in and out, and thus it was difficult to form an overall picture of the dependencies between the design activities. A big part of the physical phase scheduling grid was to stand in front of it and get an overview of the whole phase, which makes it easier for the disciplines to collaborate and discuss. It was difficult to have an overview of milestones and what the other disciplines were to deliver. It thus required more attention and focus from the participants to get the same results as the physical counterpart. The participants felt they had a less sense of ownership when using the virtual post-it note technique. It was experienced as easier to postpone a task to a later time, and this caused delays for other disciplines which were dependent on that specific task to be finished.

How Digitalization of the Phase Scheduling Process Can Improve

Improvements will be to ensure that good conversations are facilitated and that interdisciplinarity is maintained with this type of work methodology. This can be done by good planning by the design manager. This is by only including the most relevant disciplines in the meetings and getting the relevant parties to participate in conversations they may be important in.

DISCUSSION

The discussion is structured based on the three digitalized CPD elements. The research questions are reviewed under each element.

As the guide to Collaborative Planning in Design (CPD) by Veidekke (2013) states, a part of the start-up session is to promote cooperation and trust between the participants. This was barely achieved when it was digitalized. Getting to know each other and promoting good cooperation and trust was not emphasized enough. It turned out that the lack of focus on the social aspect in the digital start-up phase has consequences for the collaboration in later stages of design. If the start-up session is to be conducted digitally, it is therefore recommended to focus more on getting to know each other. A teambuilding activity can be a good starting point for getting people to collaborate and trust each other more. Another improvement is to schedule breaks better and stick to that schedule. To get optimal results, however, it is recommended to have the start-up session physically in the future. This will ensure that cooperation and trust get promoted to the fullest, which probably will lead to better collaboration between the CPD participants.

Of the three elements that have been looked at in this paper, digital ICE sessions is the one that came out the best from digitalization. It was easier to communicate effectively, it was easier to document, and all parties saved time. These strengths are applied when the ICE session focused on BIM related work and not for phase scheduling using virtual post-it notes. The weaknesses with digital ICE sessions can be reduced, to provide a meeting structure that can be better used in the future. Optimal digitalized ICE sessions can be done through the following recommendations prepared from the findings:

- Mandatory to have the camera on.
- Only use fully digital meetings, not semi-digital ones.
- Spend more time figuring out who is most needed to invite to the meeting. The rest of the participants should be on stand-by.
- Encourage all participants to sit in their offices.

Based on the findings the suggested method for the future is to use a hybrid solution of both digital and physical ICE sessions, dependent on what type of work is scheduled for the session. This is to get the collaboration benefits of physical meetings, and the effectiveness of digital meetings. The ratio between digital and physical ICE sessions should be determined through discussions between all the participants, and through trial and error. The suggestion of using digital ICE meetings is mainly when working with BIM, and not when working with phase scheduling using virtual post-it notes.

The post-it note technique is very dependent on good dialogue between the various participants. This is difficult to achieve through digital meetings. It is important to plan well who will be present at the meetings so that there will be as few as possible in the meetings. This will make sure that communication and collaboration will be better. In the future, it is recommended to not have digital ICE sessions when working with the phase schedule. The phase scheduling grid should be on a physical wall during the ICE sessions and should immediately be converted to a virtual format after the session. This is because it was much easier to collaborate, keep track and see the dependencies between the different design activities with a physical grid. It will be an extra step to convert to a virtual phase scheduling grid, but the usefulness and efficiency are both increased when the grid is on a physical wall.

CONCLUSIONS AND FURTHER WORK

The purpose of this case study was to find out how digitalized Collaborative Planning in Design (CPD) is achieved, its strengths and weaknesses, and how it can be improved. CPD is a version of LPS adapted for design and is used to manage the progress of the design process. The focus of this paper was on three elements from CPD. The elements are the digitalization of the start-up session, the ICE sessions, and the phase scheduling process. The findings show that the digitalization of CPD has worked to varying degrees, and some parts of it are here to stay. In the future, it will be important to keep and develop the strengths, while eliminating or compensating for the weaknesses.

A limitation of this case study is that only one project was researched, and this project was only researched for a limited time. The long-term consequences have not been considered and these findings will therefore not apply to all projects. However, one can learn from this project. There should have been follow-up interviews of the interview candidates from the turnkey contractor. This is to present the findings from their subcontractors and see if the turnkey contractor can further elaborate.

The theoretical contributions of this paper collected Veidekke and their subcontractors' experience with digitalized CPD. The findings show that some aspects of digitalization probably will continue to be used in the future. Mainly the use of digital ICE-session, and phase scheduling using virtual post-it notes. The strengths of digitalization are mainly time-saving and effective meetings through video conferences. The weakness is the lack of collaboration between the CPD participants because of the digital medium.

The practical contribution is how Veidekke can make use of this paper's findings. This will include the use of a physical start-up session when possible, the use of both fully digital and physical ICE sessions when working with BIM, and making sure collaboration is possible in phase scheduling using post-it notes. For phase scheduling, it is suggested to mainly use the physical alternatives and convert the plan to a digital format. An overview of improvements for the different elements in digital CPD looked upon in this paper is presented in Table 1.

Table 1: Improvements of the digitalized Collaborative Planning in Design (CPD) elements

Elements in digital CPD	Improvements
Start-up session	Teambuilding activities
	More focus on the personal presentation slide
	Have the start-up session physically if possible
	Schedule breaks better and stick to the schedule
ICE-sessions	Include more decision-makers during the special meetings
	Schedule more time for the joint summary at the end of a session
	A better plan of which disciplines were needed during the session
	Mandatory to have the camera on
	Only use fully digital meetings, not semi-digital ones
	Encourage all participants to sit in their office
	Use of both digital and physical meetings (depends on the task)
Phase scheduling process	A better plan of which disciplines were needed during the session
	Have the phase-scheduling process physically if possible
	Converting the physical grid to a virtual format immediately after a session

For further work, it will be beneficial to look at the long-term effects of digitalization and try to find trends that apply to several projects. This will validate the findings given in this paper. It will then be possible to form a correct picture of which elements of digitalization are lasting, and which changes were only a response to the restrictions of the pandemic. It may also be interesting to see if there are any correlations between the average age of the design participants and their experiences with the digital execution of CPD. Looking at the differences between digital CPD when working from home versus working from the office could indicate how the use of digitalization will develop in the future.

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RELATIONS BETWEEN PRECONDITIONS, CATEGORIES AND IMPACTS OF MAKING-DO WASTES

Tatiana Gondim do Amaral[1], Pedro Dantas Bezerra Braga[2], Sara Vieira Vieira[3] and José de Paula Barros Neto[4]

ABSTRACT

Civil construction is known for its high production of waste and low productivity. Understanding the causes of making-do waste makes it possible to minimize waste in construction processes. This study aims to analyze possible causes and consequences among possible relations between prerequisites, categories and impacts of making-do waste in order to act more effectively in combating waste reducing the main problems identified that cause their occurrence. Some existing prerequisites can be determined: information, materials and components, and labor, are highly likely to occur. Concerning the categories, the following can be highlighted: component adjustment, sequencing, and storage. These combinations generally affect the seven impacts caused by making-do waste. The main contribution of this study was to analyze the possible causes and consequences of the relationship between prerequisites, categories and impacts of making-do waste. Using the dashboard developed in the Power BI platform, relations between the chosen parameters could be determined, and how prerequisites, categories and impacts interacted with other variables in the database.

KEYWORDS

Making-do. Improvisation. Waste. Rework. Business intelligence.

INTRODUCTION

Studies in different countries indicate that construction waste represents 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).

In the construction industry, high production costs are related to waste throughout the construction processes and should be understood as any inefficiency when using equipment, materials, labor, and capital (Formoso et al., 1997; Viana; Formoso; Kalsaas, 2012).

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In the current scenario of the civil construction sector, productivity is a constant concern for any construction company to establish itself competitively in the market, facing fierce competition and increasing demands for quality and performance by clients. The lack of a strategic vision from managers work needs interferes with productivity and causes waste related to production actions.

Koskela (1992) marked a milestone in terms of translating the principles and practices of lean production for construction, including the concept of wastes as proposed by Ohno (1988) and the Seven Wastes of TPS (Toyota Production System). Later, Koskela (2004) suggested an eighth category of waste, which is a characteristic of construction called making-do, arising from situations in which a particular task is started or continued without all the resources necessary for its execution being available or the execution of a task is continued although the availability of at least one standard input has ceased Formoso et al., 2017).

Several studies have been conducted aiming to identify causes and effects of making-do waste in construction, notably Sommer (2010) and Fireman (2012). However, few studies have sought to identify specific cause-and-effect relationships related to this type of waste.

Making-do waste can occur in different ways. There are numerous possible combinations of prerequisites, categories and impacts in the construction environment. Authors highlight that improvisation can be found at all stages of the construction site, making it difficult to identify and avoid them, 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).

Formoso et al. (2011), Leão (2014), Formoso et al. (2015), Formoso et al. (2019), Fireman & Formoso (2013), Saurin and Sanches (2014) and Kalsaas (2012) reported difficulties in identifying and classifying making-do waste, thus pointing to the need to improve the methods used.

Another gap highlighted by some authors is the need to develop more quantitative analysis and acceptable limits of classification of making-do waste (SAURIN; SANCHES, 2014). Given these gaps, this article aims to analyze the possible causes and consequences of the relationship between the prerequisites, categories and impacts of wastes related to making-do, using a dashboard developed on the Power BI platform.

THEORETICAL FRAMEWORK

IDENTIFICATION AND CLASSIFICATION METHOD OF MAKING-DO WASTE

Based on the classification of input flows in construction processes, Sommer (2010) proposed a method to identify making-do practices at construction sites. This proposal took into account the assumptions made by Koskela (2004), Santos (2004), Ballard (2000) and Machado (2003).

Table 1 summarizes a method of classifying making-do wastes based on identification (category), precondition and impact (evaluation) proposed by Koskela (2000), Sommer (2010) and Fireman (2012).

Importantly, the category entitled "Sequencing" emerged from Fireman & Formoso's (2013) studies but had been cited previously in a study conducted by Ronen (1992) and Santos (2004).

Table 1: Classification of making-do waste. Source: Santos and Santos (2017).

IDENTIFICATION/CATEGORY	AUTHOR	PRE CONDITION	AUTHOR	IMPACT/ EVALUATION	AUTHOR
Access/ Mobility	Sommer (2010)	Information	Sommer (2010) Koskela (2000)	Low productivity	Sommer (2010)
Adjusting Components		Materials and Components		Decrease in quality	
Workspace		Manpower		Rework	
Storage: stock of materials or components		Equipment/ Tools		Material Wastes	
Equipment/tools		Space		Compromises safety	
Interim installation: water and electricity supply		Interconnected Services		Demotivation	
Protection		External Conditions		Lack of Terminality	Fireman (2012)
Sequencing	Fireman (2012)	Facilities: workspace infrastructure	Sommer (2010)		

In the two studies by Sommer (2010) A and B, the most affected category was access and mobility, accounting for percentages of 36% and 33%. In Amaral et al. (2019), the most affected category in the three studies A, B, and C was sequencing with 32.5%, 45.5%, and 46.2% respectively. In Amaral et al. (2020), sequencing appeared first as the most affected category with 41.55%. In Santos et al. (2020), although the most affected category was sequencing for study A, with 28.6%, the adjustments and components category can be mentioned as they accounted for 21.4%, which were the most evident in studies B and C with 35.3% and 58.3%, respectively. According to Santos et al. (2020), the category adjustments of components was observed in different situations: change of material specified in project and reuse of material previously used or that had damaged parts.

RESEARCH METHOD

RESEARCH CLASSIFICATION AND SELECTION CRITERIA

Data from this research, an exploratory and descriptive study, were carried out using surveys in nine construction companies in Goiânia/GO, with thirteen projects, two companies in Fortaleza/CE, and one construction company in Toulouse/France. The purpose was to identify events that cause making-do wastes.

The criteria used to select the companies were: 1) Interest in participating in the research; 2) having a Quality Management System (QMS), allowing access to information such as: standardized and documented work instructions, plans, budgets and their follow-ups, service verification forms, among others; 3) current projects that produced data collection for the research.

The companies worked with high-standard buildings and multi-storey commercial buildings. Only one company has no certification, and the others have PBQP-h - level A (a specific quality Brazilian program for the building industry) and ISO certifications. After defining the companies, they were characterized. The stage of execution in which the work was executed at the time the survey was recorded (Table 2).

Table 2: Characterization of the Enterprises.

Company Code	Code Work	Description	Total Enterprise Area (m²)	Type of labor	No. of storeys
A	A	High-end residential townhouse	432,00	Own	1
B	B	High-end multifamily building	31,128,20	Own	34
C	C	High-end multifamily building	30,221,85	Outsourced	36
D	D	Medium standard residential building	31,698,24	Own	27
E	E	High-end multifamily building	12,706,83	Own and outsourced	28
F	F	High-end multifamily building	26,341,54	Own and outsourced	38
G	G	Shopping Center	11,062,88	Own	6
H	H-E1	Medium standard residential building	47,789,71	Own	28
	H-E2	High Standard Vertical Residential Condominium	16,000,000,00	Own	1
I	I-E1	Medium standard residential building	20,853,13	Own	27
	I-E2	Hotel/ Residential Building	19,572,45	Own	28
J	J-E1	Medium standard residential building	27,169,88	Own and outsourced	28
	J-E2	Medium standard residential building	29,279,84	Own and outsourced	29
K	K	Retrofit work	23,219,83	Own and outsourced	1
L	L	Medium standard residential building - 3 towers	43,044,63	Own and outsourced	20

The analysis began with a comprehensive data collection, which involved some research tools such as: questionnaires to characterize the companies and construction sites; questionnaires to investigate the planning process; semi-structured interviews conducted with Production Managers, Team Members, Directors; documental analysis (photos, designs, drafts, notes and documents). Table 3 details the material and method used for data collection to support future discussions.

Table 3: Materials and methods used in the research.

ACTIVITY	PARTICIPANT	DATA COLLECTION
Awareness of the problem	– Production managers. – Team members. – Directors.	– Non-participant observations at construction sites for *making-do* waste data surveys. – Data survey stored in the QuizQuality management platform. – Semi-structured interviews on the routines and processes (cost estimates, problems with lack of completeness, planning and monitoring).
Understanding of the company management and its enterprises	– Directors. – Engineers responsible for the company's planning. – Production managers; – Team Members.	– Analysis of the short, medium, and long term planning of the enterprises.
Suggestion and Development	– Production managers. – Team Members.	– Meetings to discuss and adjust information about the workflow and routines.
Evaluation and Conclusion	– Directors. – Production managers. – Team Members.	– Alignment meetings between the partners to present the most relevant results of the research. – Discussion rounds with the focus groups to evaluate the protocol for surveying and analyzing *making-do* wastes.

These documents were analyzed to prove the facts and obtain a correct classification of the wastes. Having this information, at the end of each follow-up, the projects and respective activities were analyzed to prove possible execution errors, which could cause or influence wastes that had been identified.

RESEARCH AND DATA COLLECTION STEPS

The stages of the research are described below.

Step 1: Identifying making-do wastes events.

Visits were made, whose non-participant direct observations were the main sources of collected evidence. Thus, we sought to identify the events that generated making-do wastes, in order to classify, define the origin and their impacts. The wastes were separated into stages and sub-stages according to the predefinitions of NBR 12721 (ABNT, 2005).

Step 2: Defining a protocol for making-do wastes.

Based on the previous studies, data collection protocols were proposed. The causes, categories and impacts of making-do wastes were defined. The wastes were classified according to the stages and sub-stages following the predefinitions of NBR 12721 (ABNT, 2005). The impacts were classified according to the adopted parameters of decreased productivity, demotivation, material waste, rework, reduced safety, reduced quality and lack of terminality (Ronen, 1992; Koskela, 2004; Fireman & Formoso, 2013).

Based on the waste information formatting in Microsoft Excel® format, a dashboard was developed for data processing in Microsoft Power BI® to provide an interactive data analysis (Caldini; Varela, 2020). The software made it possible to perform interactive graphical analysist so as to interact and reflect on the results (Lopes, 2020). When integrating the database with Microsoft Power BI®, the parameters to be analyzed were chosen. They were divided into eight items related to the prerequisites, eight for the categories and seven for the impacts.

Stage 3: Understanding the company management and its ventures.

To this end, it was necessary to have access to information about the short, medium and long term planning and the schedule. We tried to understand if the wastes were due to failures in planning the work, what the level of control of the executing company was, in which stage the waste occurred, and what the impacts were on the initial planning.

It was identified whether the wastes originated from the subdivision of the formal or informal work packages. The formal packages are those that are planned and executed according to the initial planning and informal ones are the tasks related to the correction of previously executed work; inclusion of tasks required due to the fact that a work package was not completed in the previous (planned) week; and new work packages that were not planned for that week or in planned batches but did not follow the planned sequence (Fireman & Formoso, 2013).

Step 4: Graphical representations chosen for data analysis.

The distribution of making-do wastes were interpreted by the graphs of the hierarchical tree diagram and the analysis was done in Microsoft Power BI® (Figure 1). Based on this interpretation, the waste count can be analyzed sequentially from the prerequisites, categories and impacts of these wastes, thus enabling us to identify which prerequisites have greater influence on the occurrence of wastes.

The graphical 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 enable the analysis of the work stages and their relations with the teams with higher occurrence of wastes), and tracks (to identify the relations between the chosen parameters, and how the prerequisites, categories, and impacts interacted with the database), to present a better presentation of the analyzed results.

Step 5: Validation by the companies of the protocol for surveying and analyzing making-do wastes.

Alignment meetings between partners to present the most relevant results of the research and to evaluate the protocol for surveying and analyzing making-do wastes.

FINDINGS AND RESULTS

The distribution of making-do wastes can be interpreted by the graphs of the hierarchical diagram analyzed in Power BI (Figure 1). Thus, it was proposed to analyze the waste count sequentially from the prerequisites, categories and impacts of the making-do wastes. This identified that the prerequisites of information and materials and components are the most influential, respectively.

In Figure 1, 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. Thus, on the left of Figure 1, it is highlighted in blue that, from the prerequisite information, the category with the highest number of wastes is component adjustment (52%), followed by sequencing (37%), as both match the fact that the information is directly related. Moreover, the highlight (in blue in Figure 1) from adjustment and components present rework as its main impact, corresponding to 57% of the wastes, and it can also be identified that the data are consistent, as the lack of information causes adjustments, and consequently, rework.

On the right side of Figure 1, the prerequisite materials and components, with the category component adjustment (44%), followed by sequencing (38%) as the category with the highest number of wastes are highlighted in blue. Moreover, the blue highlight of the component adjustment category has quality reduction (53%) as the main impact.

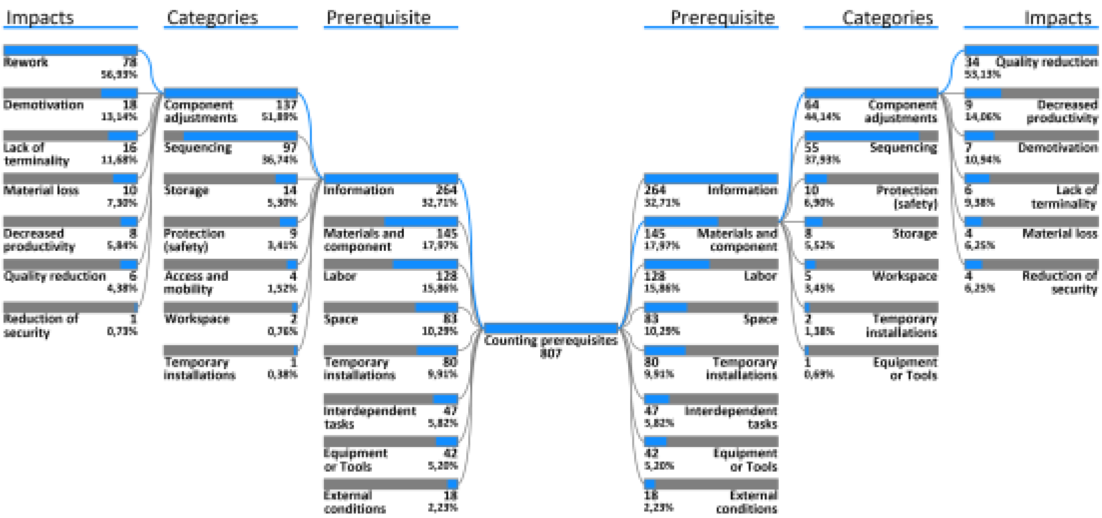

Figure 1: Diagram of the relationships between wastes by prerequisite, category, and impact.

Both present coherent analyses as materials are directly related to wastes regarding their adjustment. Appropriate materials and incorrect sequential use of materials are not necessarily used. When the adjustment of components is emphasized, it is the reduction of quality that is the main impact, accounting for 53% of the wastes. The understanding of the relationship of these topics is also coherent, because when inappropriate materials are used, there is a consequent reduction in the quality of the final service.

In Figure 2, the total wastes related to making-do are presented by the work stages analyzed, in order to present a more specific analysis. The data were highlighted in blue for the bricklayer teams (left side) and for the design team (right side), presenting 42% and 12% of the total, respectively (Figure 2), highlighted by the significance of the impacts in making-do wastes.

When analyzing the construction stages, the design team has the highest number of wastes when related to stages such as technical services (61%) and infrastructure, because it is identified that there are wastes related to exchanging information between the designers and the work and in infrastructure services. Thus, it can be identified that there are problems arising from project conceptions, as the impacts generated by the lack of technical service are related to the details and definitions that need to be passed on to the execution team. Moreover, it is identified that the infrastructure projects present deficiencies in terms of their scope and detailing, because 42% of the impacts generated by this service are due to errors in the projects and surveys made in the field by topography designers.

Meanwhile, when analyzing the stage per bricklayer team, it is possible to see that the services of provisional installations (68%), wall and panels (49%), superstructure (50%) and hydro-sanitary installations and gas (53%) are the ones that present the greatest wastes from the total corresponding to the stage, because they are intrinsically related. Thus, the team executing the service generates a greater rework of the activities already performed due to problems related to a lack of information. This is often due to errors in the interpretation of the projects, or in their preparation, as well as the lack of defining the constructive sequencing and in adjusting components, which often depend on the speed of the manpower itself.

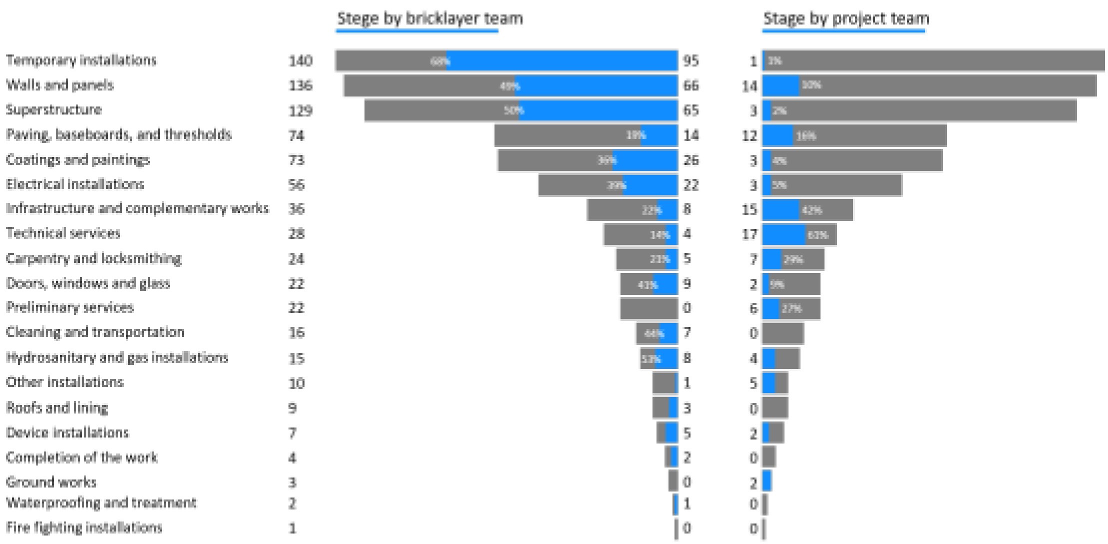

Figure 2: Analysis of the construction stages highlighted from the bricklayer and design teams.

Based on the analysis of the main occurrences of wastes, segmenting the prerequisite information (33% of the total) and the sequencing category (34% of the total), it can be observed that the information is intrinsically related to the performance of wastes in the design team and the engineering team (Figure 3), with 91% and 52%, respectively. Thus, the technical teams ended up retaining information necessary to avoid constructive problems, as well as the need for possible changes and rework. Moreover, the sequencing category directly affects the design and management teams, therefore it can be inferred that the lack of definitions of the designers and management, as well as the needs of physical progress of the work, corroborate with constructive sequence problems.

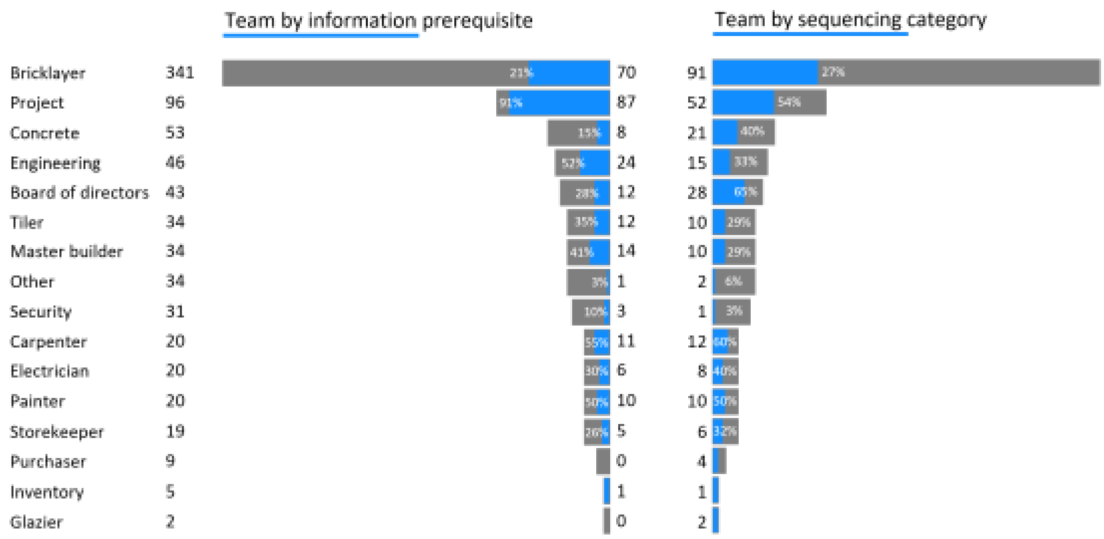

Figure 3: Information prerequisite and sequencing category analysis highlighted from the teams.

In Figure 4, making-do wastes are analyzed related to the prerequisites and impacts. Thus, it can be identified that rework (57%) corresponds to the greatest impact in all prerequisites, especially the impacts related to deficiency of information, materials and components and labor, which together account for 67% of the wastes. Thus, it is identified that in addition to the information, the materials used in the services are inadequate or incorrectly applied, generating rework, as the workforce is sometimes unqualified or not qualified with the necessary information to carry out the task.

Furthermore, it can be analyzed that problems related to information deficiency and adopting an unusual construction sequence end up leading directly to rework, representing 87% of the cases. The other impacts present a more uniform distribution throughout the prerequisites, as 56% of the rework wastes are concentrated in the bricklayer, design, and engineering teams.

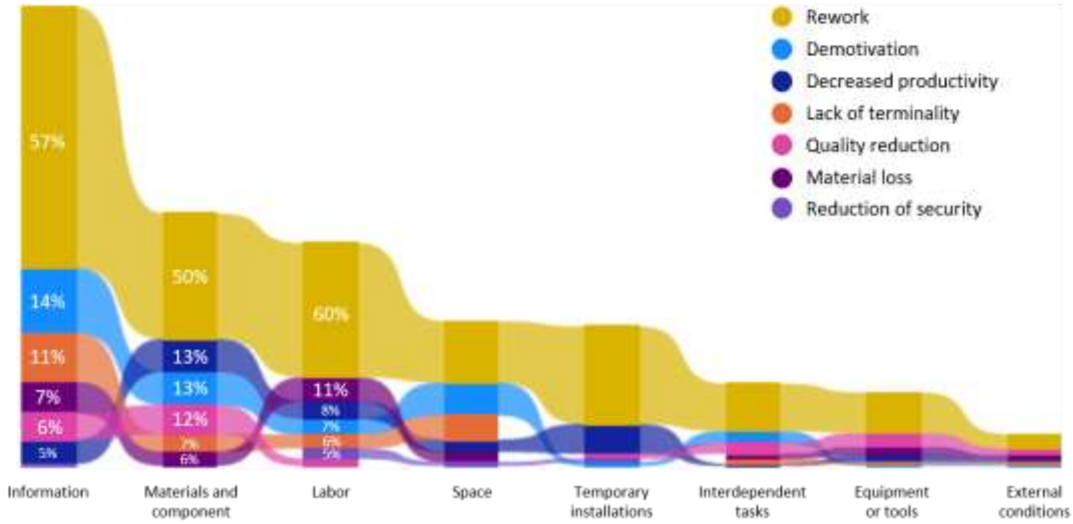

Figure 4: Waste count for prerequisites by impact.

In Figure 5, the waste counts per making-do are analyzed from the categories by impact. Considering this, it can be seen that *component adjustment* and *sequencing* present 34% of the total amount in both categories.

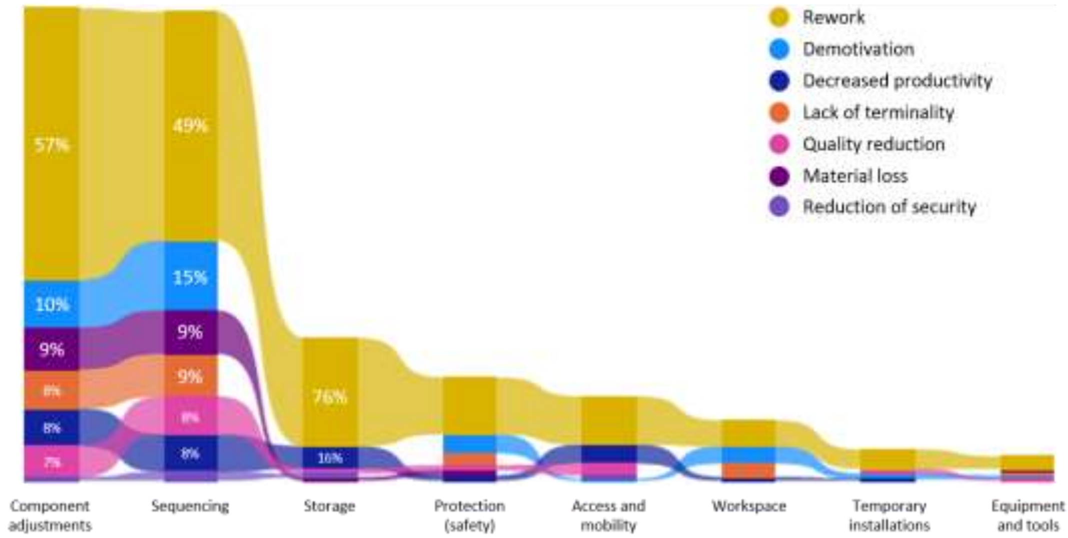

Figure 5: Waste counts for the categories by impact.

When analyzing the *component adjustment* and *sequencing* categories, it can be observed that the impacts are also related to the *information and materials and components* prerequisites, presenting a greater synergy between these variables. Considering this, it can be inferred that the execution team ends up having to determine definitions that will impact on wastes related to making-do. Thus, it is identified that *rework* is the item that represents the largest number of wastes in all categories of analysis, and it can be highlighted that *storage* presents high rates of wastes, as unnecessary transportation takes place at the construction site. Meanwhile, the other impacts are distributed in the other categories.

Table 4 shows a summary consisting of the categories, prerequisites and impacts that most influenced making-do wastes. Thus, it was identified that the database presented the main prerequisites similar to those reported in the literature, as is the case of information and materials and components. In the case of the category as component adjustment and sequencing it can be related to the improvisation character, also due to the lack of information reported as a prerequisite, of the construction companies reported in the database. The main impact is identified as rework, which is characterized by improvisation and inadequate execution of the services identified.

Table 4 – Comparison between researches related to making-do wastes.

	OUR DATABASE	SOMMER (2010)	FORMOSO (2017)	ELIAS AND BRANDÃO (2018)	BRAGA (2018)
MAIN CATEGORY	34.08% Component adjustments. 33.83% Sequencing.	34.50% Access and mobility.	34.50% Access and mobility.	41.40% Sequencing.	37.18% Protection.
MAIN PREREQUISITE	32.71% Information. 17.97% Material and components.	81.50% Installations.	81.50% Workspace infrastructure.	27.30% Information.	27.47% Installations. 20.00% Material and components.
MAIN IMPACT	55,51% Rework.	72.00% Reduced safety. 72.00% Materials waste.	70.50% Material waste. 65.00% Reduced safety.	24.00% Rework.	45.12% Reduced safety. 26.67% Quality reduction.

CONCLUSIONS

The relationships between the chosen parameters were observed, and how the prerequisites, categories and impacts interacted with the other variables in the database using the dashboard developed in the Microsoft Power BI® platform.

Regarding the prerequisites, the *information* item (33%) is the one that presented the highest number of associated wastes and was strongly related to the *component adjustment* and *sequencing* categories. Thus, the *component adjustment* and *sequencing* categories presented, in both variables, 34% of the total analyzed, which were the categories with the main bottlenecks in solving problems with *making-do* wastes.

The technical department should detail all the necessary information for the production teams at the design stage. In addition, the supply management must supply all the production and internal logistics' needs to reduce wastes related to sequencing and adjustment of components.

The limitations of the research are related to the sample analyzed, and there may be an expansion of data and inclusion of the analysis in different countries, states, and construction typologies. Considering this, the database may present a greater variability of samples to better understand the most diverse situations and civil construction companies. Future research may focus on expanding the sample to other regions, through institutional collaborations, either nationally or internationally. In addition, the database can be used to develop a model to help identify prerequisites and categories by detecting existing impacts in the construction site.

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BUILDING INTERDISCIPLINARY TEAMS THROUGH STUDENT DESIGN COMPETITIONS: A CASE STUDY

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ABSTRACT

The owner, architecture, engineering, and construction (OAEC) industries have grown increasingly complex, necessitating improvements to both design and construction procedures—requiring increased collaboration among all lean stakeholders. However, universities are often criticized for not developing essential, generic skills in their graduates, especially the ability to work collaboratively in teams. Attempting to better prepare students, academic institutions are creating vehicles to help their students acquire effective teamwork skills. Competitions, for example, have spread to almost every discipline, including the OAEC-related ones, since they have much to offer students of the built environment. The researchers assessed the participants' experience of an interdisciplinary design competition to determine if such competitions are an effective means to impart teamwork skills to future collaborative stakeholders of the built environment. Additionally, this research aimed to identify areas where educators should prioritize their efforts to better prepare students for enhanced teamwork performance. In addition to highlighting that teams should be appropriately composed of members with critical, needed skill sets, results from a post-event survey of the case study competition also suggest there is a need to teach students how to develop clear and shared goals, develop clear and understandable roles, and communicate more effectively when working in teams.

KEYWORDS

Teamwork, collaboration, OAEC / AECO, interdisciplinary competition, Lean Integrated Product Delivery / Lean IPD

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INTRODUCTION

COMPETITIONS AND THE OAEC INDUSTRY

In the owner, architecture, engineering, and construction (OAEC) [3] industries, interdisciplinary project delivery (IPD) contracts are becoming the norm. The educational approaches for these disciplines, however, have been slow to embrace this transition to a more collaborative structure (Irizarry et al., 2010). Gusmao Brissi et al. (2019) argue that changes in the education of students in the stakeholder fields offer a way to enhance collaboration in the OAEC industry. Arguably, students in these disciplines should be exposed to an education that provides the type of collaborative mindset needed for their future careers. For example, in recent years, builders and building management companies have become increasingly interested in approaches to improve quality, to reduce project risk, and to reduce conflict and waste, despite potentially high upfront costs (Nguyen and Akhavian 2019). A review of the literature suggests that Lean-Integrated Project Delivery (IPD) is an effective approach because it involves key stakeholders through mutually developed goals and shared decision-making at a very early stage in the project timeline (El Asmar et al., 2013). Lean-IPD aims to enhance project outcomes by aligning the incentives and goals of the team. It is therefore likely that teaching collaborative decision-making can improve time, cost, quality, safety, and stakeholder morale on construction projects (Kulkarni et al., 2012; Rybkowski et al., 2013).

Competition in academia has spread to almost every disciplinary field. Research has shown that competitions have much to offer to students and should be adopted by academia (Verhoeff, 1997). Guilherme (2014) argues that "competitions, in particular international competitions, test [an] architect's capacities beyond controlled systems of social relations, comfort zones, age, gender or even expertise, in a fast sublimation process, as well as induce a recognition and publicity that surpasses the investments in time, energy and financial resources..." (p. 433). Haupt et al. (2019) concluded that "teaching a design studio based on [an] architectural competition assignment shows that entering a prestigious event is a great motivation for students to undertake more difficult tasks, as well as to bring them to a successful end" (p. 342).

It stands to reason then, that interdisciplinary competitions can offer a similar opportunity to jump-start students' understanding of the need for collaborative skills, as well as respect for their partnering stakeholders on a project.

TEAMWORK

Why are certain teams successful while others are not? What attributes are required for success? Research has indicated that the existence of some key attributes is vital to successful teamwork. Tarricone and Luca (2002) concluded that there is a strong correlation between adopting some key traits by team members and how successfully they perform in terms of collaboration and developing a quality product. Strong teams do not form by accident. Team building can improve team performance in a long-term, positive, and measurable way (Land, 2019). One of the most important aspects of a team, according to the literature, is its emphasis on a single objective and a defined purpose. Furthermore, the primary disciplines historically associated with building ownership, architecture,

[3] While the acronym AECO is sometimes used to describe the architecture, engineering, construction, and owner stakeholders, this paper instead uses OAEC to emphasize that it is the *owner's* "Conditions of Satisfaction" (CoS) that should be prioritized during the project design and delivery process, in keeping with lean construction philosophy and principles.

engineering, and construction have recently undergone significant adjustments to adapt to new processes and demands in the industry. Because these professions should be working toward a shared objective of delivering a completed built structure, communication between architects, engineers, and construction managers is necessary (Gusmao Brissi et al., 2019). Several characteristics that are required for successful teamwork have been identified through a literature review. Many of these characteristics have been observed repeatedly. Table 1 summarizes the literature on elements essential for effective teamwork.

In reality, each team is unique and faces its own challenges. Not all perform as successfully as planned, and of course, teams can also fail. Researchers have observed a variety of factors that can lead to unsuccessful teamwork: *lack of clear purpose and goals, lack of effective leadership, lack of trust, poor communication,* and *unclear roles or insufficient skill*s (Parisi-Carew, n.d.; Maldonado, 2015; Eckfeldt, 2017). While the list of characteristics that lead to failed teamwork appears to primarily represent an antithesis of attributes that lead to success, there is one notable exception. For example, although trust was not explicitly mentioned by the authors cited in Table 1 as a critical factor for effective teamwork, *lack* of trust has been cited by others as one cause for *in*effective teamwork (Maldonado 2015; Parisi-Carew 2015; Wanamaker 2018).

Table 1: Key Attributes for effective teamwork

Author	EC	ATC	EL	RA	CUR	CSG	I
Azmy 2012	×		×		×		
Bannister et al. 2014	×	×		×		×	×
Fapohunda 2013			×	×		×	
Fisher et al. 1997						×	
Holland et al. 2000	×	×	×		×		
Katzenbach and Smith 1993		×				×	
Khoshtale and Mahdavi Adeli 2016					×		
Kline et al. 1996	×		×			×	
Mickan and Rodger 2000	×		×		×	×	
Setiawan and Erdogan 2018			×	×			
Sohmen 2013			×				
Svalestuen et al. 2015		×					
Szewc 2014	×		×				
Tarricone and Luca 2002	×	×		×		×	×
Yusuf 2012	×						

EC, *effective communication*; ATC, *appropriate team composition*; EL, *effective leadership*; RA, *responsibility and accountability*; CUR, *clear and understandable roles*; CSG, *clear and shared goals*; I, *interdependence*

Extant literature reveals that few studies had been conducted to identify a competition's full impact on the students participating in these competitions. Although some studies have been conducted regarding the importance of design competitions to the OAEC disciplines, most existing research does not identify the attributes that are critical for teams to win—or lose—a collaborative design competition. These elements are helpful to know because student design competitions can arguably serve as a proxy for stakeholder collaborations in the professional world. In addition, these attributes can help institutions identify the areas on which they should focus efforts in order to prime a more sophisticated future workforce by offering appropriate training in their curriculum. The success or failure of a project in the "real world" is likely built on collaborative skills that are formed when OAEC professionals are still students at universities. The intent of this research is to analyze competitors' experiences immediately following participation in a university-level interdisciplinary design competition. The research will probe an interdisciplinary student competition as a case study to identify which teamwork skills are naturally in play and which skills need to be better transmitted to future collaborative stakeholders of the built environment.

METHODOLOGY

RESEARCH DESIGN

This case study assessed post-competition responses to an annual interdisciplinary design competition entitled the Harold L. Adams Interdisciplinary Charrette for Undergraduates (HA-ICU) held during the weekend of February 25-27 of 2022 in the College of Architecture at Texas A&M University. This college-wide design competition was designed and organized by five members of faculty and five student "ambassadors" (organizers) selected from the departments of architecture, construction science, landscape architecture and urban planning, and visualization, and the program of university studies. Competition participants were recruited by the student ambassadors from all five departments and programs. Although their professional skill sets were still in their infancy, first and second-year undergraduate students were recruited as competition team members as it has been observed by several faculty members that students from the OAEC disciplines appear to be most open to learning from other disciplines during their early years of study, before disciplinary silos become hardened. The competition challenged entrants to collaboratively submit a design based on a specified prompt. The teams were asked to:

- develop a sustainable space to enhance awareness of the impacts of each discipline in the practicing world;
- design a structure or shade cover that should consider relationships to the context, the volume of traffic throughout the area, and microclimatic factors;
- recommend unique solutions to enhance access between the buildings that house the College of Architecture's students, faculty, staff, centers, studios, and labs; and
- incorporate the College of Architecture's mission to address three environments: the natural, built, and virtual.

For this research, a literature review was used to identify key attributes for effective teamwork. Based on these findings, a survey was administered to the student competitors following the competition. To streamline the survey process, the questions for this research were included as part of a multi-year survey that was being conducted by a separate researcher regarding participant knowledge growth during the competition.

STUDENT RECRUITMENT

An organizational team of five interdisciplinary faculty—from the departments of architecture, construction science, landscape architecture and urban planning, and visualization, and the program of university studies—selected five student ambassadors from their respective departments. The selected ambassadors were hired as student workers to collaborate closely with the faculty committee for a month prior to the competition to organize the 5th annual HA-ICU 2022 competition. The student ambassadors took on different responsibilities, including poster design, advertising, participant recruitment, design prompt development, t-shirt design for participants, meal ordering and delivery for the weekend of the competition, etc. The ambassadors met weekly with the faculty committee to ask for guidance to avoid potential problems.

The ambassadors designed a poster as well as announcement emails to recruit participants. To build excitement among first- and second-year students, the recruitment process was conducted both virtually (via email) and in-person (by making announcements in classes and through the posting of the posters). This multi-level recruitment strategy was adopted to increase the likelihood that email recipients would read the competition announcements.

DATA COLLECTION

To collect student reactions regarding their experiences of teamwork during the three-day competition, a survey was administered using Qualtrics–an online survey service. Online administration of the survey made the data collection and analysis more efficient compared to paper (i.e., the data collected thorough Qualtrics were later converted into Excel spreadsheet for data analysis). However, paper copies of the survey were also made available to students who did not have their laptops or cell phones available at the time of the survey or who preferred to respond by paper.

The competition took place from 5:00 pm Friday, February 25 until 2:00 pm on Sunday, February 27, 2022. To avoid potential respondent bias based on the receipt of a prize, this study was conducted via a survey administered to student participants following their presentations to the competition jury, but *before winners were announced*. To maximize the number of survey responses, participants were given approximately 30 minutes to complete the survey and were awarded with tickets upon completion which gave them access to enter the auditorium where the winners were to be announced.

STUDENT PARTICIPATION

Although the original goal was to recruit participation of 50 students (10 teams of 5 interdisciplinary students each), the competition hosted 43 students (7 fewer than expected) as some of the registered students cancelled their registration due to conflicting work schedules and other personal matters. Ultimately seven teams of 5 students each, and two teams of 4 students each participated in the weekend-long competition. Table 2 presents the detailed number of students registered from each department.

Table 2: Disciplinary composition of student teams, by number of students. Numbers varied according to student availability.

Team	A	CS	LA	V	US
1	2	2	1		1
2	2		1		1
3	2	1		1	1
4	2	1		1	1
5	2	1	1	1	
6	2	1	1		1
7	2		1	1	1
8	2	1		1	
9	2	1	1		

A, *architecture*; CS, *construction science*; LA, *landscape architecture & urban planning*; V, *visualization*; US, *university studies*

SURVEY QUESTIONS

The primary purpose of administering survey questions to competition participants was to identify patterns of need that could help guide universities about how to better prepare OAEC students for collaboration. The survey research was based on responses to five survey questions:

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1. Do you think you will win one of the top three prizes in this competition?

   _____ Probably Yes

   _____ Probably No

   Why did you select the response you did?

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2. For the following questions please rate how you think your team performed with respect to each attribute of teamwork. Mark on a scale of 0 to 7 where 0 is poor and 7 is excellent.

	Poor							Excellent
Effective Communication	0	1	2	3	4	5	6	7
Appropriate Team Composition and Skillsets	0	1	2	3	4	5	6	7
Effective Leadership	0	1	2	3	4	5	6	7
Responsibility and Accountability	0	1	2	3	4	5	6	7
Clear and Understandable Roles	0	1	2	3	4	5	6	7
Clear and Shared Goals	0	1	2	3	4	5	6	7
Interdependence	0	1	2	3	4	5	6	7
Trust	0	1	2	3	4	5	6	7
Other (Please Explain)	0	1	2	3	4	5	6	7
Other (Please Explain)	0	1	2	3	4	5	6	7
Other (Please Explain)	0	1	2	3	4	5	6	7

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3. If the organizers were to offer training in advance of the workshop on team collaboration, where do you think their focus should be? (Pick only 3)

Effective Communication	☐
Appropriate Team Composition and Skillsets	☐
Effective Leadership	☐
Responsibility and Accountability	☐
Clear and Understandable Roles	☐
Clear and Shared Goals	☐
Interdependence	☐
Trust	☐
Other (Please Explain)	

   Why did you recommend what you did?

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4. What is your Team ID? (This information will **not** be used to identify you)

   ☐1 ☐2 ☐3 ☐4 ☐5 ☐6 ☐7 ☐8 ☐9 ☐10

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5. Overall, was this a worthwhile experience?

   _____ Yes

   _____Somewhat

   _____ No

RESULTS

SATISFACTION WITH COMPETITION AND PERFORMANCE WITH RESPECT TO EACH ATTRIBUTE OF TEAMWORK

This section describes results obtained from the post-event survey conducted immediately following the competition to determine if interdisciplinary student competitions are capable of imparting teamwork skills to future collaborative stakeholders of the built environment, and to identify areas where educators should prioritize efforts to better prepare students for enhanced teamwork performance. After the weekend-long competition, student competitors were asked to rate how they felt their team performed with respect to each attribute of teamwork identified in the literature review. Participants were also asked to identify which of the attributes they felt should be given to participants through a separate, dedicated training before the competition to enhance their performance on teams.

The fifth annual HA-ICU 2022 competition united a total of 43 students from the departments of architecture, construction science, landscape architecture and urban planning, and visualization, as well as the undergraduate studies program. The post-event survey was conducted on Sunday, February 27, 2022, and 42 participants participated in the survey (one participant could not attend the winner announcement session due to a family emergency). Results showed that a majority of participants (95.23%) found this competition worthwhile as a learning experience (Figure 1).

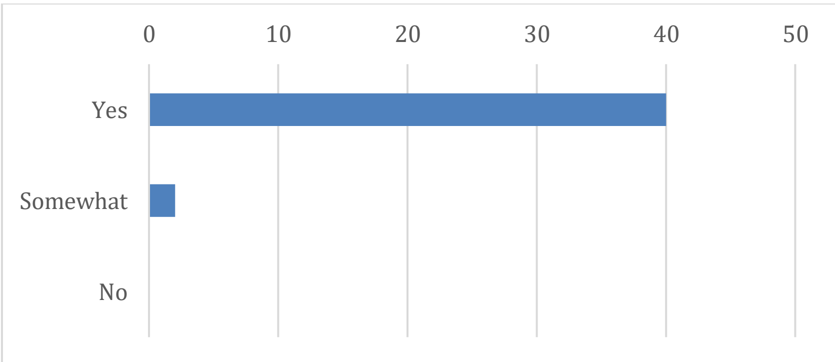

Figure 1: Participants' response to survey question "Overall, was this a worthwhile learning experience?" (Measurement is by number of respondents, n=42)

With respect to the listed attributes of teamwork (Question 2), participants indicated that *trust* (an average of 6.17 out of 7) and *interdependence* (an average of 6.17 out of 7) rated highest among all the teamwork attributes previously identified by the literature review and listed in the survey. However, respondent results also showed *appropriate team composition and skillsets* (an average of 5.90 out of 7) and *effective communication* (an average of 5.98 out of 7) were rated the lowest by the participants, revealing that these areas were more problematic for teams to overcome during the competition. Figure 2 summarizes responses to this question.

IDENTIFICATION OF ATTRIBUTE TRAINING NEEDED

Another core question that participants were asked in the post-event surveys was "If the organizers were to offer training in advance of the workshop on team collaboration where do you think their focus should be?" The attributes revealed by the literature were again listed for respondents, along with a follow-up question asking them to add any attribute that they think may be critical but that was not listed in the survey (ie. "other" (please explain)).

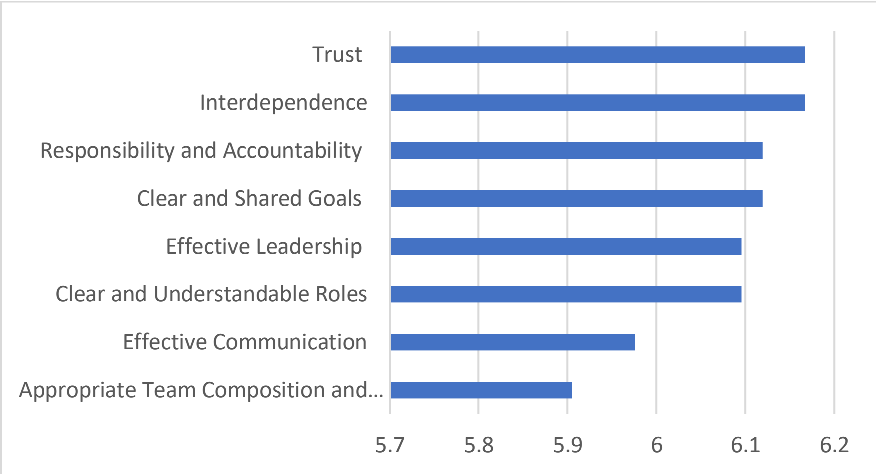

Figure 2: Participants' response to the survey question: "Please rate how you think your team performed with respect to each attribute of teamwork."
(Likert scale is from 0 to 7, where 0 is lowest and 7 is highest)

Data collected for Figure 3 of the survey revealed that *appropriate team composition and skillsets* (52.38%), *clear and shared goals* (47.61%), *clear and understandable roles* (45.23%), and *effective communication* (45.23%) were identified by most participants as areas that needed training prior to the competition.

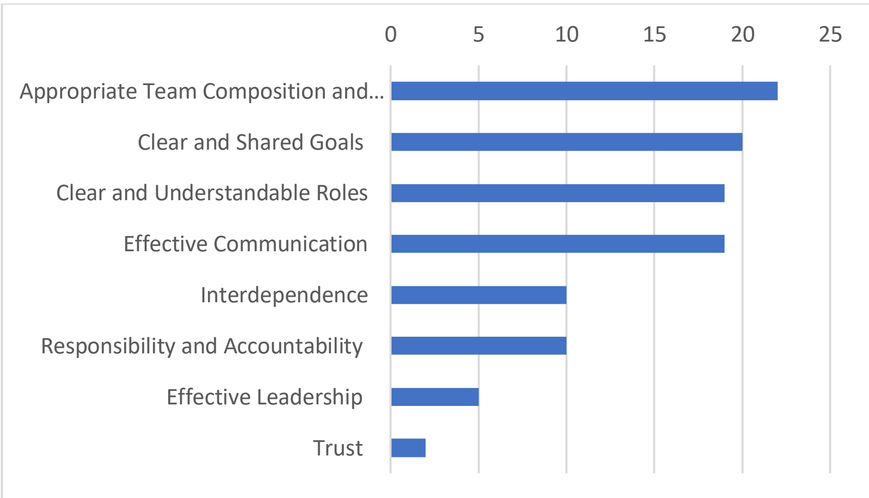

Figure 3: Participants' response to the survey question: "If the organizers were to offer training in advance of the workshop on team collaboration, where do you think their focus should be? (Pick only 3)"
(Measurement is by number of respondents, n=42).

As with Question 2, the participants were again invited to also suggest any other attribute they thought was important but not listed in the survey (e.g. "other" (please explain)). While two students recommended hosting pre-competition workshops on software and programs to better prepare competition participants, most respondents did not suggest any additional attributes other than those listed, which suggests that the attributes listed were likely the most critical ones believed by participants to be necessary for effective team collaboration.

WINNING TEAMS VS. NON-WINNING TEAMS

Data analysis of participants' responses to question #2 revealed that all winning teams performed well regarding *clear and shared goals*. On the other hand, although the teams that were rated lowest by the panel of judges indicated that they struggled in having clear and shared goals and effective leadership, there is no evidence as to which factor was most critical for not winning the competition.

LIMITATIONS

There were some limitations to this study. Although this research is about teams, it explores the attributes of student teams in academia, which may differ from those of teams in firms/companies where an experienced individual is often placed in charge. Also, the argument that student design competitions can serve as a proxy for OAEC collaboration on actual projects needs evidence. There were two additional limitations, namely: there may be differences in the way the respondents interpreted the specific meaning of each of the teamwork attributes, and although follow-up interviews with the respondents could have shed additional light on how the results should be interpreted, a number of logistical issues prevented follow-up interviews from being included. Despite these limitations, the authors found the survey results of value and worth sharing.

CONCLUSIONS

In summary, results from this case study point to a recommendation that holding interdisciplinary competitions is worthwhile for OAEC undergraduates as a learning experience and can be helpful for them to appreciate the importance of the attributes that play a role in team success. It is interesting that team members in this competition felt a sense of *trust* and *interdependence* among their team members since these attributes can help team members feel comfortable about opening up, exposing vulnerabilities, and collectively overcoming existing problems. However, it must be acknowledged that both these characteristics–trust and interdependency–can also be adversely affected by a lack of necessary skillsets, which apparently challenged some participants of this case study competition. While the need to better equip students with more polished skillsets might suggest the competition should instead comprise upper-level student participants rather than first- and second- year undergraduate students, it is worth investigating to see if the vulnerability these more junior students felt may actually heighten their motivation to better equip themselves with the skills they need to become effective as professionals. A longitudinal study of the future performance of these students could offer some interesting insights.

Finally, and perhaps most importantly, results from the post-competition survey suggest that OAEC students appear to be calling for educators to not only teach disciplinary skills, but also how to develop clear and shared goals, to develop clear and understandable roles, and to communicate more effectively.

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ESTABLISHING DESIGN METRICS TO INFORM DESIGN CHANGE, INCREASE PROJECT TEAM COMMUNICATION, AND REDUCE WASTE: A HEALTHCARE CASE STUDY

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ABSTRACT

This study aims to evaluate via a case study the process in establishing post-construction performance goals and their perceived impact to a design and construction project team's culture. Performance goals were established from an iterative quantitative approach, while the impact to the design and construction team were evaluated by a qualitative method. Preliminary results appear to indicate a likely positive impact to a project team's culture, level of effort, and trust. Specifically, results may indicate a net positive impact from unambiguous post-construction performance goals to a project team's perception of its communication and overall project environment, reduction in traditional sources of process waste, and a positive impact to elements associated with cost, schedule, and quality.

KEYWORDS

Collaboration, Case study, Integration, Value, Integrated Project Delivery

INTRODUCTION

Pediatric inpatient behavioral health facilities have historically been designed to maximize patient safety and staff security, as well as operational efficiency, often at the expense of other healing goals. Such care practices can trigger a patient's experience of trauma during treatment. This induced trauma can create adverse effects on healthcare staff and family members and create barriers to providing patient care. Trauma-informed design recognizes the role the environment plays in supporting trauma-informed care (SAMHSA, 2022). Trauma-informed and family centered design approaches aim to

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facilitate care which minimizes re-traumatization for the patient and provides family support during treatment and recovery.

The shift in behavioral health to trauma-informed care is relatively new. As such, there are few programmatic and design precedents to draw from which can support this new standard in care delivery. Having defined performance goals post-construction are essential for the design team to propose and test potential design interventions which aim to meet those goals. The importance of trauma-informed care is a significant design element for the architectural and engineering design teams and is therefore assumed to be of significance to the construction trade partners. This assumption is based on the effort and significance that such programming priorities are disseminated throughout a project team and over the project duration. The establishment of these programming priorities provide an opportunity to understand how these priorities may impact project team members.

This study aims to evaluate what, if any, impact there is to a project team's culture, level of effort, and interpersonal trust stemming from clear and measurable post-construction performance goals based on existing and/or industry established systems of measurement (to be referred hereafter as "design metrics). Design metrics were used to quantify how patient, staff and family outcomes were impacted from an existing behavior health design, and how these were used to inform design and construction of a new pediatric inpatient behavior health unit. Though these design metrics are specific to an individual pediatric behavior health unit, intent of this study is to highlight efficiencies gained by design and construction team using measurable and achievable design metrics.

Specifically, this research looks to evaluate the impact of unambiguous design metrics to a project's cost, schedule, level of communication, and level of effort, trust and overall satisfaction of the project team its culture. This research will assume the following in its evaluation:

Proposition 1: Programming design metrics have a positive impact on communication, level of trust, and project culture.

Proposition 2: Programming design metrics assist in reducing waste within a collaborative environment.

Proposition 3: Programming design metric has positive impact on project success (success may be defined in terms of any of the parameter of cost, time, quality or H&S).

LITERATURE REVIEW

There has been limited research into the impacts of design metrics on project team communication and overall collaboration. Established research includes areas specific to designing via project goals/ metrics to increase trust, collaboration and increase communication within the built environment (Hanna, 2016, Abdelaal, 2016; Gibson et al., 2006; Korin & Taplin, 2004). Distinct from this area of research though, and specific to the purpose of this paper is to evaluate the impact of design metrics on a project team rather than the impact of a designed space on occupants' post-occupancy. For instance, Lamb and Shraiky (2013) reviewed post-occupancy data of healthcare classroom environments and identified common design concepts common to facilities that enhance collaboration amongst its users. Leder et al. (2016) evaluated employee and project client satisfaction of green office buildings and found on increased satisfaction when certain green design principals were utilized. Uusitalo et al.(2021) evaluated the impact of design issues and quality to trust, collaboration, and overall communication.

More generally, existing research evaluates the impact and applicability of evidence-based design (EBD) and the effect of design to healthcare environments. Elf et al. (2020) reviewed existing literature of EBD and noted that most of the research to date has reported on patient's and staff's psychosocial experience as compared to medical and/or physiological responses to the environment. Similarly, Anåker et al. (2017) performed an extensive literature review on EBD design quality in healthcare settings and concluded that clear definition of design/project quality is needed to meet the needs of stakeholders. Stakeholder involvement with design/project goals was specific to the research of Sadler et al. (2008) when reviewing the connection between design quality and positive patient outcomes.

Research linking construction metrics and benchmarking to project success are more numerous, but do not necessarily address design metrics to the three research propositions. Construction related metrics such as number of request for information (RFI), change orders, schedule changes, amount of rework, punchlist items, safety issues, behavior/leadership observations and the like have been reviewed by numerous researchers including Umstot et al. (2014), Hanna (2016), Bonilla & Costillo (2020), Bølkviken et al. (2017), Alarcon & Serpell (1996), Korkmaz et al. (2010), Swarup et al. (2011), Azari & Kim (2014), and Esmaeili et al. (2013). Additional research has considered the impact of design to quality issues during and post construction that may impact end-user post-occupancy, such as Lam et al. (2010), Riley and Horman (2001), Hamzeh et al. (2019), and O'Sullivan et al. (2004). None of these though specifically address the purpose of this paper, and/or the three research propositions.

RESEARCH METHODS AND DATA

This research follows a traditional mixed-methods approach utilizing data from a single case study (Guetterman & Fetters, 2018; Korkmaz et al., 2011). Mixed-methods typically indicates a combination of qualitative and quantitative methods and data types (Ladner, 2019). This research method was chosen as an ideal methodology to explore the seemingly inconsistent impact (qualitative) of the project design metrics to the project team by the constant (quantitative) project design metrics. Though it is common in design and construction to use mixed method research to use a quantitative analysis to quantify an issue and then use a qualitative analysis to understand the why (Fellows & Liu, 2015), here we use a qualitative analysis to understand the impact from the results of a quantitative analysis on the project team.

Following the literature review, a two-stage process similar to other case-study research (Ozorhon, Abbott, & Aouad, 2014; Souza de Souza & Koskela, 2014) was conducted to confirm the research propositions. The first stage involved establishing design metrics that met the performance criteria that was of importance to the end-users and justified the business case for the project by the hospital system. This was a quantitative process, based on the data analysis originated from the project owner. Once the design metrics were established and had been in use for the design phases and majority of the construction project, the second stage of conducting a qualitative analysis with the project team was undertaken to understand the impact.

CASE STUDY

This paper presents findings from a $23million Integrated Project Delivery (IPD) (AIA-C191) pediatric behavior-health expansion project located in the Rocky Mountain west of the USA. The hospital provides a complete continuum of psychiatric services including outpatient, partial hospitalization, inpatient and emergency services for children and adolescents, as well as non-behavior services. The project was spread over 4 floors of a building, totaling roughly 80,000sf. Each floor contained separate behavior health care modalities, as well as support administrative spaces. Design began in the fall of 2019, with construction starting during the summer of 2020 and is scheduled to be fully completed during early summer of 2022. The hospital design team was an interdisciplinary team that included psychiatrists, psychologists, clinical social workers, licensed professional counselors, nurses and creative art therapists to address the unique treatment needs of the patients. Design and construction members were selected during the onboarding selection process, while hospital clinical members were selected by hospital leadership and in-house design and construction staff.

STAGE 1 – ESTABLISHING DESIGN METRICS

Project Goals and Design Concepts

The first stage began during the initial phases of design, during the spring of 2020. Input from the owner and end-users were utilized to frame and document the project goals.

The project team focused on the following goals which best framed opportunities for innovating the design of the milieu to support the delivery of trauma-informed care.

Goal 1. To optimize staff safety and health, reduce staff injury

Goal 2. To elevate patient experience, reduce acute stress and aggression triggers

Goal 3. To promote family recovery, engage parents in inpatient care delivery.

For the purpose of this research, only goals 1 and 2 relate to the physical space and will be the focus of study. Goal 3 was intended to be operationally focused, is routinely post-admission, and will not be studied. After the project goals were established, the project team next created design and process concepts to support these goals (Figure 1). In some cases, the design concept drove the need for new operational processes and in other cases, the aim for new care practices drove the need for innovative physical environments.

Figure 1: Impact areas (central core) and project goals (outer ring) associated with supporting trauma-informed and family centered care in a pediatric behavioral health inpatient setting

Design metrics and Analysis

Once the project goals and supporting design concepts were established, diagnostic post-occupancy evaluation (POE) was used to assist in the establishment of the project design metrics. The POE correlates physical environmental measures with subjective occupant response measures for the purpose of creating new knowledge about building performance (Preiser, 2001). This POE utilized multiple methods to provide a more complete assessment to align outcomes with the design. Descriptive statistics were used to analyze data collected across the existing and renovated facilities to evaluate the ability to formulate project design metrics (Table 1). Quantitative analysis of facility and patient (de-identified) data was obtained to set a baseline for future analysis of the new construction, post-occupancy. Once these were established, the project team could then use project design metrics to evaluate design objectives.

Table 1: Data type and source based on project goal

Data Acquisition Question Based on Goal	Data Source	Project Design Metrics
Can staff injury be reduced by decreasing events associated with physical and verbal aggression?	De-identified patient data	Decrease in restraint use: incidences and frequency
	De-identified patient data	Decrease in seclusion use: incidences and frequency
	De-identified staffing and security data	Decrease in staff injury: incidences and frequency
		Decrease in staff turnover rate
	De-identified patient data	
Can patient acute stress and aggression triggers be reduced	Facility data	Decrease in building repair requests resulting from patient behaviors: number and type of repair
	Facility data	Process maps for behavior events
	Lighting & acoustics survey	Staff ratings of environmental attributes to patient spaces
	Staff surveys	Staff characterization of patient triggers, types, and locations
	Staff surveys	Staff rating of environmental attributes in patient spaces

STAGE 2 – IMPACT ANALYSIS

The second stage of analysis focused on what, if any, impact these design metrics had on the design and construction team. Specifically, did the presence of definable project design metrics change, alter, and/or facilitate communication and/or reduce waste during the design and construction phases? As noted previously, this was abridged to the three research propositions (see Introduction).

To understand the perceived impact, a survey was conducted via Qualtrics and sent to project participants. The survey was sent to a total of 22 project participants, with preliminary responses currently being reported (*final results will be published in time for final submittal*). Questions asked were based on a 5pt Likert scale, with logic being applied to questions based on their familiarity with the project metrics.

Questions asked were:

(1) (2) (3) (4) (5)

None at all A great deal

a) How familiar ere you with the project design metrics?

For those that responded with a value response of 4 or 5, the following questions were asked:

- *b) Project Design Metrics increased communication*
- *c) Project Design Metrics assisted in reducing waste*
- *d) Project Design Metrics had a net positive project effect to traditional cost, schedule, and quality aspects*

For those that responded with a value response of 1, 2, or 3, the follow questions were asked:

1) (2) (3) (4) (5)

None at all A great deal

- *a) Familiarity with Project Design Metrics would have increased communication*
- *b) Familiarity with Project Design Metrics would have assisted in reducing waste*
- *c) Familiarity with Project Design Metrics would have had a net positive project effect to traditional cost, schedule, and quality aspects*

Results:

Preliminary results shown in tables below. (Note these are preliminary results presented for illustration purposes. Complete results will be available and analyzed in time for final submittal). Table 2 presents a breakdown of responses by project role, namely 50% owner/ owner rep, 33% Designer, and 17% Contractor.

Table 2: Survey Responses by Project Role

Project Role	% Responses
Owner/ Owner Rep	50%
Designer – Arch/ Eng/ Consultant	33%
Contractor – GC/ Sub	17%

Table 3 displays averaged (5pt Likert) results of respondent's familiarity with the project design metrics. Whether responding with a higher familiarity with the project design metrics (83.4%) or no familiarity with the metrics (16.6%), all respondents noted that the project design metrics either had a positive impact on project elements or would have if the respondents were familiar with the project design metrics.

Table 3: Project Design Metrics Impact Survey: 5pt Likert Scale

Statement	Mean Response	Standard Deviation
Your level of familiarity with program metrics	4.5	1.2
Design metrics increased communication	3.8	0.4
Design metrics assisted in reducing waste	3.6	0.9
Design metrics had a net positive impact to cost, schedule, and quality	4.2	0.4
Familiarity with the design metrics would have increased communication if known	4.5	0.7
Familiarity with the design metrics would have assisted in reduction waste if known	2.3	0.6
Familiarity with the design metrics would have had a net positive impact to cost, schedule and quality if known	4.0	0.0

Table 4 shows results for the impact of the project design metrics on communication, for respondents that noted an elevated (survey response of slight or very) familiarity with the design metrics. The majority of responses noted that the project design metrics increased communication during the programming (40% of response) and design phases (40% of responses).

Table 4: Project Design Metric Phase Impact: Communication

What Phase(s) Did Design Metrics Increase Communication	% Responses
Programming Phase	40%
Design Phase	40%
Pre-Construction Phase	20%

Table 5 displays results for the impact of the project design metrics on reducing waste, for respondents that noted an elevated (survey response of slight or very) familiarity with the design metrics. The majority of responses noted that the project design metrics reduced wasted during the programming (40% of response) and design phases (40% of responses).

Table 5: Project Design Metrics Phase Impact: Reducing Waste

What Phase(s) Did Design Metrics Assist in Reducing Waste	% Responses
Programming Phase	40%
Design Phase	40%
Pre-Construction Phase	20%

Table 6 shows results for the impact of the project design metrics on cost, schedule, and quality aspects of the project, for respondents that noted an elevated (survey response of slight or very) familiarity with the design metrics. The majority of responses noted that the project design metrics impacted the construction phase the most (38% of response), followed by pre-construction (25%), project close-out (13%), programming (12%), and design phases (12%) phases.

Table 6: Project Design Metrics Phase Impact: Iron Triangle

What Phase(s) Did Design Metrics Have on Cost, Schedule, Quality Aspects?	% Responses
Programming Phase	12%
Design Phase	12%
Pre-Construction Phase	25%
Construction Phase	38%
Project Close-out	13%

DISCUSSION AND CONCLUSION

Results of the survey show an interesting mix of responses. Most responses either noted the project design metrics had or would have had on impact to the three research propositions, with one exception. For respondents who were unfamiliar with the project design metrics, responses averaged a lower impact to reducing waste. This may be the result of a smaller sample size, or respondents felt that the impact would have been less compared to the impact to communication and cost, schedule, and quality. Either way that this is viewed, the results show a positive impact from establishing project design metrics.

Results seem to suggest that the project design metrics had an impact on outcomes related to programming and design phases, except in the case of "cost, schedule and quality aspects" where respondents acknowledged the benefit to outcomes equally among design and construction phases. For a collaborative IPD team, this may reflect the importance of specific and quantifiable project goals on construction phase outcomes.

Results from this research highlight the importance and potential outcomes across the design and construction process from establishing quantifiable project metrics at the beginning of a project. A qualitative analysis was then conducted to quantify what, if any, impact the project design metrics had on the project team. Based on results from a project team survey, the results appear to indicate a likely positive impact to project team communication, traditional cost, schedule, and quality aspects, as well as possibly reducing project waste.

Due to the relatively small sample size, these results may or may not be generalizable to every project. But based on previous research on the importance of project metrics, it can be assumed that these results would be transferable to similar project structures. Future research may want to review what impact project design metrics have on specific project roles, and impact to project risks.

DISCLAIMER

The views expressed in this article, book, or presentation are those of the author and do not necessarily reflect the official policy or position of the United States Air Force Academy, the Air Force, the Department of Defense, or the U.S. Government

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EVALUATION OF CONSTRUCTION PERFORMANCE WITH THE USE OF LPS AND PRECAST SLABS IN RESIDENTIAL BUILDINGS

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ABSTRACT

The implementation of the Last Planner System (LPS) and off-site construction has been identified as means to improve production management and, thus, increased productivity and project performance. Nevertheless, the sector lacks an evaluation system that allows clients, designers, and contractors to identify areas for continuous improvement and encourage further adoption of the LPS and off-site manufacturing. Therefore, this paper aims to analyze performance during the construction of the reinforced concrete structural frame of two similar high-rise residential projects in Lima-Peru. Both projects used the LPS. However, the first case used traditional on-site poured slabs, and the second used a mix of precast slabs and additional on-site pouring. Data was collected during the construction process and included labor data, production data, schedules, site visits, and observations. Data were analyzed to obtain cycle times, production and productivity rates, and labor density. The results show that the building using precast slabs performed 14% better in terms of time and 16% in terms of productivity compared to the traditional slab. Further research can measure performance and productivity by implementing other precast components such as shear walls, beams, and columns.

KEYWORDS

Last Planner System, Off-site construction, performance measurement, productivity, Lean Construction.

INTRODUCTION

Globally, the construction industry has grown just 1% per year over the past two decades, and this is reflected in the lagging productivity, skilled labor shortages, and unpredictable

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materials costs (McKinsey & Company, 2020). This results in low project performance, cost overruns, and execution times more than planned (McKinsey & Company, 2020). In Peru, building construction exhibits traditional processes such as onsite formwork and concrete pouring that have been the norm for many decades. However, the transition from traditional methods to precast structural components is a major task. The construction sector is well known to be reluctant to change. For example, the penetration of innovations such as Building Information Modeling (BIM) has been slow. One of the reported reasons for the lack of adoption is the little evidence of the relative advantage of adopting such innovations. Ultimately, senior managers and decision-makers require evidence before making investment decisions. Therefore, performance must be evaluated, reported, and continuously updated to drive change. Furthermore, technological advances in the production of precast elements have expanded the possibilities for faster, more sustainable, and high-quality construction, with designs and applications that respond to the challenges of contemporary buildings.

Lean Construction (LC) aims to minimize the waste of materials, time, and effort while generating maximum value for the customer (Khalife & Hamzeh, 2020). The application of lean methods and tools has reported benefits such as organizing an improved production system, increased productivity, and improved occupational health (Howell et al., 2017). Bertelsen and Koskela (2004) argued that LC contains five main principles: specify a value for the customer, identify value stream, make value flow, pull value, and pursue perfection through continuous improvement. The Last Planner System (LPS) is the LC's method for production planning and control. LPS divides the planning system into four levels; the master schedule, the phase schedule, look ahead planning (LAP), and the weekly work plan (WWP). The LPS focuses on reducing uncertainty and variability in the process workflow, including the management tools such as the Plan Percent Complete (PPC) and the Reason of Non-Compliance (RNC). PPC measures the performance of the planning system (i.e., the number of completions divided by the number of assignments for a given week). RNC investigates the root cause of non-compliance in the PPC to learn from repeated failures and prevent their repetition in the future (Ballard & Tommelein, 2021). In addition, it has been shown that there is a correlation whereby the earlier the PPC is controlled, the higher the probability of a successful project and the lower the RNC (Lagos & Alarcon, 2020). Moreover, a collaborative contract with key subcontractors is pivotal to ensuring continuous flow during LPS implementation (Murguia et al., 2016; Khalife & Hamzeh, 2020).

Some existing body of literature has studied performance improvement because of the use of LC and prefabricated components. For example, some studies have shown that the implementation of Lean Construction serves to control, plan, and execute work in the field, presenting itself as an efficient solution to improve productivity, meet deadlines, and safety management (Verán & Brioso, 2021; Ballard & Tommelein, 2021). On the other hand, some studies have analyzed the benefits of using prefabricated components together with BIM and standardized processes. These studies have found increased performance in construction, such as reduced rework, reduced lead time, and better productivity (Xiaosheng & Hamzeh, 2020; Schimanski et al., 2021). Nevertheless, existing literature does not contain quantitative performance metrics. Therefore, the lack of performance information in construction is considered a problem in the industry. For this reason, the main objective of the research is to comparatively evaluate two residential projects implementing the LPS. However, one project has implemented precast slabs, whereas the other project has used traditional in-situ slabs. The results might provide evidence of the performance improvement through the combined adoption of LPS and precast components.

LITERATURE REVIEW

Previous research has reported that the implementation of lean construction methods such as the LPS, Kanban System, Just in Time (JIT), and prefabrication have contributed to improved project performance (Xing et al., 2021). However, the industry lacks a consistent performance measurement framework to benchmark project performance across the construction industry, identify common targets and assess performance improvement due to the adoption of innovations (Murguia et al., 2022). Furthermore, the trend in the construction industry is to integrate lean construction with prefabrication and BIM to achieve increased productivity (Saieg et al., 2018). Additionally, lean construction and prefabrication have been studied to analyze energy consumption and carbon emission reductions (Heravi et al., 2020). It is claimed that prefabrication reduces onsite inventory and allows continuous on-site workflow and waste minimization (Tam & Hao, 2014). Another significant advantage is that prefabricated components can allow flexibility in design by tailoring to desired shapes and dimensions as required (Richard et al., 2019). Furthermore, it is highly recommended to have a supplier that manufactures precast elements with a lean production approach. Lean capacity and capability can be assessed by the contractor to ensure collaboration and a balance between the factory supply and onsite demand. The synergy between the manufacturer, the labor subcontractor, and the contractor must be incorporated into collaborative contracts to achieve the desired performance (Murguia et al., 2016).

Prefabrication of components requires a holistic supply chain management which includes optimizing the design, production, storage, transport, and installation of the precast elements, in addition to improved coordination between the interested parties (Phang et al., 2020). Previous literature suggests that there are positive results of the implementation of LC and off-site construction by implementing lean tools through simulations in the manufacturing process (Darwish et al.,2020). However, it is more focused on the off-site production in factories as reported by Ballard et al. (2003) and Sacks et al. (2003). The proposed recommendations focused on restructuring the production plant in cells rather than distinct departments. Also, they suggested reorganizing functions with an emphasis on workflow, rather than resources, to reduce lead times and minimize waste.

However, there is a lack of studies focusing on performance measurement with the collective use of production management principles such as LPS and off-site construction. On the one hand, the construction industry is complex and data across projects is not standardized and cannot be used for useful comparisons (Costa et al., 2004). On the other hand, there is not a significant number of studies showing production and productivity metrics that can be used for national or international benchmarking. For this reason, the current research aims to provide key project performance indicators of projects using LPS and off-site construction. This would be a valuable contribution that can trigger the report of performance data of similar projects.

METHODOLOGY

To achieve the proposed objectives, this study has selected a case study. A case study is an empirical inquiry that investigates a phenomenon (i.e., the case) in depth and within its context, especially when the boundaries between the phenomenon and the context may not be evident. As such, the main research questions are "how" or "why" questions, the researcher has little control over the behavioral event, and the focus of the study is contemporary as opposed to a historical phenomenon (Yin, 2014). Qualitative and quantitative data were collected in two high-rise residential buildings in Lima, Peru which were under construction between 2020 and 2022. The types of data collected were the start and end day per level, m2 of gross external area, quantities of concrete (m3), formwork (m2), reinforced steel (kg), and the number of workers per crew. Based on Murguia et al. (2022), the following indicators were established: cycle time (days), the production rate (m2/day), labor productivity (m2/mh), and the density of labor (m2/worker). These metrics are in line with the research aim which intends to provide evidence-based project performance because of the implementation of the LPS and off-site manufacturing.

T-tests were selected as the statistical tool to find significant performance differences between the two projects. Both buildings are comparable as they have the same structural frame of reinforced concrete, have a similar footprint area, and use the same construction technology. The study collected data daily during the erection of the main structural frame. Three main activities were included in the data collection process: (1) rebar installation; (2) formwork and (3) concrete pouring for both vertical (columns and shear walls) and horizontal (beams and slabs) elements. The cost metric (Total cost/m2) was not selected as a performance indicator as the cost between both systems is similar. However, a potential reduction of time translates into economic benefits due to reduced overheads. In addition, there are wider benefits for the client and investors as reduced project time improves the return on investment.

CASE STUDY DESCRIPTION

Project A is a high-rise residential building consisting of 4 basements and 18 stories. The construction of the main structural frame started in January 2020 and was hit by the outbreak of the COVID19 pandemic in mid-March 2020. However, the works resumed in June 2020 and the structural frame was finished in September 2020. Project B is a high-rise residential building consisting of 4 basements and 20 stories of the construction of the main structural frame project started in November 2021 and finished in February 2022. Project A has a traditional construction with all structural elements being poured in-situ. However, project B has implemented precast slabs that consist of a thin precast element (5 cm.) which acts as a slab itself and substantially reduces the propping system and the concrete pouring. Also, the precast slab includes the sagging rebar which also reduces the rebar installed on site. As a result, the crews install the hogging rebar and pour the reduced volume of concrete. Figures 1 and 2 show images of projects A and B. Also, Table 1 shows a summary of the project's characteristics.

RESULTS

The Last Planner System was implemented in tandem with takt-time planning in both projects. Each level was divided into some locations and a pull system was designed to ensure continuous flow among crews and activities. The takt-time plans (TTP) were designed with a takt equal to one day as shown in Figure 3. Plans were designed considering five days a week; however, the construction sites operated half a day on Saturdays. Thus, time buffers were included in the plans. Project A was divided into four zones whilst project B was divided into three zones. Project B was split into lower zones due to the ability to install precast slabs at a higher speed. The divisions were made to ensure similar quantities for rebar, formwork, and concrete pouring in all zones. Figure 4 shows the division of zones on a typical floor plate on Projects A and B. Project B exhibited more complex logistics due to the JIT delivery, and vertical movement with the crane to their final position.

Table 1: General Information of Projects A and B

Project	A	B
Use	Residential	Residential
Location	Lima	Lima
Structural frame	Reinforced concrete	Reinforced concrete
Number of levels	18 + Rooftop	20 + Rooftop
Basement area (m2)	4,260	3,446
Building area (m2)	11,880	13,118
Type of slab	Traditional	Precast

Figure 1: Project A - traditional propping system for slabs

Figure 2: Project B - Precast concrete slabs

Item	Takt Production System Project A Activity	Day 1	2	3	4	5	6	7	8
1	Vertical rebar (Columns and Shear Walls)	P1S1	P1S2	P1S3	P1S4				
2	Embedded MEP in vertical elements	P1S1	P1S2	P1S3	P1S4				
3	Vertical formwork		P1S1	P1S2	P1S3	P1S4			
4	Vertical concrete pouring		P1S1	P1S2	P1S3	P1S4			
5	Beam formwork (base)			P1S1	P1S2	P1S3	P1S4		
6	Beam rebar			P1S1	P1S2	P1S3	P1S4		
7	Beam formwork (sides)				P1S1	P1S2	P1S3	P1S4	
8	Slab formwork				P1S1	P1S2	P1S3	P1S4	
9	Slab rebar					P1S1	P1S2	P1S3	P1S4
10	Embedded MEP in slabs					P1S1	P1S2	P1S3	P1S4
11	Slab concrete pouring					P1S1	P1S2	P1S3	P1S4
12	Slab concrete finishing					P1S1	P1S2	P1S3	P1S4

Item	Takt Production System Project B Activity	Day 1	2	3	4	5	6
1	Vertical rebar (Columns and Shear Walls)	P1S1	P1S2	P1S3			
2	Embedded MEP in vertical elements		P1S1	P1S2	P1S3		
3	Vertical formwork		P1S1	P1S2	P1S3		
4	Vertical concrete pouring		P1S1	P1S2	P1S3		
5	Beam formwork (base)			P1S1	P1S2	P1S3	
6	Beam rebar			P1S1	P1S2	P1S3	
7	Precast slab propping			P1S1	P1S2	P1S3	
10	Precast slab placement			P1S1	P1S2	P1S3	
11	Embedded MEP in slabs			P1S1	P1S2	P1S3	
12	Slab rebar				P1S1	P1S2	P1S3
13	Slab concrete pouring				P1S1	P1S2	P1S3
14	Slab concrete finishing				P1S1	P1S2	P1S3

Figure 3: Project A and B production systems

The construction technology is described as follows. First, the vertical rebar is placed. Then, the formwork for vertical elements is installed and this is followed by the concrete pouring of columns and shear walls. After the vertical element's erection, the beam's rebar and formwork are placed. Also, the plumbing and electrical system are installed before the concrete pumping. This is followed by the slab formwork, slab rebar, and slab concrete pouring. Project B has changed some steps of this process due to the precast slabs. The system needs a substantially reduced propping system which is installed before the precast slabs are placed in position. Slab hogging bars are then installed and finally, concrete is poured for the remaining slab thickness.

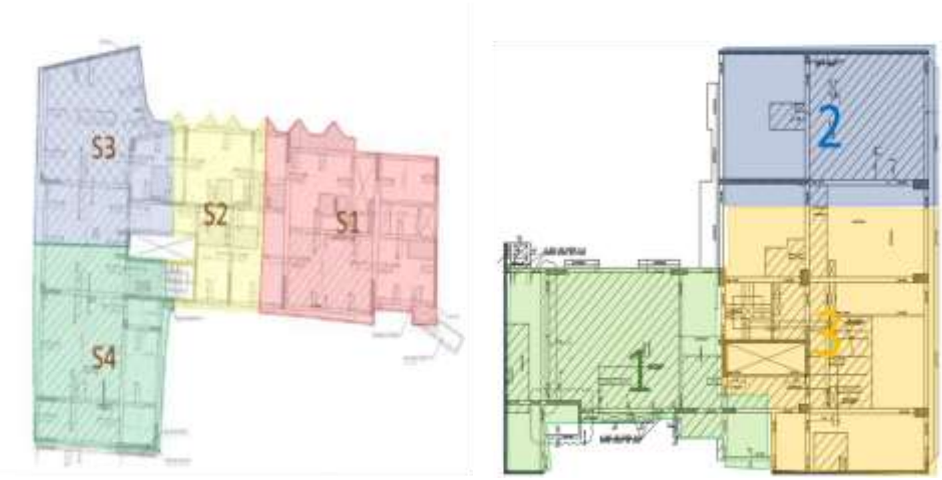
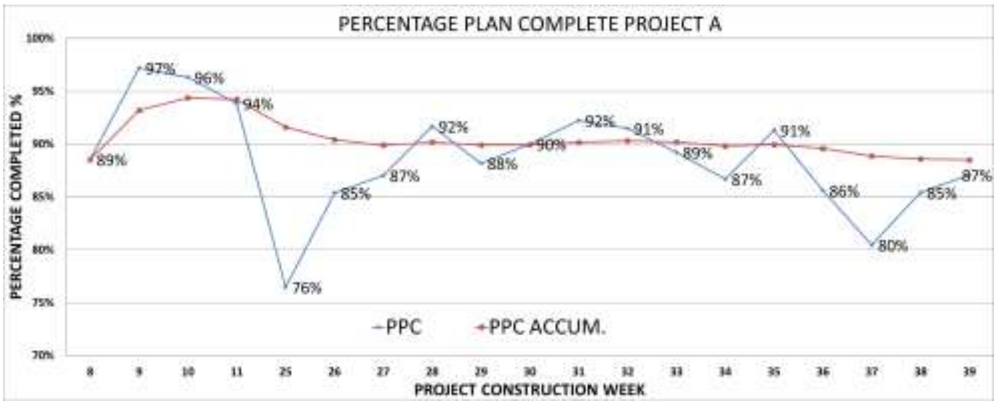


Figure 4: Division of zones for projects A and B

Despite the best efforts to design a continuous flow and to remove restrictions, there was variability due to power supply problems, crane logistics, lack of personnel due to COVID19, inoperative concrete pump, and crane installation. The collaborative sessions with foreman and subcontractors served as a platform to reduce variability. The PPC was recorded as shown in Figure 5. In projects A and B, the PPC accumulated was 88%. Furthermore, as the figure shows, the variability in project B was less in comparison to project A PPC.



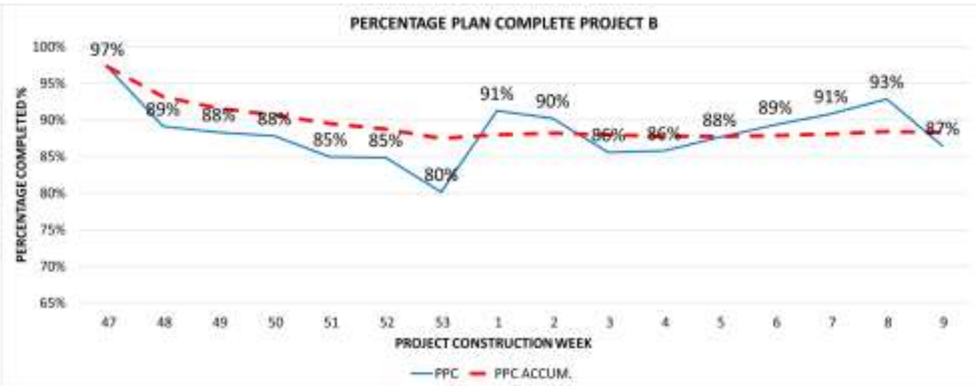


Figure 5: A sample of the PPC of Projects A and B

Table 2 presents a summary of the performance indicators selected for this study. First, the cycle time for each floor was calculated, considering the installation of the vertical rebar of the first zone as the start day, and the slab concrete pouring of the last zone as the end date. The cycle time for Project A was 9 days on average whereas it was 7 days for Project B which means a 29% reduction. Second, the production rate (m2/day) per level was also calculated. T-Test was conducted and found a significant statistical difference ($p<0.001$) between 63 m2/day in Project A and 73 m2/day in Project B. Globally (from level 1 to the top floor), the performance was 123 m2/day in Project A and 135 m2 in Project B. This global performance improvement is due to the takt-time planning that allows overlap between schedules at consecutive levels. Third, the productivity measured in m2/mh was estimated at 0.25 m2/mh for Project A and 0.30 m2/day for project B. T-test was conducted and there is a significant difference between the two projects ($p<0.001$). It should be highlighted that this calculation does not include the hours used by MEP workers (electricians, plumbers, etc.). Traditionally, these services are embedded within the slabs in Peruvian buildings. However, we have dropped these hours to allow for international comparisons. Finally, there was not found a significant difference in the density of workers onsite which is explained by the transformation of only one structural element. It would be expected to have fewer workers/m2 when more components are prefabricated.

Table 2: Summary of performance indicators for Projects A and B

Project	A	B	Difference
m2 per level	565	500	-13%
Cycle time per level(days)	9	7	-29%
Total man-hours (mh) per floor	40,684	33,600	-21%
Production rate - per level (m2/day)	63	73	+14%
Production rate - global (m2/day)	123	135	+9%
Productivity (m2/mh)	0.25	0.30	+16%
Density (m2/Worker)	8.19	7.81	-5%

DISCUSSION

The results suggest that the implementation of precast slabs has a better performance compared to the traditional system in terms of time and productivity. The use of precast slabs required collaborative work between the main contractor, the manufacturer, and the crews as it requires a Just in the Time production system and more complex logistics. It has to be acknowledged however that it was not possible to get off-site manufacturing data (i.e., labor required to fabricate the precast slabs) to compute total productivity. However, the scope of most studies is how the use of prefabricated components impacts the production system on site. The use of precast slabs had further positive impacts such as the reduction of concrete waste, and the installation of rebar and embedded electrical conduits in the factory. Furthermore, the surface of the precast slabs does not require further plastering or rework as is required in the traditional system. Thus, the number of downstream activities is reduced. Some additional benefits cannot be quantified but can be qualitatively reported such as increased cleanliness of working areas, less rework, and improved safety.

However, the improvement in productivity and production rate goes hand in hand with design and technical aspects. For example, the initial design of Project B was traditional and was changed during the construction of the basements. This required close coordination between the client, structural designer, site managers, digital teams, and the manufacturer. A 4D simulation was required to assess the new production process and understand the logistics required given the constraints of the site, as shown in Figure 6. This allowed for a detailed planning of the trucks' arrivals, the impact on the neighborhood and the traffic, and the lifting process.

Another aspect that requires further attention is the cultural change to implement off-site components and the buy-in from the client and construction workers. The contractor implemented precast slabs for the first time in Project B. Regarding opportunities for improvement in the implementation of LC in the use of pre-manufactured. In the beginning, there were problems with dispatches due to logistical failures with the factory, problems with transport units, unloading schedules, quality failures in the first pre-slabs, and reduced installation speed, among other factors that were improved with a learning curve and the implementation of the LPS to quickly learn from the mistakes, improve communication with stakeholders and short and medium-term planning to reduce the variability and acknowledge the complexity of the new process to make purposeful changes to make it work. For civil construction work and foremen. They quickly learned the system and with a learning curve, they managed to improve productivity and communication as the levels progressed. They communicated in the weekly meetings that they liked the system and felt the improvement in the system and the savings in rework. In addition, in the beginning, the client was afraid of the joints of the pre-slabs, but when finishing the painting and architecture details, they were convinced of the productive capacity of the system and the good quality of the finishes.

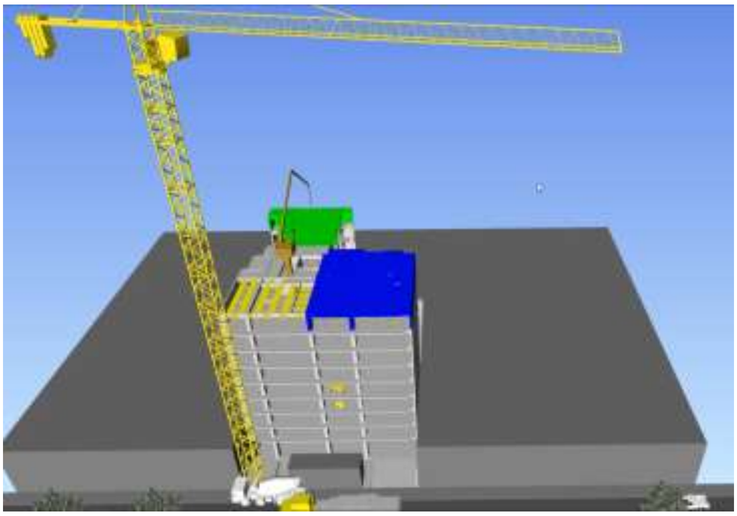


Figure 6**:** A snapshot of a 4D model for improved visualization and constructability analysis

CONCLUSIONS

The construction sector must continue promoting continuous improvement options to develop residential building projects to reduce the industrialization gap and increase productivity. In this paper, two projects with the same characteristics have been quantitatively analyzed and compared, where it is shown that the use of precast slabs allows an increase in productivity (m2/mh) of 16% compared to the traditional method and an increase of the production rate (m2/day) of 14%. These results would provide practitioners with useful information to decide on the implementation of precast components in construction projects along with the implementation of the LPS needed for appropriate production planning and control. However, the use of precast slabs requires greater look ahead planning of logistics which requires the support of all stakeholders involved in a collaborative environment. The leadership of site managers was pivotal for planning, implementation, and control. Future research could report performance metrics with further precast elements such as columns, shear walls, and beams. It is expected that production rates and onsite productivity would continue to improve. This research can also be extended to the examination of construction flow metrics to provide the evidence-based performance of production flows in industrialized construction (Sacks, 2020).

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QUANTIFYING PARTICIPATION: AN IPD CASE STUDY

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ABSTRACT

As the construction industry moves to greater project collaboration, greater participation and involvement by project team members is necessary for project success. Quantifying participation by project participants can present challenges though. The COVID-19 epidemic presented an opportunity to quantify participation due to the government mandated limitations of in-person meetings and the subsequent transition to videoconferencing. This paper presents a method via a case study utilizing videoconferencing to quantify project member participation. Findings indicate that utilizing videoconferencing is a possible method to measure project member participation but may not evaluate characteristics of the participation.

KEYWORDS

Case Study, Collaboration, Participation, Commitment, Relational

INTRODUCTION

The construction and design industry is moving towards a more collaborative approach that encourages the early participation of contractors and vendors (Franz, et al., 2017). To facilitate a heavily collaborate team environment, strategies such as co-located work spaces, shared financial incentives, and design/construction teams structures to enable collaboration have been utilized (Pishdad-Bozorgi, 2017). Fundamental to these strategies is the benefit of early involvement from multiple project team members (Assainar & El Asmar, 2014; Bascoul et al., 2018) and the ability of project members to work in near proximity to each other to increase the speed and quality of communication over more formal methods of communication.

Due to the COVID-19 pandemic, alternate strategies to facilitate collaborative team environments in non-collocated environments were needed. Government mandated social distancing requirements, travel restrictions, and other means to reduce the risk of transmission from the Corona virus meant that in-person meetings and co-location workspaces could no longer be used to promote engagement and collaboration amongst project participants. In lieu of in-person meetings, videoconferencing was rapidly adopted as a necessary alternative.

The use of videoconferencing for many project teams presented challenges and opportunities, as engagement by participants were affected with this alternate communication method. Specifically, videoconferencing can facilitate more task-oriented

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decision making, but peripheral discussions and non-task-oriented decision making may be reduced when compared to face-to-face meetings (Gallo, Carpenter, & Glisson, 2013). An unforeseen benefit with videoconferencing, however, was the possibility to monitor participation and possibly engagement of team members. To test and explore this new dataset, a project was selected as a case-study. This research aimed to gather and analyze case-study data to validate the application of content analysis as a proxy for participant engagement via video conferencing. To test this, the following research propositions were assumed:

Proposition 1: Project team members' participation can be quantified using videoconferencing data, and may be used as a proxy for participation.

Proposition 2: Videoconferencing data can be used to evaluate the impact of project roll on participation level from an individual.

Proposition 3: Videoconferencing data can be used to evaluate the impact of a company's fee at risk on their representative's participation level.

For the purpose of this research, only the quantity of recorded content was reviewed and not the quality of content.

LITERATURE REVIEW

This paper builds upon existing research and evaluates the potential to utilize videoconferencing data in construction research. Reviewed research included literature specific to in-person versus online meetings challenges, impact to a team's performance, and the impact to a team's decision-making ability. Concerning the impact of on-line meetings to a team compared to that of in-person, Archibald et al. (2019) evaluated the effectiveness of both the researchers and research participants using videoconferencing and found videoconferencing to be useful in conducting qualitative interviews. Similarly, Lilian (2014) reviewed previous research on the challenges that virtual teams face in communicating online and how this may present additional leadership difficulties due to limitations within that media. In slight contrast to Lilian's findings, Mühlfelder et al. (1999) research found no difference in the quantity of trust promoting behavior acts between face to face and virtual meetings. In another study, Anderson et al. (2007) simulated virtual team meetings and noted the challenge of having mixed team interfaces: individual videoconferences versus a meeting room sharing a terminal.

The impact to a project team from on-line meetings was reviewed by Mesmer-Magnus et al. (2011) on the effects of information sharing between virtual teams. Findings included different types of team information sharing as well as the extent to which the degree of "viturality" and type of information sharing set important boundary conditions for the information sharing-team performance. Fiol and O'Connor (2005) studied the differences between face-to-face, virtual, and hybrid (using both face-to-face meetings, as well as virtual) teams in developing a team identity, and among their findings they noted that virtual teams had the fewest "politeness rituals" that may impact a team's polarization of issues. Leadership dynamics of virtual and partially distributed teams were reviewed by Ocker et al (2011). Among their findings was that multiple cues are available for teams that share a physical space that aren't available to virtual teams. Additionally, leaders must use their "telepresence" which may impact the time it takes to express the same idea when compared to in-person meetings (Ocker et al., 2011). In other research, Gallo, Carpenter, and Glisson (2013) studied what, if any affects, teleconference versus face-to-face meetings had on scoring peer reviewed grant applications. There was "little difference" found in the scoring metrics between either review method, but a decrease in discussion times was noted with the teleconference option when compared to face-to-face meetings. This is a worthy note to consider in that discussion time (this measurement would be based in large part by the total amount of words used) was less with teleconference, but based on scoring, no less substantive.

Concerning the effect of participation with decision making, Barki and Hartwick (1994) developed a participation measurement method. It was noted in their research that participative decision making is more closely related to perceived decision making, whereas decision quality is more closely related to actual participation. Simoff and Maher (2006) used text analysis to measure different aspects of participation in online collaborative design university course. The research did not compare their results to collaboration in a face-to-face environment but did provide a method for participation analysis. These methods included content analysis principals of word use, word use per expression, and comparison between participant roles. Warkentin et al. (1997) reviewed the effectiveness of virtual teams versus face-to-face, and found no significant difference in the proportion of unique information exchanged between the two groups but did cite a lower level of cohesion and satisfaction with decision processes within the virtual teams.

RESEARCH METHODS AND DATA

This study was conducted utilizing a recorded videoconferencing session from a construction project team meeting over a two-week period to test the applicability of this method. This involved tracking and measuring participation by reviewing i) participant word count and ii) times spoken. Recordings were transcribed with an online tool and then was reviewed with a content analysis software. Measurements were taken from a meeting comprised of project team leaders for a healthcare building construction project.

CASE STUDY

This paper presents findings from a $23million pediatric behavior-health expansion project located in the Rocky Mountain west of the United States. The project was an integrated delivery project (IPD), utilizing an AIA-191 contract. The project was spread over multiple floors of an existing building, roughly 80,000sf. Each floor contained different behavior health care modalities, as well as support administrative spaces. Design began in the fall of 2019, with construction starting during the summer of 2020 and is scheduled to be fully completed during early summer of 2022.

For this analysis, a recurring IPD leadership progress meeting was selected over a multi-week period during early schematic design. The project team had met previously during project interviews, but due to timing had not had a project progress meeting in-person before the COVID-19 outbreak.

The project leadership team met regularly to review design and construction progress and was comprised of individuals that were signatory to a multiparty agreement (see Table 1). Purpose of meetings were to evaluate and address design/project process and progress with IPD contract participants. Participants knew that the sessions were being recorded but were unaware of the recordings use in analysis, apart from one of the hospital owner representatives (who is co-author of this paper). Two separate meetings were used for analysis, with both meetings lasting just over an hour in length. Meetings reviewed were limited to reduce variability between meeting participants to establish this as a viable means of research and tracking of participant participation.

Table 1: Project Team Membership

Participant	Position	Relationship
General Contractor 1a	Project Executive	Supervisor
General Contractor 1b	Project Manager	Employee
Architect 1	Design Principal	No Relationship
Owner 1a	Department Director	Supervisor
Owner 1b	Project Manager	Employee
Engineer 1	Design Lead	No Relationship
Sub-Contractor 1	Project Manager	No Relationship
Sub-Contractor 2	Project Manager	No Relationship
Sub-Contractor 3	Project Manager	No Relationship

RECORDED MEETINGS

Due to the COVID-19 related prohibition of in-person meetings, in-person meetings transitioned exclusively to videoconferencing. Meetings were conducted with a web-based, videoconferencing program (for this analysis, Zoom was used). The meetings were recorded, an optional setting within the program, to allow for review, analysis, and archiving of project decisions.

Each meeting member participated either from their computer or their smartphone device. Though the audio and video were both recorded, at times participants disengaged their video recording, which for the purposes of this research, did not affect analysis.

TRANSCRIPTION OF MEETING

After the meeting was completed, the audio and video recording were downloaded from the videoconferencing program. The videoconference program automatically compiled the meeting into both mp4-video and mp4-audio files. The recorded sessions were then uploaded to a separate program for the transcription (for this analysis, Otter was used).

MEETING ANALYSIS

To analyze the meeting, the transcription was reviewed via a three-part process; i) downloading the transcription to a word processing program, ii) content analysis review, and iii) tracking of meeting metrics.

Download to Word Processing Program

Upon completion of transcribing the meeting, the speaker's individual content was separated and copied into an individual word processing document. For this research MS Word was used.

Upload for Content Analysis

The documents were then uploaded into a content analysis software for review. For this research, NVIVO was used. The content analysis software provided details on word count, words per sentence, common word use, among many others. For this research, data pertaining to word counts and times spoken were used.

Data Analysis

Data obtained from the content analysis software were then downloaded to a spreadsheet program to analyze the output of each speaker. For this research, MS Excel was used.

Data was separated by the following: a) date of meeting (each meeting separated by tab), b) speaker (separated by name), c) role (general contractor, owner, architect, engineer, sub-contractor), d) corporate position (project manager, director, principal, lead, etc), e) relationship between company affiliation (boss, employee). Only content from the start of the meeting until meeting completion was analyzed, and content during the participant logging on period was not reviewed.

RESULTS OF ANALYSIS

MEETING 1

For meeting 1, all project leadership members were present and participated in the project meeting. Table 2 and Figure 1 show the breakdown of participation by each meeting participant. Based on this data and the roles noted from

Table 1, Figure 21 details the active participation by word count by project industrial role. Figure 2 summarizes total work count by project role. Figure compares the participation by employment relationship of supervisor and employee with the same company.

Table 2: Meeting 1 Participation Breakdown

Participant	Words Used	Times Spoken	Word Count/ Times Spoken
General Contractor 1a	992	23	43
General Contractor 1b	4,563	58	79
Architect 1	646	15	43
Owner 1a	2,610	27	97
Owner 1b	1,862	34	55
Engineer 1	1,572	32	49
Sub-Contractor 1	316	13	24
Sub-Contractor 2	293	5	59
Sub-Contractor 3	178	12	15

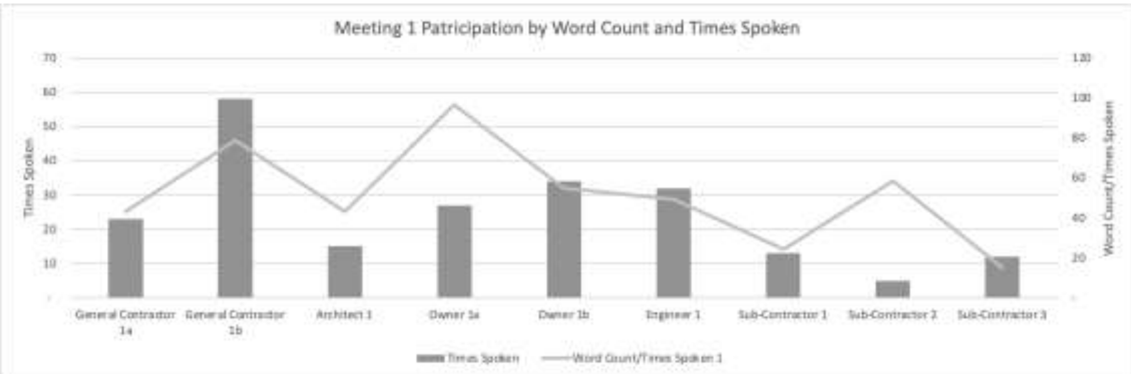

Figure 1: Meeting 1 Participation Breakdown

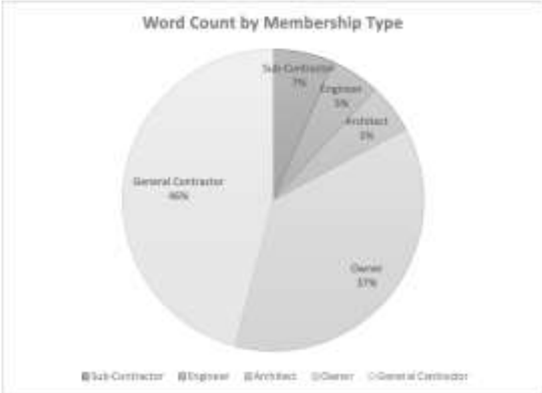

Figure 2: Word Count by Membership Type

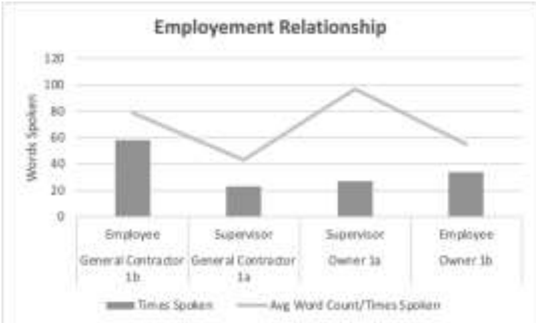

Figure 3: Participation by Employment Relationship

MEETING 2

For meeting 2, all project leadership members were present and participated in the project meeting. Table 3, based on the membership noted in

Table 1, shows the breakdown of participation by each meeting participant. Based on this data and the roles noted

Table 1, Figure details the active participation by word count versus total word count by project industrial role. Similar to Figure 2, Figure 5 summarizes total work count by project role. Figure 6 compares the participation by employment relationship of boss and employee.

Table 3: Meeting 2 Participation Breakdown

Participant	Words Used	Times Spoken	Word Count/ Times Spoken
General Contractor 1a	2,425	38	64
General Contractor 1b	1,886	33	57
Architect 1	1,679	40	42
Owner 1a	1,367	21	65
Owner 1b	1,066	34	31
Engineer 1	644	8	81

Sub-Contractor 1	149	12	12
Sub-Contractor 2	92	2	46
Sub-Contractor 3	46	2	23

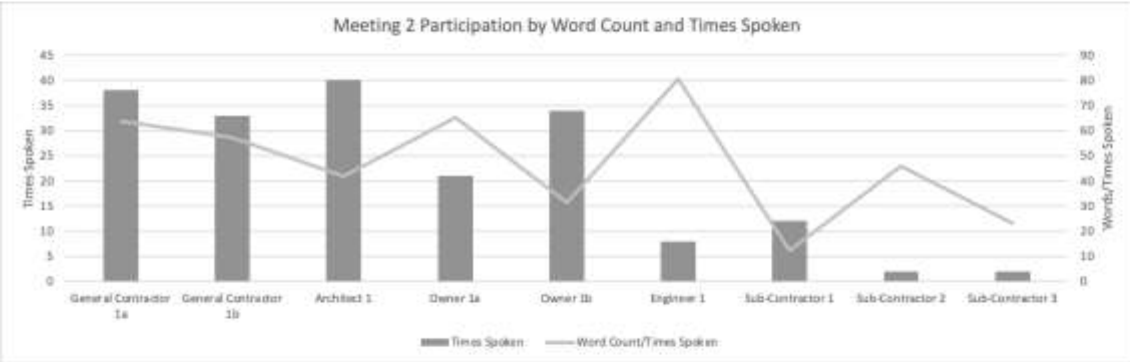

Figure 4: Meeting 2 Participation Breakdown

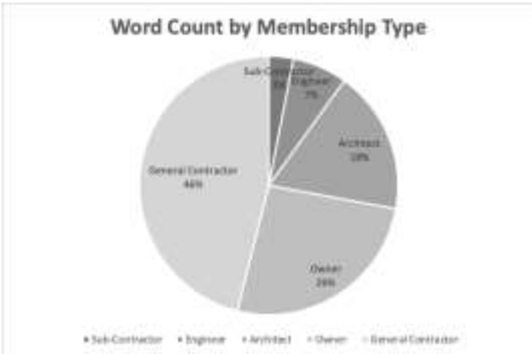

Figure 5: Word Count by Membership Type

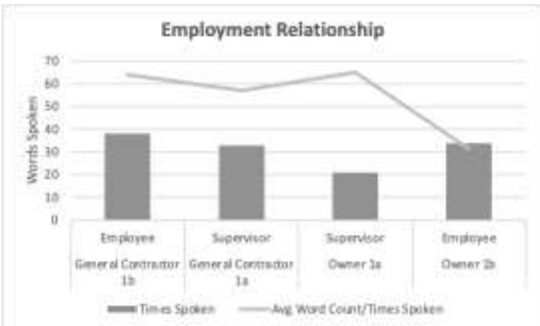

Figure 6: Participation by Employment Relationship

DISCUSSION & ANALYSIS

Results generated using the videoconferencing dataset suggest that such a dataset is valuable and provides an innovative method to analyze and compare the active participation of project team members. With construction moving to more collaboration amongst designers and contractors, a method to review the participation of team members to assist in evaluating the effort of team members could provide valuable insight for research related to collaboration in construction teams. As can be seen from Figure 1 and Figure 4, project participation varied amongst team members, but greater participation by the owner and general contractor can be seen. Based on this, this method appears to validate Proposition 1 and Proposition 2. For meeting 1(76.9%) and meeting 2 (72.1%), roughly three-quarters of the words spoken were from the general contractor and owner. The topic for both meetings centered on the impact of design to the overall budget, and input from each project member was encouraged.

As previously noted, words spoken and/or times spoken may not directly correlate to the content or quality of the words spoken itself, it does correlate to the participation of team members (Simoff & Maher, 2006). For project teams that work in collaborate environments and where profits of participants operate in an "at risk" scenario, it is important to evaluate the input of participants. Figure 77 notes the differences in the amount spoken by each team member, versus the percentage at risk by the same team member. It appears that in reviewing Figure 7, the amount of fee at risk (as a percentage of the total sum of fee at risk between the IPD contracted parties) had little to no impact to an individual's participation. The participating sub-contractors had comparatively larger fee at risk compared to the other meeting participants, but routinely participated far less than other project members. This would indicate that this method may be used to evaluate the impact of fee at risk on participation (Proposition 3), but the impact appears to be negligible.

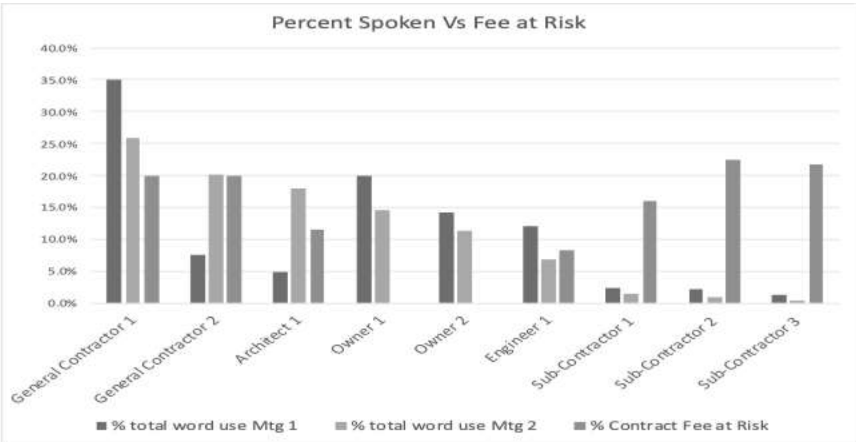

Figure 7: Comparison of Percent Spoken versus Fee at Risk

Another aspect that was reviewed with the data obtained was the impact of an employee's participation with their supervisor present in the meeting. Figure 3 and Figure 6 compare the number of times spoken and words spoken per time spoken for two examples of an employee/ supervisor relationship. Though the sample size was small, the variation between each employee/ supervisor couple was enough to presume that this hierarchical relationship did not anchor or impact participation of the employee.

It is interesting to review the results with the understanding that participation of individuals in meetings may not correlate to substitutive contribution, but a lack contribution most certainly would correlate to no substitutive contribution. The software was not used to evaluate the content of the contribution for each individual. It is assumed though that in a professional setting the general goal would be at least a substitutive contribution by each participate.

CONCLUSION AND IMPLICATIONS OF THE FINDINGS

A method to analyze the participation of project participants utilizing videoconferencing data resulting from changes due to the COVID-19 pandemic were presented. Word count and times spoken was used a proxy for individual participation. Quantity, and not the quality, of content was reviewed by the authors. Results suggest that the research based on analysis of videoconferencing data provides an innovative and valuable method to quantify participation of project team members. Due to the sample size, results may not be generalizable but was meant to highlight the possibility applications of the method used.

As construction project teams move away from in-person meetings, either due to geographic proximity or due to social distancing requirements, a tool to monitor team member participation was developed. This method adds to the body of knowledge by providing a method to capture and analyze participation. Whether this method is practical for every meeting is beyond the scope of this paper. This method of analysis is not meant to be a tool to forcibly encourage participation by individuals. Instead, it may provide the ability for participants to examine if their participation is limiting the involvement by others. Projects that successfully implement lean concepts and reduce waste, do so by the influence and involvement of project participants (Coffey, 2000). Integrating teams to reduce waste is based on the collective knowledge of project participants and their success may not be related to equal participation, but would certainly be hindered by limiting the participation of project members. This method to quantify participation may assist IPD projects in encouraging a more equitable discourse of project participants to leverage a more diverse experience set.

This research method allows for multiple opportunities to examine different aspects of project teams. First as technology changes, this method will certainly become easier and will generally improve. Real-time transcribing is becoming more common and offers an accelerated approach than that of what the authors were subject to. Overall, future research can look at how such data may impact a project team and associated behaviors. It can be assumed that behaviors would be impacted from the observer effect, which would thus alter natural behaviors. Other influencing factors such as age, gender identity, experience, project type, project phase, number of project participants, to name a few, may all produce interesting results that may be useful to academia and industry alike. Further, this method could also be used to review the quality of participation, and if this quality is impacted by project role, project length, and/or if this quality is impacted by project incentives.

DISCLAIMER

The views expressed in this article, book, or presentation are those of the author and do not necessarily reflect the official policy or position of the United States Air Force Academy, the Air Force, the Department of Defense, or the U.S. Government

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IMPACT OF FRAGMENTATION ON VALUE GENERATION-TOWARDS A BIM-ENABLED LEAN FRAMEWORK

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ABSTRACT

Fragmentation in the construction sector has been identified as a main concern by several scholars over the years as it creates silos not only between the actors and stages across an asset's lifecycle but also across a portfolio of projects. Among other things, fragmentation has a negative impact on the flow of information between participating organizations, thereby affecting value generation. Despite the rising digitization of this sector, these challenges remain and even compound issues such as the effective management of information throughout the built asset's lifecycle. Research and development pertaining to the management of information and generation of value has mainly focused on separate phases of assets or the delivery stage. However, a gap in knowledge and theory for information management and requirements management throughout the use phase of the asset's lifecycle still remains. This paper highlights the consequences of fragmentation from an information management perspective and its impact on value generation across an asset's lifecycle.

KEYWORDS

Lean construction, value stream, benefits realization, BIM, Fragmentation.

INTRODUCTION

The Architectural, Engineering, Construction and Operations (AECO) industry has a highly fragmented structure despite the vast amount of information created, managed, and used across an asset's lifecycle (Fellows & Liu, 2012). This structural fragmentation, or separation between asset phases, is recognized as a major source of challenge within the construction sector. It negatively influences project performance, productivity, knowledge production, and innovative solutions and increases the complexity of the interaction of actors (Forgues et al., 2009).

The fragmentation (separation) between project phases and asset lifecycle management is well documented in the literature by many scholars (Koskela, 2000, Hoeber and Alsem, 2016; Forgues et al., 2009). However, the fragmentation (separation) between the Construction and Operation and Maintenance (O&M) phases across the asset lifecycle is, as of yet, poorly defined (Figure 1).

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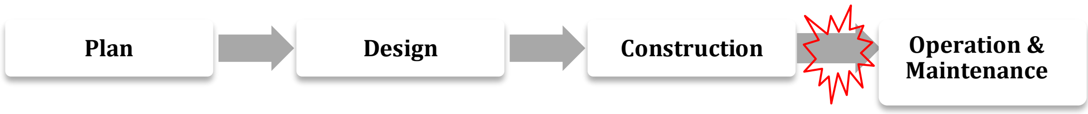

Figure 1: Fragmentation across asset lifecycle between project construction and O&M phase

The main cause of this fragmentation is the project management approach, in which the building asset lifecycle divide into independent phases, known often as planning, design, construction, and operation and maintenance (O&M). Also, fragmentation is observed in the relationships between multiple stakeholders, as they come from different disciplines and are involved in each phase but often have limited communication, interaction, and information exchanges among themselves. The management of information flow across an asset's lifecycle is known as asset lifecycle management (ALM) (Hoeber &Alsem, 2016). Information processing is a key part of ALM, but it is often error-prone and inefficient. For example, information may get lost over different phases as it is copied to other structures or stored without a consistent and predefined structure. Consequently, inadequate information management (IM) throughout an asset's lifecycle will lower the potential for value generation (Kagioglou et al., 2000).

Ensuring the value creation across an asset's lifecycle in the construction sector, while considering the involvement of many stakeholders with different backgrounds and objectives, requires having a common ground and mutual understanding of the "value concept" or "expected value" of construction projects (Zhang & El-Gohary, 2016; Drevland et al., 2018). This can be achieved only through effective collaboration and communication, which are efforts that depend on the willingness to compromise within the position or authority of different stakeholders (Khalife and Hamzeh, 2019). Of all the stakeholders involved across an asset's lifecycle, asset owner representatives, or asset managers, have the highest power of authority, which means they have a significantly influential role in value creation.

The critical role of asset managers stems from their financial involvement in the built asset's lifecycle, and their role shifts from the consumer of information during the design and construction phase to information management during operation and use. Thus, it is essential to leverage their benefits realization and ensure their investment can generate value that responds to their business needs. The asset owners are investors, but they also develop the requirements at the start of a project and expect other stakeholders (planners, designers, contractors) to deliver them. However, avoidable factors, such as lack of understanding of the asset owner's requirements and inaccurate information circulating among supply chain organizations, lead to value loss.

Several studies on productivity, efficiency and construction performance worldwide have led to technological advancements and the development of standards and guidelines that support their implementation (i.e., ISO19650). Many of these have been developed to enable seamless and continuous information exchange (IE) and information flow across the asset lifecycle to improve the AECO sector's performance (Tzortzopoulos et al., 2020). While inefficient information management (IM) hinders the total potential value that could be gained, the solution is to apply available technologies, and IM is recognized as a strong catalyst for digital transformation in organizations (Succar & Poirier, 2020). As pointed out by KPMG (2021, P.14), *"Effective IM allows organizations to do more (output) with less effort (labour and materials inputs) – freeing up resources to either do more of the same or re-deploy those resources towards more productive activities.*"

In response to this challenge, along with the demand for more complicated structures within the AECO sector's market (i.e., requirements for more efficient and effective information exchange with the use of technologies), new theories and approaches, such as Lean Construction (LC) and Building Information Modelling (BIM) have emerged within the AECO industry (Tzortzopoulos et al., 2020). The combination of Lean Construction and BIM application, a new view of information flow and value generation presents an opportunity to improve new and different information management within the construction domain. This paper aims to provide a deeper understanding of the impact of Fragmentation on the generation of value in the built asset industry and frame lifecycle information management as a potential avenue to reduce this impact.

A review of the papers published by the IGLC website indicated that fragmentation within the construction is not addressed in a broad range of topics. Thus, this research has several objectives. It aims to provide insight into the impact of fragmentation during the operational and use phases of an asset's lifecycle from the asset owner's perspective. It also aims to provide an overview of the importance of efficient information management across the lifecycle of assets, its relation to value generation, and the need for a framework for practitioners and scholars within the Lean Construction Community. Considering the authors are currently conducting further research on the same subject. The research questions are as follows: 1) How does fragmentation across the asset lifecycle hinder value creation from an information management (IM) perspective, and 2) what response is required to overcome these challenges, both from a pragmatic and hypothetical point of view? To answer these questions, the research presented in this paper consists of an in-depth literature review on the impact of various types of fragmentation on information management (IM) and their impact on value generation for asset organizations.

This paper draws attention to the consequences of fragmentation between the construction and operation phase on information flow and exchange across the asset lifecycle and justifies the need for a new framework to improve value generation. Thus, this paper highlights the value loss for construction professionals caused by inefficient information management due to existing fragmentation, both in theory and practice. It is worth noting that this research paper is a first step towards understanding the need for a new framework for the efficient management of information and explicit identification of value generation approaches and future research endeavours.

FRAGMENTATION ACROSS BUILT ASSET LIFECYCLES

Fragmentation within the construction sector is recognized as one of the significant challenges related to performance, delays, cost overruns, low satisfaction, etc., within the construction sector worldwide (Riazi et al., 2020). Godager et al. (2021) stated that the term "fragmentation" is the separation between project phases or working in silos, and the same definition is considered in this paper. The AECO sector is prone to three types of Fragmentation (Fergusson 1993) known as horizontal, vertical and longitudinal (Fergusson 1993; Poirier 2015). Figure 2 illustrates the three types of fragmentation in the construction industry: Horizontal fragmentation refers to the actors at a specific stage of a project, vertical fragmentation occurs between project stages, and longitudinal fragmentation occurs as project actors disband towards the project completion. As stated by Hall et al. (2014, P.3), *"Team members lose tacit knowledge about how to [….] This result in a learning disability and slows innovation diffusion."*

This paper will focus on a type of fragmentation part of vertical fragmentation situated between the construction and operation phases. Consequently, the information derived from the construction stage will not be useful for the operation stage and Facility Management (FM) team. The next section explains the role of technology to overcome or facilitate resolving the associated challenges.

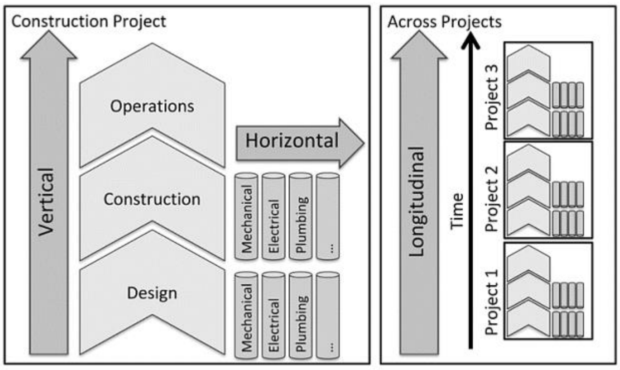

Figure 2: Three types of Fragmentation in the AEC industry (Figure 1 in Hall et al. 2014)

The impact of digitalization on fragmentation

Fragmentation hinders information flow and knowledge sharing among the project actors (Fellows & Liu, 2012), which results in information loss across the project stages (Teicholz, 2013). Among the 46 fragmentation issues within the construction sector identified in the study by Riazi et al. (2020), three are shown to be dominant (the first being the highest dominant and the third the lowest), as follows: 1) isolation of project professionals-geographically distributed at different locations, 2) the sequential nature of construction processes execution, and 3) confrontational culture between project parties.

To overcome challenges associated with fragmentation within the construction sector and improve information flow and management, Information Technology (IT) has come onto the construction industry scene by challenging the traditional ways of managing the re-evaluation of building asset lifecycle and creating integrated virtual temporary organizations (Betts 1999). Furthermore, many Information and Communication Technologies (ICT), such as BIM, Artificial Intelligence (AI), Augmented Reality (AR), Internet of Things (IoT), etc., have been adopted by the AECO sector to provide opportunities for efficient and effective information flow across all asset lifecycles. Whereas IM is often referred to as capture, re-use and sharing among stakeholders (Xu et al. 2014), Godager et al. (2021, p.42271) refer to IM as *"[...] [IM] is about ensuring that the right information is available when needed at the right destination at the right time to fulfil a specific purpose."*

One of the main challenges of fragmentation in the construction domain refers to further separation and disconnection between the on-site and off-site stakeholders. Despite technological advancements to facilitate information flow among stakeholders, regardless of their geographical location, and due to the willingness of stakeholders with various motivations in terms of conflict in economic incentives, unequal access to information and desire to spread the risk cause further separation challenges among stakeholders. As stated by Sacks et al. (2010b, p.56), *"The industry has failed to connect the "last mile" of information flow, between the office and the site, effectively."* Because construction projects are composed of many temporary stakeholders with different motives and have conflicts in economic incentives with various access levels to information, it is difficult to achieve smooth, continuous, and efficient information flow (Tzortzopoulos et al. 2020). Furthermore, Forgues et al. (2009) refer to socio-cognitive factors related to the behaviours of different stakeholders, which hinder collaborative working. It is difficult for stakeholders with various specialties and backgrounds to speak a common language in a project. Thus, the lack of common language among stakeholders is another challenge within the AECO sector because of its impact on communication and information flow (Jallow et al., 2014, p.506). Thus, as Forgues (2009, p.54) states, *"[...] technology proved to be sometimes more a nuisance than a benefit to collaborative work."*

Indeed, this next section will examine the challenge related to information interoperability issues caused by technological tools. For example, BIM is introduced into the construction domain to enhance information sharing, communication, and a set of interoperable technologies at the project level, but it does not address the issues of interoperability with and between asset management-related technologies (Poirier, 2015). Gallaher et al. (2002) state that inadequate interoperability and information exchange costs more than $9B during the O&M, compared to $2.6B during planning and design and $4B during construction. Asset owners and facility operators often store information received from the construction phase at handover and do not use it, and the FM tools are used without their being connected to the information received from previous stages (design and construction). But mostly, there are information interoperability issues between the various software platforms, or the FM team is unable to use information from previous stages properly (Godager et al. 2021).

Digital transformation strategies for the construction industry need to be integrated from the beginning (Godager et al., 2021). Their technological capabilities are not yet sufficiently advanced to overcome challenges associated with interoperability. This results in challenges and resistance to the efficient implementation of BIM during the O&M stage and the preference for manual and ad-hoc approaches among FM operators. As in the past, facility managers are not readily adopting new technologies for the O&M stage (Heaton et al., 2019): the BIM-enabled projects are not able to benefit from information stored during design and construction in the operation stage due to a lack of FM knowledge and their rare involvement from the beginning of the projects. Therefore, digital technologies and IT have entered the construction sector with the aim of improving the information flow among stakeholders to promote value creation. Hence, many organizations have invested in adopting and applying digitization across the asset lifecycle. However, information interoperability and the varying motives of stakeholders involved within the construction domain do not allow full potential value achievement of available technological improvements. This is mainly because digital advancements and transformation strategies require integration at their core (Godager et al., 2021). Thus, the next section provides further details about the consequences of fragmentation on value creation.

THE IMPACT OF FRAGMENTATION ON VALUE GENERATION

Value Concept - An Overview

First, it is essential that the meaning of the term "value" be clear, as various stakeholders are involved in the AECO industry, each with different backgrounds, objectives, and values (Khalife & Hamzeh, 2019; Drevland et al., 2018). There is a need to ensure that the value of all stakeholders involved is aligned with the asset owner organization's perspective on value. The term "value" also has several meanings in the literature, such as orals, standards, and rules, which reflect the behaviour of individuals and have an impact on the assessment of individuals within projects and services. Moreover, value is defined as benefits, or more specifically, it is defined as what you give and what you get, or cost minus benefits . Due to the importance of the concept of value within the AECO sector, there is an increasing demand to improve environmental, social, and economic value (Zhang & El-Gohary, 2016). According to the axiology-based value analysis study of Zhang & El-Gohary 2016), the National Research Council (NRC) addresses value understanding and assesses its influence on decision making as a "national imperative" (NRC, 2009). However, Drevland et al. (2018, p. 31) state, "*Value should be considered as something that fathoms more than the very narrow needs-based view that is common in much of the LC literature*." Thus, Drevland et al. (2018) define value as an evaluative judgement, where the judgment is based on the values and the evaluator's available knowledge. Similarly, Khalife and Hamzeh (2019) address the dynamic nature of value due to multi-disciplinary stakeholders within the construction sector. The dynamic nature of value is addressed in the conceptual framework developed by Khalife and Hamzeh (2019) (Figure 3). As construction projects are prone to change, any change in the scope, budget, organizations involved, and mode of operation would have an impact on other factors as all these factors are interrelated (Khalife & Hamzeh, 2019).

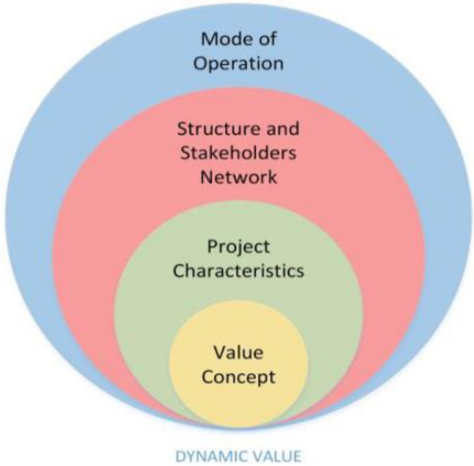

Figure 3: Integration of value-related aspects rendering value as dynamic (Figure 2 in Khalife & Hamzeh, 2019)

In this paper, the term "value generation" refers to the definition of both Lean Construction and BIM. On the one hand, according to Lean Construction pundits, value generation is the main goal of every project (Koskela 2000) as the client's business needs are linked to the client's business requirements within a project (Dave et al. l. 2013). To ensure value generation based on LC, Koskela (2000) identified five principles: 1) ensure all customer requirements are captured; 2) confirm all information required is progressively transformed to the next stage without disconnection in the information flow; 3) make sure all requirements of customers have guidance and direction to be followed; 4) ensure there is enough capability to deliver requirements; 5) certify the value is generated for the customer. On the other hand, from the perspective of business value and BIM, there are six categories: management, commercial, efficiency, industry user and technology, as defined by Munir et al. (2019). Table 1 shows in which dimensions BIM may have a positive impact and enable values to benefit at the organizational, end-user, and economic levels along with productivity, ecosystem, and functionality improvement.

Table 1. BIM Business value in Asset Management (Adapted from Munir et al. 2019)

No.	Value Category	Value benefits description according to value category
1	Management	Organizational– Enable value at strategic, tactical, and operational levels for organizations.
2	Commercial	Economic – Improve financial performance and profitability.
3	Efficiency	Productivity – enhance operations in AM.
4	Industry	Ecosystem – enable delivery of exclusive or collective functionalities and services.
5	User	End-User – Improve daily tasks for individuals.
6	Technology	Functionality – enable 3D visualization, real-time coordination, interactive real-time reporting, etc.

Impact of Fragmentation on value generation

Fragmentation, that is, the separation between project the construction and operation and use phases of construction assets, causes value loss as oftentimes, operators are not knowledgeable enough to use information derived from the construction phase for operations, so a lot of information is unusable by the operator's team. For asset owners, this has an impact on the achievement of total potential value and leads to value loss. On the one hand, asset owners are aware of technological innovations and are willing to invest in technologies to generate the "best possible value." On the other hand, due to interoperability and information exchange challenges along with a lack of operator knowledge on how to use information from the design and construction phases, the rate of return on investment (ROI) drops, causing value loss. However, set in their ways, facility managers are resisting the adoption of new technologies for the O&M stage (Heaton et al., 2019) and prefer manual and ad-hoc approaches. Hence, Information Flow and Information Quality, despite the existing trend in Information and Communication Technology (ICT) (Tzortzopoulos et al., 2020), are impacted, and this results in value loss.

Another challenge triggered by Fragmentation pertains to the asset owners' poor requirements management (RM), which causes value loss. The limited ability to identify and understand the asset owners' requirements, which refer to expectations, needs, wishes and objectives, and their coordination with other actors cause value loss. The challenges associated with the asset owners' requirements are stated by Jallow et al. (2014, p.506) as:

- Absence of a defined approach to managing and sharing asset owners' requirements
- Lack of storage and repository of asset owner's information requirements
- Insufficient coordination, sharing and control of required information
- Absence of a structured and standardized approach to change management
- Lack of interoperability and integration of change management systems with requirements management

The PAS1192-3 and ISO19650 address the information requirements (Munir et al., 2020) and present the relationship between precontract documents, which are Organizational Information Requirements (OIR), Asset Information Requirements (AIR), Employer Information Requirement (EIR), and post-contract documents of Project Information Model (PIM) and Asset Information Model (AIM). When the OIR is being developed, accordingly, the AIR is created, and as a result, the EIR is generated. Upon the contract award, the PIM contributes to AIM, and generally, the AIR document generation is from the bottom-up, meaning it is a technical document generated for the FM operators' use only. Most often, the financial, environmental, and reputational aspects of OIR are missed.

The lack of alignment of OIR with asset AIR to be used during the O&M stage causes value loss due to the absence of asset information AIR generation (Heaton et al., 2019). During the early stages of the project or many asset owners are not aware of what information is required for their operational stage for effective Asset Management (AM) purposes (Munir et al. 2019). The main reason for this is that asset owners usually get overloaded with information that is difficult or impossible to filter to ascertain the essential information needed to perform FM/AM tasks (Munir et al., 2019). Even with the availability of standards, such as BS1192, PAS1192-3:2014, and ISO19650 series, which recommend the development of OIR, the challenge still remains. Mostly, this is because there is a very limited application for AIR development in the industry. Also, most organizations set aside the development of the OIR, or if they do develop one, it contains technical information that is not usable and/or is challenging for the FM operators to use (Heaton et al., 2019). As stated by Heaton et al. (2019, p.14), *"Asset-related information that is not collected in alignment to the organizational requirements will restrict the performance of capital investment decisions, risk management and operational performance throughout the whole life of the asset portfolio [...])."* Thus, access to information– that is, having accessibility to the required information at the required time – causes the project many inefficiencies in terms of extra cost (Eastman et al., 2011).

PROPOSED SOLUTION DOMAIN - TOWARDS A BIM-ENABLED LEAN FRAMEWORK

The construction industry's performance and success factors are not limited to cost, time, quality, safety, and customer satisfaction. The success of the construction sector relies on meeting expectations of plan, design, construction, scope, budget, and asset owner satisfaction, which falls within the notion of value. The construction sector's asset management is changing through the application of BIM and Lean construction (LC). In a sense, enabled by technological advancements, BIM is a collaborative process that aims to optimize project delivery across a project's lifecycle. Similarly, Lean construction is a management philosophy aimed at creating value and eliminating non-value-added activities. Although both BIM and Lean construction originated from different domains, both approaches have made a positive and noteworthy impact on the AECO industry (Dave et al., 2013; Tzortzopoulos et al., 2020)

Several scholars have pointed out the beneficial application of both BIM and LC (Dave et al., 2013). As Tzortzopoulos et al. (2020, p.32) state, "*The links between BIM and Lean have attracted much interest since 2011."* Eastman et al. (2011, p.386) stated, "*The Lean construction and BIM are likely to progress hand-in-hand, because they are complementary in several important ways.*" Moreover, Eastman et al. (2011, p.298) stated, *"[...] there is a strong synergy between LC and BIM, even the use of BIM facilitates fulfilment of lean principles."* The use of an integrated LC and BIM workflow improves information flow across the asset lifecycle and benefits all organizations involved in the process. In other words, the workflow will be improved through the synergy of both BIM and LC. When acknowledging the impact of Fragmentation on the flow of information along with understanding the vital role of asset owners within the AECO sector, it is essential to address the management of requirements, information flow, accessibility, quality and alignment of the owner's requirements with the project deliverables across the asset lifecycle. Amongst all the stakeholders involved in the AECO sector, building asset owners play a vital role in the value generation of assets as they are at the forefront of procurement and operations of assets. To ensure the owner's project requirements (OPR) are addressed across the asset's lifecycle and ensure access to the correct information at the required time, a continuous exchange of information between the owner and all other actors is to be maintained in an electronic document, located on a cloud repository. Thus, the basis of a conceptual building performance evaluation (BPE) model as an innovative approach for the asset lifecycle is illustrated in Figure 4 by Preiser & Vischer (2005), which will be adopted as a foundation for project stages and feedback loops.

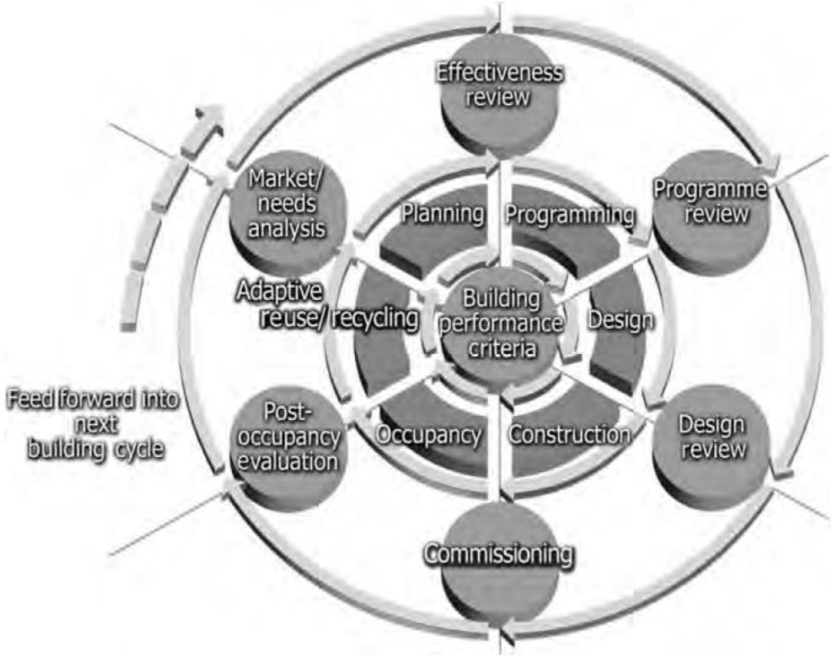

Figure 4: Building performance evaluation (BPE) process model. (Figure 2.1 Adapted from Preiser & Vischer, 2005)

Hence to overcome the challenges influenced by Fragmentation between the construction and operation phases of the asset's lifecycle and redefine the construction industry's business model regarding the management of information to maximize the generation of value, there is a need for a new framework. Thus, Table 2 presents a summary of the fragmentation challenges to be addressed and their relationship with their associated influence on information management and value generation, based on the two concepts of BIM and LC. As a canvas to develop a framework to help ensure efficient information management across all asset lifecycle, a feedback and evaluation loop at every step is needed, which requires an asset owner's (or asset owner representative's) evaluation and assessment.

This will also ensure that asset information requirements will be based on the FM team's requirements for operation and maintenance. Finally, to overcome the challenge of an information repository, a cloud-based CDE template will be devised to ensure efficient information exchange across organizations and preserve the rights of the asset owner in terms of security, data ownership and intellectual property (IP). There will be feedback and evaluation loops between each project phase to ensure all of the owner's requirements are communicated across all organizations involved.

Table 2. Summary of fragmentation issues and their influence on IM and Value

Criteria	IM Dimension			Value-based on LC and BIM						
				LC	BIM					
Points of consideration to overcome fragmentation challenges	Flow	Accessibility	Quality	Client Satisfaction	Management	Commercial	Efficiency	Industry	User	Technology
Ensure availability of information repository	×	×		×					×	×
Ensure development and update of Brief document at an early stage		×		×						
Facilitate RM through feedback and assessment loop at every milestone/phase	×		×	×	×		×		×	
Ensure development of OIR document at an early stage				×						
Ensure AIR development at an early stage aligned with the FM/AM team of operations	×	×	×	×	×		×	×	×	×
Consider 7 stages of asset lifecycle based on the PAS1192 document	×			×						
Address cloud-based common data environment	×	×	×	×	×				×	×
Ensure the FM/AM team's knowledge of using BIM models for operations purposes				×						
Ensure information security, IP, ownership		×	×	×	×	×			×	
Ensure collaboration among teams virtually	×	×	×	×	×		×	×	×	×
Ensure information interoperability between the platforms, if possible			×	×	×	×	×		×	×

CONCLUSION

This research focus on the fragmentation between the construction and operation phases of asset lifecycle and their effect on value generation from an information management perspective. A conceptual solution is subsequently proposed through application of both BIM and LC notions as a response to overcome the challenges caused by inefficient information management, mainly for asset owners. According to the literature, the integration of BIM and LC could enable the effective and efficient management of information across the asset's lifecycle and improve value generation. Value is referred to in seven categories, namely: asset owners' satisfaction, management, commercial, efficiency, industry, user, and technology. Future research and modes of evaluation and testing of the need for a framework in this paper are currently in progress by the authors at the conceptual level. Thus, the literature review presented in this paper will be used as a theoretical foundation to construct the basis of the consequences of Fragmentation on value generation. This will be further detailed using actual case studies from Canada. It is worth acknowledging the limitations of the present work, as this paper is at the theoretical level, and further research should be conducted for its practical application.

ACKNOWLEDGMENTS

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VDC IN PRACTICE: A PRELIMINARY CATEGORIZATION OF PRODUCTION METRICS REPORTED IN SCANDINAVIA AND LATIN AMERICA

Tulika Majumdar[1], Steinar G. Rasmussen[2], Alexandre Almeida Del Savio[3], Katrin Johannesdottír[4], Eilif Hjelseth[5], and Martin A. Fischer[6]

ABSTRACT

Architecture, Engineering and Construction (AEC) teams are increasingly using emerging management methods involving collaboration, lean construction, and digitization for managing projects. Production metrics (PM) are being used to assess the impact of these methods on project performance during run-time. A lack of common vocabulary hinders comparison of PM, making it difficult to repeat strategies used for improving project performance and for benchmarking PM across projects.

Through a detailed content analysis, 2 datasets of 904 PM reported by 195 Virtual Design and Construction (VDC) practitioners in Scandinavia and Latin America were curated. Qualitative coding was used to categorize the PM into the three key VDC elements, i.e., Integrated Concurrent Engineering (ICE), Building Information Modeling (BIM) and Project Production Management (PPM) and to validate the categorization.

This research enabled a comparison of PM categories across the two regions for the first time. PM categorized as ICE and PPM were reported by more than 68% professionals in both the regions. BIM PM had a disparity in reporting (Scandinavia: 30%, Latin America: 91%). It also opened a pathway to develop a common vocabulary of PM to compare, benchmark and standardize PM across VDC implementations.

KEYWORDS

Production metrics, continuous improvement, concurrent, standardization, process

BACKGROUND

Since 2019, the Stanford Center for Professional Development (SCPD) has been conducting a VDC certificate program (VDCCP) in collaboration with the Center for Integrated Facility Engineering (CIFE), Norwegian University of Science and

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Technology (NTNU) and Universidad De Lima (ULima). AEC professionals enrolled in the VDCCP learn the fundamentals of VDC in a 1-week introductory workshop and implement VDC on their ongoing projects for 9 months. They define PM for their projects at the beginning of the implementation and explain through monthly reports if and how the PM enabled effective course correction.

INTRODUCTION

Previous researchers have established the connection between Lean and VDC (Fosse & Ballard, 2016; Rischmoller et al., 2018). In recent years, there has been an increase in the number of AEC professionals implementing VDC on their projects (Majumdar et al., 2022). PM are an integral part of the VDC methodology. They impact project performance by providing rapid feedback on actions and decisions taken by project teams for timely course correction. Unlike several other industries, such as manufacturing, a common vocabulary of useful PM does not exist for the AEC industry. As a result, AEC project teams establish and track PM on an ad-hoc basis, which hinders comparison and benchmarking. This phenomenon was observed by CIFE researchers in the PM data provided by 279 AEC professionals from Scandinavia and Latin America who enrolled in the VDCCP in 2020.

This was the first time that PM data from a large number of projects in two different parts of the world during the same time period was available for research. This opened up the possibility of building a vocabulary of PM to facilitate learning and benchmarking and to answer the research question - *How can PM data be used for comparison and learning across projects?*

In answering the above question, this study categorized 1963 PM using the 3 key VDC elements of ICE, BIM, and PPM. While an analysis of individual PM in each of the 3 categories is beyond the scope of this study, it makes the following two contributions:

- A categorization based on key VDC elements as a first step towards building a common vocabulary of PM.
- Operationalization of VDC theory by comparing PM categories reported in practice.

Project Managers and AEC organizations can use this categorization to compare the level of collaboration, use of digital tools and lean work processes across projects. They can establish and standardize individual PM under each category. Researchers can use this categorization to build sub-categories of PM to facilitate standardization of PM in the industry.

POINT OF DEPARTURE

PM, an integral part of the VDC methodology, create a culture of continuous improvement, which is a key Lean principle (Haugstvedt, 2019).

Existing literature on PM used by VDC practitioners is either based on anecdotal information (Kunz & Fischer, 2012) or limited case studies (Belsvik et al., 2019; Fosse & Ballard, 2016; Gao, 2011). There has been no study which reports on PM used in practice on a variety of projects. This empirical research looked for evidence of PM used by VDC practitioners on ongoing projects in two different parts of the world in 2020 and categorized them for accessibility by AEC professionals and researchers.

Categorization of metrics has been adopted in other industries, such as manufacturing, for comparison, benchmarking and standardization (Gunasekaran et al., 2001). In the AEC industry, categorization has been used for comparison of facilities performance (Lavy et al., 2014). This is the first study which uses PM data reported from real AEC projects and uses the following key VDC elements to categorize them:

ICE (Integrated Concurrent Engineering): To achieve an integrated, high performing facility, project teams should learn how to share knowledge, evaluate multiple possible solutions through collaboration and consistent feedback. It therefore becomes important for the project team to co-locate, at least partially (Fischer et al., 2014) so that project team members from various disciplines can have several quality interactions to solve problems quickly and effectively.

BIM (Building Information Modeling): This refers to visualization and simulation, which are the key mechanisms to achieve integrated information.

PPM (Project Production Management): This refers to the organization of physical work tasks by treating the project as a production system. It includes managing parameters such as cycle time, work in process, capacity utilization etc. PPM has its origins in Operations Science, which is also the seat of evolution of Lean (Rischmoller et al., 2018).

RESEARCH METHOD

Conceptual content analysis was considered suitable for this study. This research method establishes whether a concept exists in a given text. The occurrence or non-occurrence of selected keywords within the target text are used to either discern the central idea of the text or extrapolate conclusions (Carley, 1990). This was used to extract PM data from each final report in .ppt or .pdf format provided by AEC professionals as part of the VDCCP and then to categorize them. Without a standard list of PM available, the survey method would be inadequate to capture the data provided in all the reports and was, therefore, ruled out. Case studies or sampling would not cover the breadth of PM data which was available for the first time, and were also ruled out.

RESEARCH TASKS

The key tasks in the research involved a) data preparation and clean-up to curate two datasets of PM, b) qualitative coding to categorize PM reported in dataset 1(Scandinavia) into the three key VDC elements, i.e., ICE, BIM and PPM, and c) qualitative coding of PM reported in dataset 2(Latin America) to validate the three PM categories.

DATA PREPARATION AND CLEAN-UP

Final monthly reports (in .ppt or .pdf formats) submitted by 175 professionals from the first large-scale VDCCP in Scandinavia and by 104 professionals from the first large-scale VDCCP in Latin America were compiled. The data was immediately anonymized for carrying out the research. The languages used in the reports were Norwegian, English and Spanish. 1963 PM found in these reports in the form of tables and charts were manually entered in Google sheets in the original language and were translated into English using Google Translate. As PM are daily or weekly in nature and are measured as short-term outcomes of actions and decisions taken by the project team, data clean-up was done to eliminate metrics which are a) measured once at project completion instead of daily or weekly, such as “deviation from final cost of project”, b) measured at specific milestones, such as "time taken to complete zoning plan", c) input metrics (Khanzode, 2011) which are actions and decisions controlled by the project team and do not measure an outcome, such as "number of ICE sessions conducted, and vague data reported as metrics, such as "problem solving".

After clean-up, dataset 1 consisted of 417 PM reported by 115 professionals and dataset 2 consisted of 487 PM reported by 80 professionals. Tables1 and 2 provide details on the roles of professionals in both the datasets after clean-up and the project types they reported PM data from.

Table 1: Role of professionals in cleaned-up datasets of PM

Company Type	Dataset 1 Scandinavia (n=115)	Dataset 2 Latin America (n=80)
Owner	8%	24%
Consultant/Owner's Rep.	11%	2%
Design/Engineering Consultant	41%	11%
General Contractor	33%	41%
Subcontractor	2%	15%
Software Provider	5%	4%
Not Available	0%	4%

The professionals used VDC on both building and infrastructure projects. Table 2 lists the breakdown by these 2 project types after data clean-up in the two datasets.

Table 2: Project types in cleaned-up datasets of PM

Project Type	Dataset 1 Scandinavia (n=115)	Dataset 2 Latin America (n=80)
Building	44.3%	83.8%
Infrastructure	52.2%	10.0%
Information not available	3.4%	6.3%

CATEGORIZATION OF PM IN DATASET 1

Through content analysis, the first author interpreted the 417 cleaned-up PM from dataset 1 using supporting documentation from the monthly reports before categorizing it. The interpretation was reviewed by industry experts from Scandinavia who had participated as mentors to the professionals during the VDCCP and were therefore familiar with the context of the projects in the reports. The second and fourth authors then did another review of the PM interpretation and categorization and updated the categories where required. For PM which were categorized differently by different authors, a mutual decision was taken to select one category over another. A few PM were found which satisfied the criteria of more than one category. As an example, "number of clashes identified in the 3D BIM during the ICE session" can be categorized as both BIM and ICE. For such PM too, a mutual decision was taken by the authors to select one category over another.

VALIDATION OF PM CATEGORIZATION IN DATASET 2

The process to interpret and categorize PM was repeated for dataset 2. After the first author interpreted the 487 cleaned-up PM, a second round of interpretation was carried out by the third author, a researcher from the University of Lima who was also the program coordinator for the VDCCP. Once a PM was interpreted adequately, a mutual decision was taken to categorize it. No PM was found in dataset 2 which could not be categorized into the 3 key VDC elements of ICE, BIM, and PPM, validating the proposed categorization.

FINDINGS AND DISCUSSION

The categorization of PM enabled a comparison of PM across the two datasets. Manual data analysis of the categorized PM highlighted a) the most reported PM category and b) the number of PM categories reported by AEC professionals across the two datasets

COMPARISON OF PM CATEGORY

As shown in Figure 2a, PM which were categorized as ICE were reported by more than 80% professionals in both the datasets (Scandinavia: 84%, Latin America: 91%). PM categorized as PPM were reported by more than 65% in both the datasets (Scandinavia: 68%, Latin America: 79%). There was a disparity in the number of professionals who reported PM which were categorized as BIM (Scandinavia: 30%, Latin America: 91%).

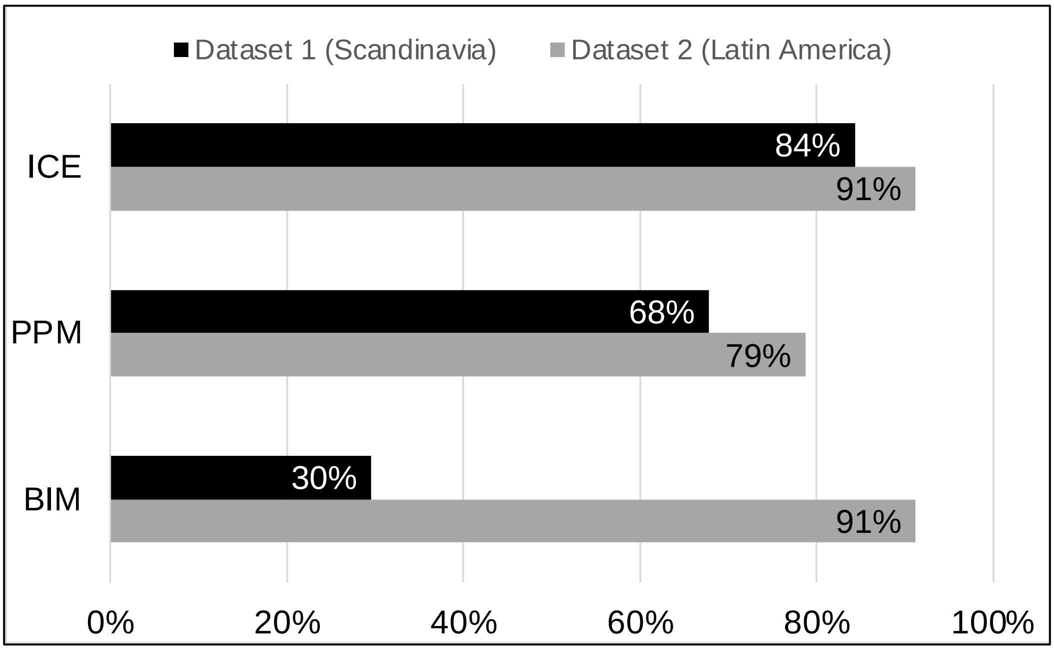

Figure 2a: Percentage of professionals who reported ICE, BIM, and PPM production metrics in Scandinavia (Dataset 1, n =115) and Latin America (Dataset 2, n = 80)

- ICE: ICE emerged as the PM category reported by most professionals in both the datasets, indicating that collocation and collaboration are picking up as a way of working across the geographies. This finding can be used by project managers and AEC organizations to invest in resources which foster collaboration, such as the big room (A. Khanzode et al., 2011.). Organizations can define standard lists of individual ICE PM which can assist project teams to assess team collaboration. Software providers can focus on product functionality which enables assessment of collaboration and recommends strategies to improve it.

- PPM: A large number of professionals across both the datasets reported PM in this category. PM which were categorized as PPM bear a resemblance to metrics tracked on traditional projects, such as "number of change orders" and "number of requests for information", indicating that they may be better understood by professionals as compared to BIM PM. "Percent Plan Complete" was the PM which was most reported in this category across both the datasets.
- BIM: It was surprising to see BIM PM being reported by only 30% of the professionals in dataset 1 as compared to 91% professionals in dataset 2. The PM which most professionals reported under BIM was the "number of clashes detected or resolved". Hard clashes, which may be better understood in the industry, are more common in building projects (Matejka & Sabart, 2018). 44% of the professionals in dataset 1 were working on building projects as compared to 84% in dataset 2. When standardizing and benchmarking PM, organizations should consider the project type.

NUMBER OF PM CATEGORIES REPORTED

Figure 2b shows the count of professionals who reported PM representing all three VDC elements (Scandinavia: 17%, Latin America: 68%) as compared to those who reported PM representing a single VDC element (Scandinavia: 36%, Latin America: 6%)

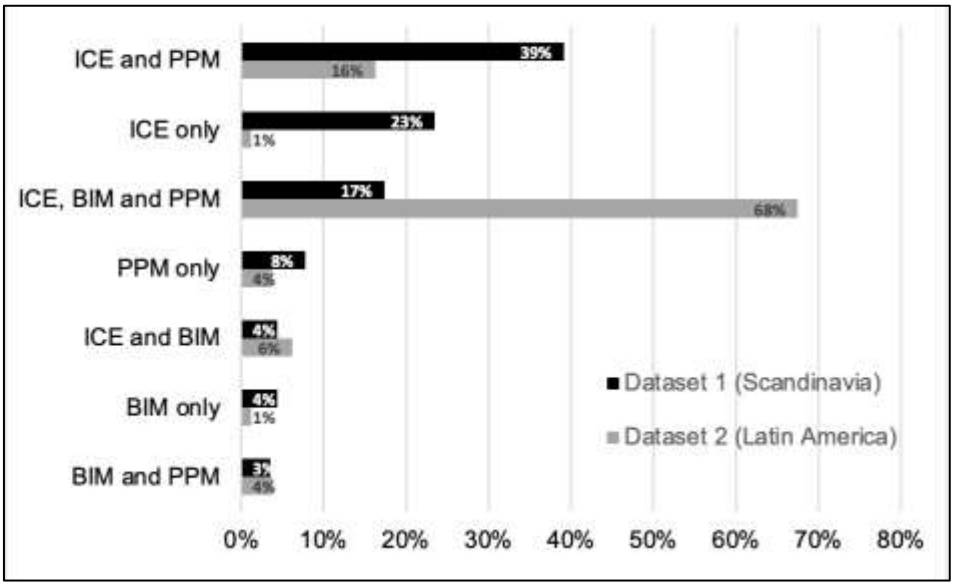

Figure 2a: Percentage of professionals who reported production metrics representing 1, 2 and 3 VDC elements, i.e., ICE, BIM, and PPM in Scandinavia (Dataset 1, n =115) and Latin America (Dataset 2, n = 80)

There was a disparity in the number of professionals who reported all the three categories of PM across the two datasets. Most professionals in dataset 2 reported PM in all the three categories while most professionals in dataset 1 reported PM in two categories. A handful of professionals reported PM in a single category. Almost 40% of the professionals in dataset 1 and 16% professionals in dataset 2 reported PM which could be categorized as ICE and PPM but none which could be categorized as BIM.

LIMITATIONS

The categorization recommended in this paper is based on self-reported PM data from the VDCCP. Monthly reports provided evidence of the use of PM in the form of pictures, tables, charts, and summaries. Triangulation, in the form of reviewing actual artefacts from the projects (such as projects schedules, RFI and change order logs), was beyond the scope of this work. While it is possible that certain PM used were not reported due to confidentiality, such PM would likely fall under one of the three categories recommended in this paper.

While this study provided insight into 3 broad categories of PM reflecting project organization, tools for visualization and simulation and processes for work tasks, it did not provide a comprehensive list of individual PM reported under each category. Comparing projects based on PM category alone is not sufficient. Individual PM for each category need to be compared for establishing benchmarks across projects.

This study did not consider differences in PM reported based on project type and phase For example, BIM PM related to hard clashes may not have been relevant for infrastructure projects. Similarly, PM related to field material delivery and site generated change orders were not relevant for projects in the design phase. Project managers should consider these factors while comparing projects based on the PM categories reported.

It is possible that a certain PM category was reported more than another because of familiarity or ease of tracking. As an example, "number of change orders", which have traditionally been managed on construction projects and are categorized as PPM, are possibly better understood by professionals. In comparison, PM related to BIM and ICE may not be understood very well. Companies should therefore put in effort towards training employees to familiarize them with BIM and ICE PM. Developers of BIM tools should expand functionality of solutions so that it is easy for professionals to track BIM PM such as "BIM rework hours".

A few PM, such as "number of tasks in the weekly lookahead plan", if identified in an ICE session, could have been categorized in more than one category. This study did not consider PM categories by combinations of VDC elements. However, the number of such PM found in this study was not significant to alter the results of the comparison.

FUTURE RESEARCH

This study provides a categorization of PM into the three key elements of VDC. Future research should:

- Include more PM data from projects in other geographies to further validate sufficiency of the three categories. In addition, PM reported by AEC professionals who did not go through the VDCCP should be included to test the applicability of the categorization.

- Define individual PM under each of the three categories. Project managers and companies will then be able to identify the top individual PMs tracked under each category to establish benchmarks.
- Compare PM categories based on project characteristics such as type (building vs infrastructure), size (small, medium, large), ownership (public, private) etc.
- Explore whether individual PM under one category are difficult to understand and report as compared to another.
- Test the exclusivity of the three categories from this study.

CONCLUSIONS

Industries such as manufacturing have standard lists of PM for comparison, learning and benchmarking across projects. This has not been possible in the AEC industry as there is no common vocabulary to report and share PM data. This results in project teams reinventing the wheel each time and bearing the risk of tracking sub-optimal PM which could negatively impact project performance. By creating two datasets of PM reported by 195 AEC professionals in Scandinavia and Latin America, this research contributed a feasible categorization of PM based on three key VDC elements, i.e., ICE, BIM, and PPM. A comparison of the PM categories showed that ICE PM were reported by most professionals in both the datasets, (Scandinavia: 84%, Latin America 91%), followed by PPM (Scandinavia: 68%, Latin America 79%) and BIM (Scandinavia: 30%, Latin America 91%). In addition, it operationalized VDC theory by comparing the PM categories reported. There was a disparity in the number of professionals who reported all the three PM categories (Latin America: 68%, Scandinavia:17%), indicating that there is a gap in theory versus practice of VDC, which recommends the use of ICE, BIM, and PPM together.

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DEVELOPING A FLOW-BASED PLANNING AND CONTROL APPROACH FOR LINEAR INFRASTRUCTURE PROJECTS

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ABSTRACT

The Last Planner System (LPS) and Location Based Planning and Control (LBPC) have been successfully used in many projects, either separately or together. Despite previous studies that have discussed the role of each of them, the complementarity between LPS and LBPC still needs to be further explained by using core Lean Production concepts. Moreover, most implementations reported in the literature of those two planning models have been concerned with building projects. Only a few cases are related to infrastructure projects, which have different types of complexity in relation to conventional building projects. This paper reports the initial results of the development of a planning and control model for linear infrastructure projects. This investigation was based on a case study carried out in a construction company from Uruguay. The development of the model considers some specific complexity features of linear infrastructure projects, such as high uncertainty, and independent linear processes spread around large urban or rural areas. The main insights provided by this study are concerned with devising a flow-based planning and control tool for look-ahead planning, the definition of criteria for devising location-based systems, the emphasis of work-in-progress control, and the use of visual management.

KEYWORDS

Flow, production planning and control, linear projects, Last Planner, Location-based management, visual management.

INTRODUCTION

Major advancements in construction planning and control has been achieved by adapting and implementing core concepts and principles of the Lean Production Philosophy Ballard & Tommelein, 2020; Brady et al., 2018; Seppanen et al., 2015). In fact, changes

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in production planning and control have played a key role in the genesis of the Lean Construction movement, due the strong impact of the Last Planner System® (LPS), developed by Ballard and Howell (1998). This system is able to increase the reliability of short term planning by shielding planned work from upstream variation, and by seeking conscious and reliable commitment of labor resources by team leaders (Ballard, 2000). At the medium term level, constraints are systematically identified and removed, with the aim of making available the necessary resources, such as materials, information and equipment (Ballard 2000). Besides LPS, another important development of construction planning and control based on the Lean Production philosophy is the adoption of location-based planning and control (LBPC) systems, which can be regarded as a set of planning and control techniques that makes an explicit connection of construction activities to work locations, such as line of balance (Olivieri et al., 2019), location-based management (Seppanen et al., 2010), and takt-time planning (Frandson et al., 2013). Location-based planning seeks to reach simultaneously continuous product flow and uninterrupted use of labour (Olivieri et al, 2019). By using visual tools, production goals can be easily communicated, and issues related to the amount of work-in-progress (WIP), batch size, and lack of synchronization between crews are made explicit (Nut et al., 2020). LPS and LBPC have been successfully used in many projects from different countries, either separately or together, and sometimes combined with Critical Path Method (CPM) (Olivieri et al., 2019).

There are clear complementarities between LPS and LBPC. From one hand, LPS is a planning and control approach that is mostly focussed on medium and short-term planning level, which is capable of dealing with uncertainty and complexity by involving subcontractors and crew leaders in planning and control (Ballard 2000). Due to short feedback cycles and strong emphasis on collaboration, LPS is effective for managing commitments and support learning (Viana et al., 2017). On the other hand, LBPC is mostly used for long-term planning or phase scheduling and is primarily focussed on the technical perspective of planning and control (Seppanen et al., 2015). It deals explicitly with some core production management concepts, such as takt time and synchronization, cycle time, batch size, and product- and workflows. Moreover, LBPS can naturally contribute to improve process transparency in production management. However, two main research gaps can be pointed out in the literature. Firstly, despite the growing number of companies have been jointly adopted LPS and LBPC (Olivieri et al., 2019), and several contributions from research studies that have investigated the combination of these two approaches (Seppanen et al., 2010; Kalsaas et al., 2014; Seppanen et al., 2015; Nutt et al., 2020), the complementarity between LPS and LBPC still needs to be further explained by using some core Lean Production concepts. These are pull planning, continuous (product) flow, WIP control, standardized work, and synchronization of interdependent work, which can be considered as key elements of the Lean Production Philosophy (Arogyaswamy & Simmons, 1991).

Secondly, most implementations of LPS and LBPC reported in the literature have been concerned with residential, industrial, and commercial building projects. Only a few studies have reported the implementation of those planning and control approaches in infrastructure projects (Olivieri et al., 2019; Kassab et al., 2020). Many infrastructure projects, such as roads, railways, water supply, power transmission, are often linear in nature, have some degree of repetitiveness, and are usually spread across large geographic areas (Yabushi, 2010; Mattila and Abraham, 1998). Moreover, those projects are more affected by uncertainty that building projects (Dave et al., 2013), due to variations in underground conditions, open-air work, and long-distance travelling.

This paper reports the initial results of the development and improvement of a planning and control model for linear infrastructure projects, which combines elements of LPS and LBPC. That model has been developed in a construction company in Uruguay, which has carried out several linear infrastructure projects, such as sewage systems, telecommunications, and electricity distribution. The research question that guided this investigation was: how to plan and control linear infrastructure projects based on LPS and LBPC? The development of the model considers some specific complexity features of linear infrastructure projects, such as high uncertainty, and independent linear processes spread around large urban or rural areas. The name flow-based approach for planning and control comes from the key role played by the management of both product flows and workflows in this type of project. The results presented in this paper are limited by the fact that these are based on a single case study. Therefore, only some initial insights towards the development of the model are provided.

RESEARCH METHOD

DESCRIPTION OF THE COMPANY

Stiler is a construction company founded in Uruguay in 1959, with has more than 50 years of experience on a wide range of engineering and construction projects, including residential buildings, hospitals, industrial plants, bridges, water and sewage systems, electricity distribution, and telecommunication networks. This company operates not only in Uruguay, but also in other Latin American countries, such as Peru and Paraguay. In 2021, this company had more than 40 simultaneous contracts. The Lean journey of this company started around seven years ago by the implementation of LPS, similarly to many other companies. In 2021, the company decided to extend the Lean implementation program, by including production system design (PSD), and by combining LPS with LBPC. In the first year of the program training courses were carried out, and three new pilot studies were undertaken in different projects. The case study reported in this paper was carried out in one of the pilot projects, named Red Manga, an infrastructure project that had three main types of construction work: 45 km of sewage system (including underground pipes, connection to existing homes, and inspection boxes), 7 km of storm drainage (including macro-drainage pipes and inspection boxes), pumping stations and roadworks (including paving, curbs, and small bridges). This project was in a large urban area (40 hectares) in the outskirts of the city of Montevideo, Uruguay. The Lean implementation program is still going on in 2022, and other pilot studies on linear infrastructure projects have been developed.

RESEARCH DESIGN AND IMPLEMENTATION STEPS

The main outcome of the case study developed in this investigation was the initial version of a planning and control model for infrastructure projects. The development and refinement of the planning and control model was divided into three main phases: (i) assessment of existing situation; (ii) implementation in the pilot study; and (iii) evaluation of implementation results. Table 1 presents an overview of the lean implementation program carried out by the company in 2021, in which there were three pilot studies – Red Manga was one of them. For each phase, the multiple sources of evidence used in this investigation are presented. All authors of this paper have been involved in the implementation of the planning and control model in the Red Manga project. Therefore, they were able to carry out direct observation, participant observation in planning meetings, and took part in the Lean workshops, in which the proposed model was presented and discussed by a group of managers and technical staff of the company.

Table 1: Stages of the study

Phase/Year	Scope of analysis	Evaluation mechanisms/Sources of evidence
Phase 1 Assessment March 2021	Whole company	1-day site visit per project: assessment of the current planning and control systems by using an evaluation protocol Participant observation in 1 weekly planning session for each project 4 sets of interviews for each project: including top managers, engineers, and architects 1 interview with a board member 1 interview with the operations manager Analysis of the current company's system for planning and control
Phase 2: Implementation April - October 2021	Number of Projects: 3 Infrastructure project: 160 km lines - 5000 connections Medium Income Residential Building: 125 dwellings Medium Income Residential Building: 40 dwellings	Participant observation in 8 PSD meetings (4h) 4 production design system feedback meetings (2h) Participant observation in 8 lookahead meetings (2h)
Phase 3 Results November 2021		Participant observation in 12 weekly planning session (1.5h each) 12 site visits 8 Lean workshops (5h) involving pilot project teams

Phase 1 – Assessment of existing situation

The focus of Phase 1 was to assess the existing planning and control model adopted in the company, particularly organizational aspects, and analyse data from a set of existing projects. Interviews and meetings were carried out with top managers, architects/engineers, site supervisors and subcontractors. Three construction projects were visited, and the existing plans and databases were analysed. The authors also carried out direct observation in construction sites and interviewed several project and production managers.

Phase 2 – Implementation

The main activities developed in Phase 2 were: (i) development of a 40-hour training course on Lean Construction for the pilot project teams; (ii) development of a production system design model for the company, and implementation in one pilot project; (iii) development of the planning and control model, by combining LPS and LBPC, and implementation in the three pilot projects; and (iv) definition of standard practices for production system design (PSD), and production planning and control. PSD can be described as collaborative and systemic pre-construction planning exercise, as described by Barth et al. (2020). The proposed model for planning and control was built on what the company had developed in previous years and kept several existing good practices.

Phase 3 – Analysis of results

Phase 3 consisted of: (i) production of manuals containing the set of practices to be widely adopted in the company; (ii) refinement of the PSD model; and (iii) evaluation of results of the partial implementation of the proposed planning and control model.

Along the development of this Lean Implementation Program, the company decided to extend the Management and Control Department by including a team of technical staff to be directly involved in training activities, development of standardized tools, and pilot studies. Besides the pilot studies, other projects were encouraged to implement the proposed PSD and planning and control models after the end of the first year of the Lean Implementation Program, with the support of the technical staff of the Management and Control Department.

Based on the reflection on the results achieved in the Red Manga project, some initial insights were produced towards the development of the flow-based planning and control model developed for linear infrastructure projects.

RESULTS

CHARACTERISTICS OF LINEAR INFRASTRUCTURE PROJECTS

The definition of the planning and control model for linear infrastructure projects was strongly based on the type of project complexity faced in those projects, both in terms of structural complexity and uncertainty. These are:

(i) Projects are spread in large urban (e.g., sewage systems, optical fibre installation) or rural (e.g., electricity distribution) areas. Moving crews and equipment from one workplace to another is often time-consuming;

(ii) There is some degree of repetition, as processes are linear and have similar sequences of operations, but there are variations in some parameters, such as depth of excavation, position of inspection boxes, and diameter of pipes.

(iii) A high degree of uncertainty exists, mostly concerned with the lack of knowledge about underground (e.g., existing utilities, soil conditions) and neighbourhood (e.g. criminality, access) conditions, as well as with the possibility of inclement weather affecting open-air work;

(iv) Some tasks depend on the permission of client organization or local community, such as connection of public utilities to existing buildings;

(v) The number of different processes is relatively small, compared to a building project. The work of different crews can be decoupled, provided no resources are shared between them. Therefore, although uncertainty is high, the propagation of variability can be limited by dividing the work of crews in different zones and by having dedicated resources for each one; and

(vi) The reduction of WIP is mandatory for some tasks (e.g., sewage systems, stormwater drainage) as holes on the ground cannot be left open for a long time due to safety issues and possibility of rain.

All these characteristics were found in the Red Manga project. In some other linear infrastructure projects of the company, concerned with electricity and telecommunications utilities, there was an additional uncertainty related to the scope of work defined in the contract. In some of those contracts, the company plays the role of a service provider for several months: orders are placed by the client organization a short term in advance (e.g., between two and four weeks) and the company needs to plan tasks in a relatively short horizon, demanding flexibility to manage capacity as new orders arrive. By contrast, building projects are usually concentrated in a single construction site, being less affected by permits to carry out tasks, as these are usually obtained before starting the construction stage. Repetition is high, especially in residential projects, although most of them have some non-repetitive work. Many different crews are involved, and there are several sources of uncertainty, especially related to the large supply chain involved. However, several processes (e.g. internal finishings) are not affected by inclement weather. Finally, increasing work-in-progress is a major type of waste in many building projects.

EXISTING PLANNING SYSTEM

Before the beginning of the Lean Implementation Program, the Red Manga project had adopted a version of LPS devised for linear infrastructure projects. The main element of this planning system was a weekly meeting, in which both a one-week short-term plan and a three-week look ahead plan were produced. Those plans were prepared in movable boards in which sticking notes were used to plan work-packages, as shown in Figure 1. Only the most important processes were included in the plan, i.e., the ones that effectively had a linear character. Each line represents a crew, and each column defines a working-day. Most packages had durations longer than a week, and often had to be divided into sub-batches to fit the one-week horizon of the short-term plan. In each weekly meeting, the first panel is removed, and a new one is added at the end of the four-week planning horizon. This visual device clearly allows the planning meeting participants to see plans as a set of parallel workflows, so that an effort is made to keep the crews working uninterruptedly in the same processes and locations. This flow-based approach for production planning and control contrasts with the traditional activity-based approach adopted in LPS. This meeting is highly collaborative, and had the participation of the site manager, planning engineer, foreman and the supervisors of the main crews. Some small non-repetitive activities, which had low interdependence with linear processes were managed separately.

Due to the high degree of variability, and emerging information about the work zones, the sequence of batches is often changed. According to the managerial team, this does not cause much disruption in the workflow, because crews can work independently from each other, and there is usually many work-zones available to be tackled. However, a major concern of the site manager is to avoid spreading crews in workstations that are far from each other, as this can increase logistic costs and cause postponement in the delivery of completed batches. Therefore, constraint analysis was limited to the one-month horizon of lookahead planning. Most constraints considered in that plan were the ones that did not involve external stakeholders, such as design details produced by the company detail design team, demolitions and set up activities that could only be undertaken immediately before the beginning of a new work package. Colourful (orange or blue) cards, i.e. *kanbans*, were used to represent constraints of different nature in the visual plan, allowing a quick identification of the nature of the existing constraints. Long-term constraints, such as material supply, acquisition of equipment, and changes in existing working utilities, were managed separately, mostly based on the long-term plan. Traditional LPS metrics were used, such as PPC (percentage of plans completed), PPC for different crews, causes for the non-completion of work packages, overall number of constraints, and percentage of constraints removed. Productivity rates were available for different process, considering different parameters (e.g., depth of excavation, and diameter of the pipes). Those rates were used for estimating the duration of each batch of linear processes. Location-based planning was not explicit used, as the long-term plan was represented by a Gantt bar chart. However, there was some visual devices in which the project was divided by two categories of zones: (i) macro-zones, defined as delivery stages of the project by contract; and (ii) micro-zones, defined by the minimum batches for short term-plans, e.g., pipe segments that were separated by inspection boxes.

Figure 1: Movable boards used for look-ahead and weekly planning.

Contract management was strongly based on a spreadsheet in which the status of the execution of each activity was monitored (e.g., started, completed, inspected, certified by the client). Although the LPS metrics were systematically analysed in planning meetings, project progress was monitored by using the earned-value method approach. Due to the high uncertainty involved in the project, many changes in the sequence of batches had to be made.

IMPROVEMENT OPPORTUNITIES

In Phase 2 several improvement opportunities, mostly related to the explicit use of LBPC and its integration to LPS, were identified in the existing planning system. These were:

(i) Establish two levels for constraint analysis and removal. The existing one was kept for constraints that needed less than one month for removal, and a constraint control tool was proposed for long lead-time items;

(ii) Introduce visual tools for controlling rhythm, similar to flowline schedules. This is a key control related to takt-time planning (Frandson et al., 2013), enabling project progress to be assessed by the pace of each linear process;

(iii) Devise a location-based system that had four hierarchical levels, instead of only two. The criteria for defining work-zones were: (a) stages of the project defined by the contract, i.e. large batches that represent deliverables demanded by the client; (b) batches that are related to the existence of topographic features of the area, including water basins, natural barriers (e.g. roads, built facilities, slopes, etc.), which might affect the work sequence; (c) batches that are flow-oriented, i.e. define a zone that need to be delivered together for efficiency purposes; and (d) minimum short-term plan batches (which were fully listed in the spreadsheet of contract deliverables). Table 2 summarizes the description of each type of work-zone;

(iv) For each hierarchical level, a matrix for controlling the production status, like the one proposed by Sacks et al. (2009), was created. This matrix allows priorities to be made in terms of batches to be finished first, prioritize processes, including those that appear as critical, as well as to control each task status - whether the task is completed, in progress, stopped or not released (not started). Then, more emphasis could be given to the analysis and control of WIP, uncompleted batches, and distances between workstations. Therefore, the production status matrix can be considered as a tool for pulling production, considering the concept of pull proposed by Hop and Spearman (2004): work is released according to system status rather than based on customer demand;

(v) Create check-in and check-out control in each work zone, based on the minimum batch defined in the short-term plan. The database of project deliverables can be adapted and used for that purpose, enabling not only a control of project progress that is consistent with PPC, but also the easy calculation of metrics on cycle time variation and WIP; and

(vi) Based on the control of WIP, two project progress curves can be produced, one that considers all tasks completed and another that only considers completed batches.

Moreover, some minor improvements related to the implementation were made, including: (i) making explicit in the plan a backlog of made-ready tasks, (ii) emphasize learning opportunities in planning meetings by discussing the causes for the non-completion of packages and deviations in relation to the planned rhythm.

Complementing Table 2, Figure 2 presents work-zones for the four levels of the location-based system: the work-zones of a lower hierarchical level are always a subdivision of a higher level. At level 1, there were 5 work-zones, while at Level 2 there were 12. At Level 3, the number of work-zones was 38 – these should play a key role in the planning decisions regarding WIP and logistics. Each Level 3 work-zones had typically 60 to 80 sewage pipe stretches. Altogether there were 1150 batches for short-term planning. Figure 3 presents some additional details on the production status matrix for levels 3 and 4. It illustrates how this tool allows a visual representation of the production units where crews are working. It also provides an overview of the project progress, pointing out problems related to the excessive amount of WIP or unfinished work. Based on the development of tools for managing LBPC, a model for long-term planning was also proposed for the company. In this model, the main elements for long-term plans are the location-based system, a graph for controlling the pace of linear processes, and the sequence of work-zones at the Level 3. No detailed sequence for Level 4 work-zones should be produced due to the high uncertainty involved in sequence of minimum work batches.

Table 2: Hierarchical structure of the location-based system

Level	Base-Unit	Amount	Types	Variables considered
Level 1	UN-L1	Total of 5 UB-L1	Contract small projects	Contracting conditions
Level 2	UB-L2	Total of 12 UB-L2	Physical mapping	Topography, basins
Level 3	UB-L3	Total of 38 UB-L3	Completed batch	Workflow, sections
Level 4	Section	40-60 sections per UB-L3. Total 1150 sections	Work batch	Pipe section

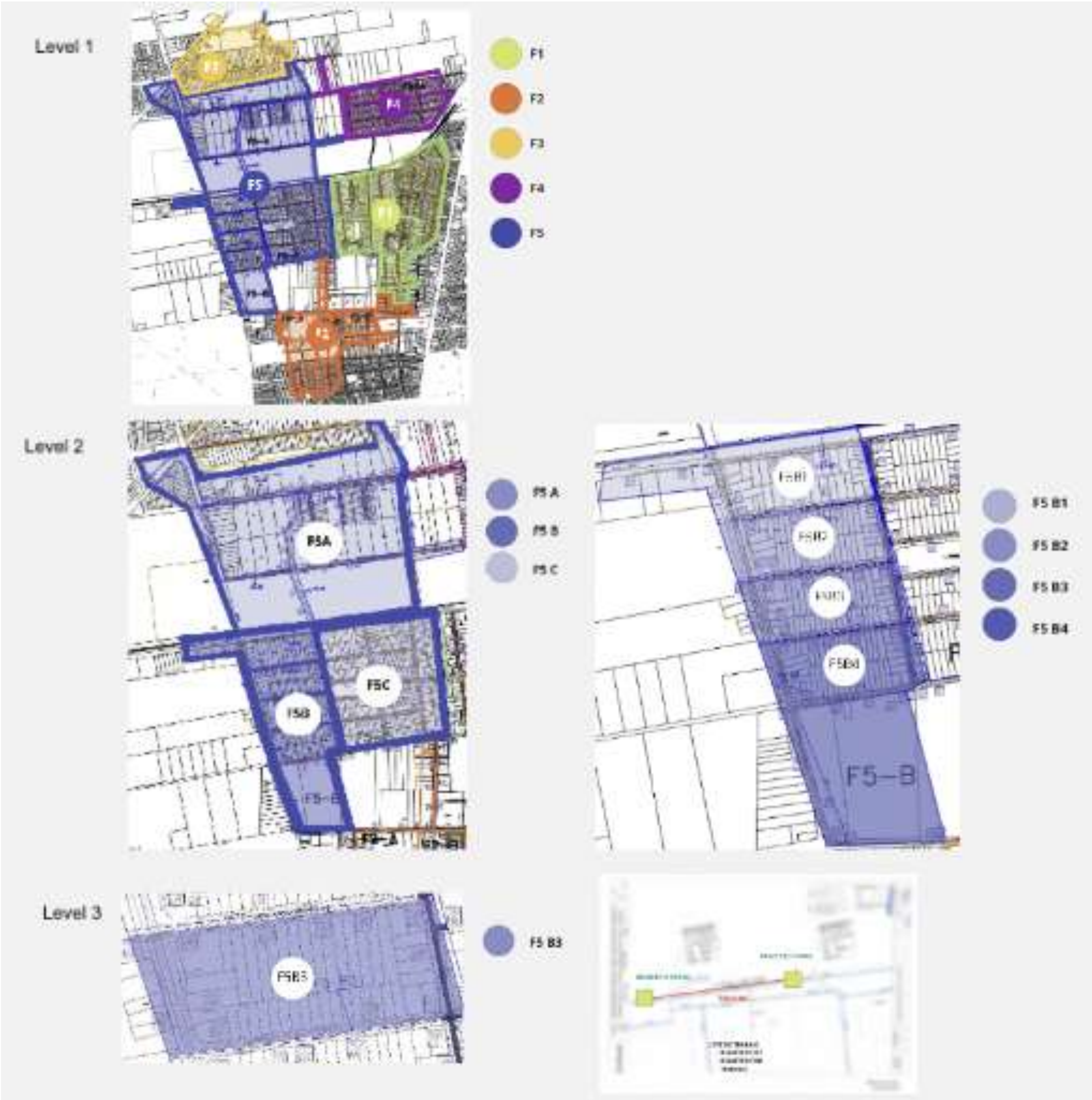

Figure 2: Hierarchical structure of location-based control levels

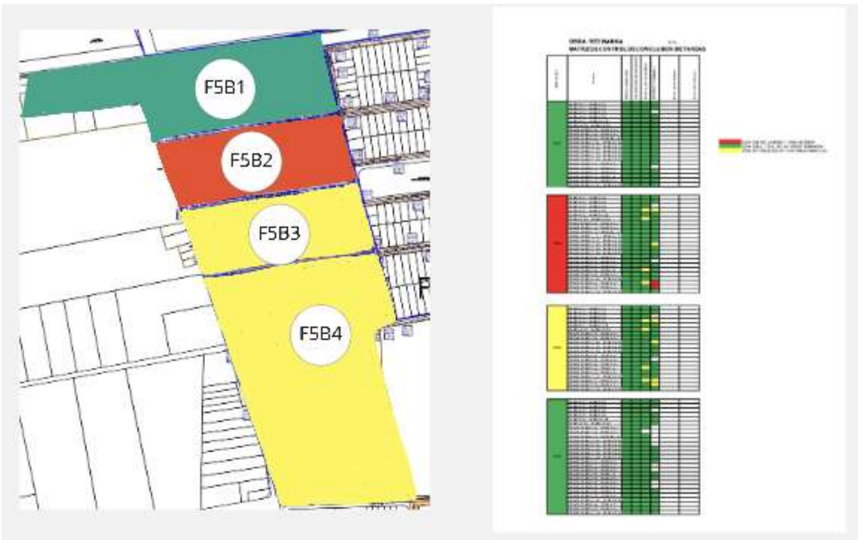

Figure 3: Transition from Level 3 to Level 4 location-based control

Some of the improvement opportunities identified in the case study have resulted in changes in the project planning and control system (e.g. graph for rhythm control, backlog of made-ready tasks), while others will be only implemented in future projects (e.g. the production status matrix, check-in and check-out control, long-term systematic constraint analysis). Figures 4 present a location-based metric that have been developed for future projects, named project progress considering only complete batches. Despite those limitations, some of the production metrics adopted have provided evidence of improvements in project performance: (i) reduction in PPC variability, (ii) increase in project progress (18% above target), increase in profit margin (0,4%).

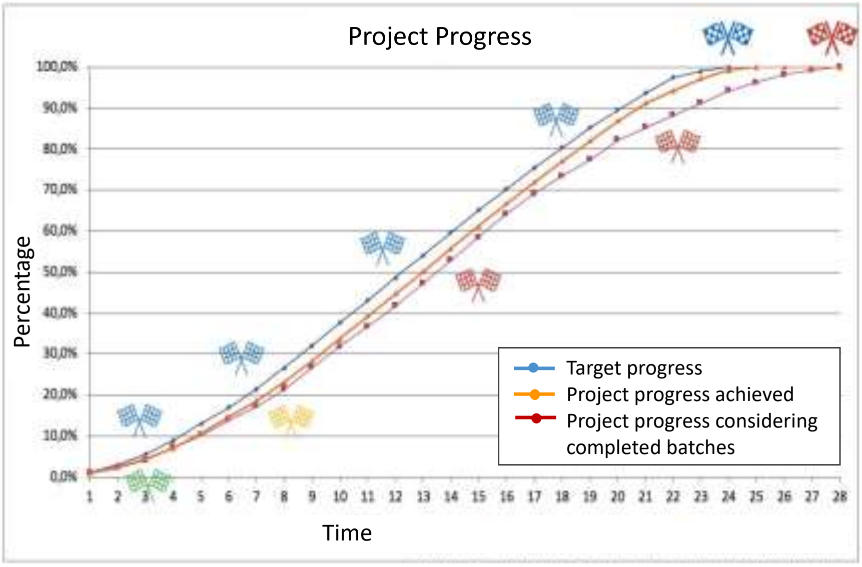

Figure 5: Example of graph for project progress control for complete batches.

DISCUSSION AND CONCLUSIONS

The flow-based planning and control model proposed for linear underground infrastructure projects has some innovations, when compared to other models devised for building projects:

(i) There is a good integration of LPS and LBPC. From one hand, LPS plays a key role in dealing with uncertainty and structural complexity by establishing hierarchical planning levels, using collaborative decision making, and creating a backlog of made-ready activities. This can be understood as a hybrid (pull-push) planning and control model, as there is clearly a mechanism for pulling production by triggering work based on the status of the system, as suggested by Hopp & Spearman (2004). On the other hand, LBPC explicitly deals with several concepts that play a key role in the Lean philosophy, such a batch size, cycle time, synchronization, and work-in-progress control.

(ii) Based on the production status control tool and on other visual control devices, the status of the system can be monitored, and this information can be used in LPS collaborative planning meetings for pull production;

(iii) Similarly to LPS, LBPC is also hierarchically organized in order to deal with the high uncertainty involved in the sequence of batches. Moreover, the proposed model strongly emphasizes to location-based control, by using several location-based metrics, such as batch adherence, cycle time variation, project progress considering complete batches, and unnecessary work-in-progress. Based on the maps of the urban or rural areas where those projects are being built, other metrics could be devised, such as average distance between workstations, which could be used as indirect measurement of logistic costs.

(iv) Dividing constraints into categories also seems to be an important mechanism for making lookahead planning more effective. Some of the constraints should be dealt clearly by site managers, e.g. by using kanban cards, while other require improvements in the integration with other sectors of the organization or external supply chain members. This type of approach for medium-term planning level has already been suggested by Brady et al. (2019).

(v) Visual management plays a key role in the implementation of the model, as a mechanism for copying with the type of complexity that exist in linear underground infrastructure projects. It is very important to visualize workflows that are longer that the short-term planning horizon, operational constraints that need to be removed within the 4-week window, deviation in the rhythm of linear processes, and the zones that must be prioritised in terms of completing batches at different hierarchical levels.

In the following steps of this investigation, other improvement opportunities will be explored, including the implementation of the standardized work approach for synchronizing processes and increasing efficiency, and the use of digital technologies for status control, including the use of performance dashboards. There are also some future opportunities that can be explored in the development of planning and control for infrastructure projects. Those projects are much more diverse than building projects. They might combine linear and non-linear work, underground, and surface activities, highly mechanised and manual work, etc. Therefore, companies that operate in that segment of the construction industry need planning and control models that are flexible to cope of those differences but based on the same fundamental core Lean concepts and principles.

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DIGITAL TWIN OF A DESIGN PROCESS: AN EXPLORATORY STUDY

Hisham Abou-Ibrahim[1], Eelon Lappalainen[2] & Olli Seppänen[3]

ABSTRACT

Digital twinning is a new approach to enhance the management of design, planning and construction operations. A construction digital twin aims to enhance the reality capture of ongoing operations using sensing technologies and AI functions to enable proactive process management. While a digital twin is clearly defined in the context of construction operations, where a digital replica is generated out of a physical site; a design digital twin lacks a clear framing as both twins are digital. This paper explores an approach to creating a design digital twin using agent-based simulation to mimic real BIM-based design projects. Accordingly, a digital replica is generated as an agent-based model. In addition, several KPIs are introduced to capture data related to BIM model dynamics. The results show that the suggested KPIs can increase the transparency of the design process, capture development dynamics at the level of BIM model elements, increase situational awareness among designers related to model development status, and identify higher clashing risk zones.

KEYWORDS

Lean Construction, Visual Management, Process, Design Digital Twin

INTRODUCTION

The importance of the design phase in overall construction project performance has been revealed in several studies (Said and Reginato, 2018; Li and Taylor, 2014; El. Reifi & Emmitt, 2013, Sacks et al., 2009). It is in the design phase where the project value is formulated and developed among different stakeholders (Khalife and Hamzeh, 2019). Several characteristics make the design process challenging to manage. Being fragmented, iterative, and exploratory in nature (Berard, 2012), the design phase is complex to plan, schedule, and control. However, despite the complexity and uniqueness of each design project, looking at design from the information generation perspective can help streamline design activities and standardize and automate design tasks.

Seeing design as an information generation process became clearer when Building Information Modeling (BIM) was introduced as a platform to create and share design

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deliverables (Barlish and Sullivan, 2012; Hartmann, 2010). Design always incorporates information generation; even with 2D drawings, it is about creating design information while solving the corresponding design problem. However, most design information was neither clearly spelled in the drawings nor connected. In this context, it is on each designer to read, understand, and connect information together as an input to his/her specific design task at any moment during the design phase. This requires each designer to always be up to date with the latest information created by other designers, which consumes time and is inefficient in increasingly complex projects (Sawhney and Maheswari, 2013). However, this is very challenging in a highly dynamic environment where information cannot be automatically traced and where management is more on the reactive side.

The use of BIM emphasizes the role of information generation during design by combining geometrical and information modeling. With BIM, design data is clearly attached to model elements in an object-oriented environment where realistic elements are created (van Nederveen et al., 2010). Thus, ideally, every designer can obtain information about a specific model element at any moment during the process. While this has enhanced transparency and access to design information among designers, tracing the dynamics of information generation is still lacking. Thus, while BIM enhances the transparency of design at the product level by visualizing corresponding geometry and information, it has less impact on the transparency of design at the process level.

Beyond BIM, the construction industry is currently witnessing the development of digital twins as a new form of managing the design, planning and production operations of construction projects. A construction digital twin aims to leverage data streams from a variety of sources, including site monitoring technologies and AI functions, to enhance reality capture and to enable proactive process management (Sacks, et al., 2020; El Jazzar et al., 2020). The research on digital twin is still in the early stages, and several academic and industrial efforts are starting to invest more in this new framework.

Digital twins are clearly framed in the context of construction execution, where the digital twin renders a real site into a digital model. Sensing technologies are installed on-site as a source of data to feed the digital model. Thus, a digital twin is continuously mapping the real brother. Sacks et al. (2020) concluded that by taking advantage of the opportunities offered by the digital twin, construction managers and workers could become more proactive through improved situational awareness. In dynamic environments, however, situational awareness is largely affected by the limitations of human working memory and attention, which can be addressed in several ways, such as automating data collection (Endsley, 2004). It has been argued that the utilization of the large amount of information contained in the digital twin in design also requires the utilization of some sort of automatic "sensing system" of design, such as those proposed by Sacks et al. (2020) and Garcia et al. (2021).

In design, digital twinning is feasible; however, both twins are happening in the digital world. This is the main difference between digital twins in the construction phase and digital twins in the design phase. In design, there are no physical dynamics, such as those happening on site, where sensors can be used to detect changes. Instead, the design dynamics are happening at the social level on one hand, and at the level of BIM models at the other hand. While tracking social dynamics can be investigated as an approach to creating design digital twins, this study focuses solely on tracking dynamics at the BIM model level. In this regard, a digital twin is developed to map a BIM model where different design dynamics are taking place. This could be thought of as putting a camera to record BIM model dynamics at the level of model elements and their attached data.

Accordingly, the broad research questions can be stated as follows: (1) what kind of useful information can this camera capture? (2) What are the key performance indicators (KPI) that should be developed to serve as camera lenses? And (3) How can we use the tracked KPIs to help a project manager better maneuver a complex design process?

Therefore, this study explores the first steps in developing a digital twin for the design process by investigating which design aspects can be automatically detected from the BIM model. This approach has not been thoroughly investigated before. Accordingly, the study suggests four KPIs that will monitor some dynamics occurring in the BIM model. There was no specific process's aspect targeted while developing those KPIs, instead, the focus is on which dynamics can be automatically detected, or sensed, in the BIM model. Once the data stream is generated through these KPIs, the authors reflected on their possible relations to actual project dynamics. In this context, agent-based modeling is used to simulate a project scenario where different model's dynamics are occurring. The simulation results are used to reflect on the suggested KPIs. Future research will include real project KPI results and will engage corresponding practitioners to give their reflections on the generated KPIs' information streams.

RESEARCH METHOD

Design science research (DSR) is the research method employed in this study. DSR enables the development and testing of innovative concepts and tools and is adequate when addressing practice-based research (Rocha et al., 2012). DSR is a constructive research method that involves first the creation of an artefact and second evaluating its performance in use (March and Smith, 1995). In this regard, DSR is iterative and incremental where several testing/application loops can take place before reaching the final desired artifact (Hevner, et al., 2004). This study follows the typical steps of the DSR method, which begin with the awareness of the problem and progresses to conceptualizing the problem and suggesting a solution to the problem, after which an artifact can be developed to solve the problem, which is finally tested and validated to draw conclusions (Dresch et al, 2015).

Models are an example of artefacts that can result from DSR research. The developed models aim to represent a sub-set of a real phenomenon by means of creating constructs and associations among them to resemble reality (Weber, 2013). In this study, an agent-based simulation model is developed following the guidelines advocated by Hevner, et al. (2004). Hevner's (2014) guidelines for the use of DSR are: (1) design as an artefact, (2) problem relevance, (3) design evaluation, (5) research rigor, (6) design as a search process, and (7) communication of research. Regarding the first and second guidelines, the aim of this study was to create an artefact arising from practical problems. Regarding the third and fourth guidelines, they will be dealt with in a limited way in this conference paper; however, in the next phase of the study, these guidelines will also be considered more comprehensively. Guidelines 5 and 6 are part of the iterative nature of the DSR method, in which this conference paper plays the role of the first iteration. As for the seventh guideline, this conference paper is the first public presentation to an academic audience. The expert panelists will be used in the latter phase of this research for feedback, and practitioners' judgments will be then gathered.

SIMULATION MODEL DEVELOPMENT

An agent-based simulation was developed to model BIM as a population of different elements as shown in Figure 1. This simulation model is considered a "Digital Twin" for an assumed BIM model. In the simulation environment created using the Anylogic software, architectural elements (in red) are added to the model space (imaginary 2D space for simplification) along with structural elements (in blue). The geometry considered in the simulation environment is simplified to a 2D space measured in pixels (overall simulation area assumed randomly at 500x500 pixels where all created elements will be randomly added). Note that the pixel scale is used in this study as no real BIM model dimensions are considered. Moreover, the geometry of the elements was not taken into consideration. Instead, unified squares of 5x5 pixels are used for each element. Also, the number of elements, their production rate, and their corresponding movement serve only as a demonstration of the research idea.

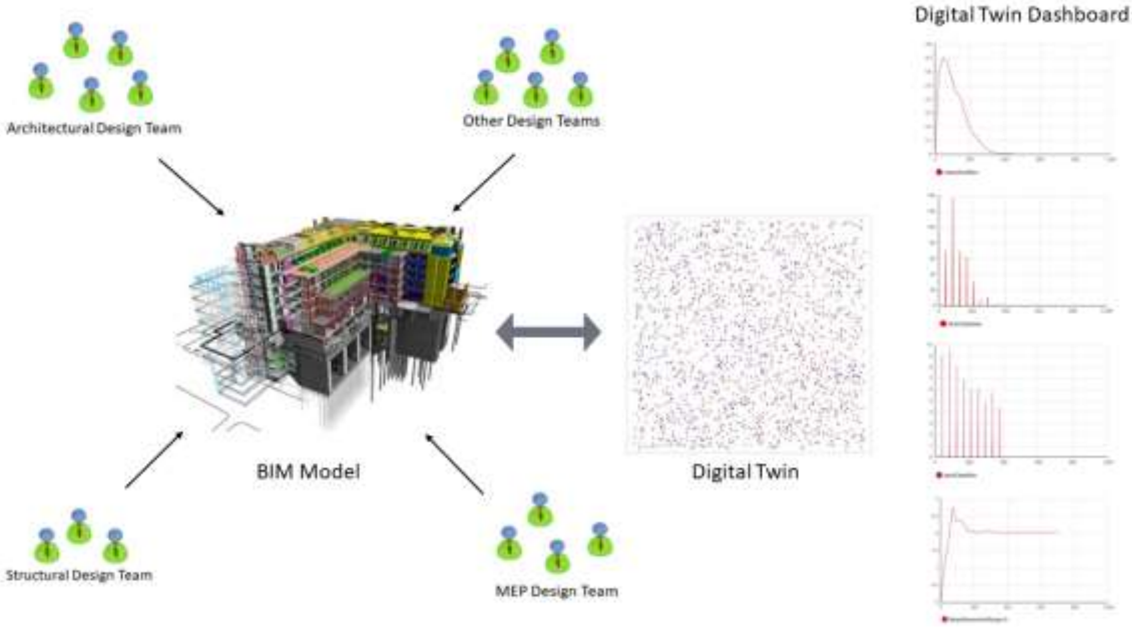

Figure 1: Design Digital Twin Schematic Representation
(BIM Model Image ©STW Architects)

An agent type is defined in the simulation model to represent all BIM model elements added to the simulation environment. Only architectural and structural elements were considered in this study for simplicity. Every element follows different states during the simulation, as shown in Figure 2. The element is first created in the simulation model at a certain location, and then it might change the location while developing the design. It is assumed that the probability of changing to a new location will decrease with time as the design converges to its final state, and, as such, more elements converge to their final positions in the BIM model.

Weekly, all elements move to a "Coordination" state where clashes are resolved. If elements clash, location adjustment is considered to remove the clash to mimic the actual elements' location coordination in an actual BIM model project. As such, elements will also witness movement after the coordination state if they clash. Note that clash detection in real projects can occur daily, weekly, biweekly or at any duration interval. We assumed in this study that clash detection is occurring weekly to demonstrate the concept only.

Table 1 summarizes the numerical values assumed in this study to run the simulation model. These values are not based on real data, nor do they represent actual model development; they are assumed to make the study tangible at this phase of the research. Future studies will replace those assumed values by actual project data to capture realistic model dynamics. For the architectural and structural element production rates, it is assumed that the production rate of elements will linearly decrease with time as the design progresses. For instance, at the beginning of the design process, the frequency of adding elements is higher, while towards the process end, most elements will be already present in the model where fewer number of new elements are expected to be added.

Other numerical values are also assumed in Table 1. The clash detection process is assumed to occur once every week (40 working hours). The final size of the architectural and structural BIM models is 1500, and elements that are in the range of 5 pixels to each other are assumed to be clashing. These numerical assumptions serve only this paper's scope and future studies can reveal more data related to those variables.

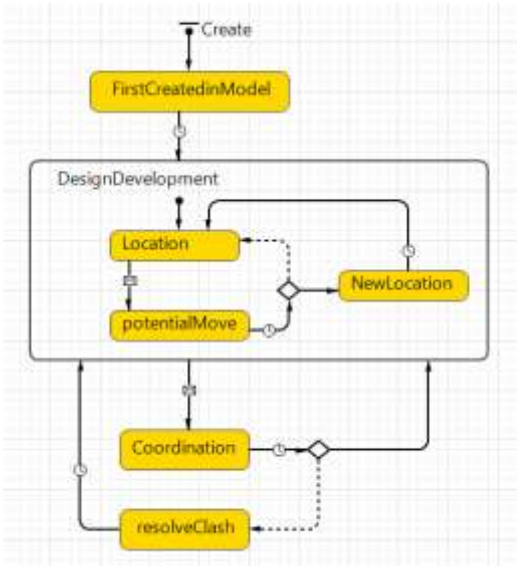

Figure 2: BIM Element State Chart

Table 1: Simulation Parameters Value Assumption

Parameter	Description	Assumed Value
Arch. Elements Prod. Rate	The rate at which architecture elements are added to the simulation environment	20 – 0.01 x (t)
Str. Elements Prod. Rate	The rate at which structural elements are added to the simulation environment	5 – 0.05 x (t)
Clash Detection Interval	Clash detection meeting intervals	40 hours
Arch. Model Size	The total number of architecture elements reached in the simulation environment	1500 Elements
Str. Model Size	The total number of structural elements reached in the simulation environment	1500 Elements
Clashing Element Range	The range at which an element agent in the simulation environment is considered clashing with another element	5 Pixels

KEY PERFORMANCE INDICATORS

Several studies have introduced different KPIs to measure aspects in the design process. The developed KPIs were highly affected by the model used to conceptualize the design process. For instance, Ostergaar and Summers (2007) introduced metrics inspired by the electric current approach where a KPI similar to electric resistance was suggested to measure the resistance value of each design task. In a different conceptualization inspired by fluid mechanics, metrics like velocity, viscosity and volatility of fluids were suggested to measure information flow (Krovi et al., 2003). Similarly, Tribelsky and Sacks (2010) developed metrics based on a Lean conceptualization of the design process suggested before by Ballard (2000) and Koskela (2000).

Previous research also introduced several KPIs tailored to the BIM-based design process. Abou-Ibrahim and Hamzeh (2020) developed a dashboard that qualitatively monitors changes occurring in the BIM model, revealing geometry changes, property changes, and model size changes. However, the dashboard is not automated and only reveals the nature of changes happening in every consecutive model version without touching on the size of these changes. Manzione et al. (2011) introduced Lean-based KPIs to monitor BIM workflows, focusing on the process level not the inner BIM model dynamics. Several studies were also done based on the Level of Development (LOD) concept as a measure to reflect the detailing level of an element (Abou-Ibrahim and Hamzeh, 2016; Hooper and Ekholm, 2012); however, the LOD concept is not designed to detect overall model status and is only used to reflect a specific element's detailing level. Nonetheless, LOD detection and monitoring are not yet automated.

In this regard, this study tries to address this gap in monitoring the dynamics occurring at the level of BIM model elements by suggesting a new set of KPIs; that will serve as sensors for the suggested Design Digital Twin. In other words, those KPIs will be used to continuously stream information related to BIM model dynamics. While several KPIs are needed to comprehensively reflect all model dynamics, this study introduces only four KPIs based on the number of elements and their movements. Different KPIs need to be developed in future studies to reflect on elements information, model quality, and design value. Table 2 summarizes the introduced KPIs, while the following sections detail the use of each of them based on the simulation results.

Table 2: BIM Model-Based Key Performance Indicators

KPI	Description
Average Movement of Elements (AME)	Average movement of elements during the overall design period
Number of Elements Clashing (NEC)	Total number of elements clashing
Average Movement due to Clashes (AMC)	Average movement of elements after resolving clashes
Elements In Range (EIR)	The average number of elements in range for a specific zone in the model or the entire model

RESEARCH LIMITATIONS

The current research effort is performed at the conceptual level to explore design digital twinning. The results of this paper are based on numerical assumptions, not on actual data from real projects. Therefore, the results cannot be generalized; however, they serve the purpose of the paper to explore insights related to design digital twinning. Future studies will include real projects' data to test the digital twin accordingly. Moreover, a limited set of KPIs was introduced in this study, which is not sufficient to comprehensively reflect on different BIM model dynamics, specifically aspects related to design value and model quality. Future studies are expected to develop new KPIs to fill this gap.

RESULTS AND DISCUSSION

The design of the simulation model was done through several iterations, where the simulation output was monitored in every iteration to ensure the model generated reasonable and realistic results as to mimic a real project according to researchers' experience. This section highlights the use of the digital twin to better understand the dynamics occurring at the BIM model level. As such, the introduced KPIs can potentially enhance situational awareness among designers, improve process transparency, and help design managers better manoeuvre design progress and information sharing.

AVERAGE MOVEMENT OF ELEMENTS (AME)

This metric reflects the average movement of elements in the model during the overall design period. It can target the entire BIM model, a specific discipline, or even a specific category of elements. Figure 3 shows the AME metric for the architectural (red) and structural (blue) BIM models respectively. Both graphs show that at the beginning of the design process, the average movement of elements increased in both models reflecting the changes occurring in models' shapes that go with the development of design.

At one point, the graphs peak and start decreasing reflecting that more elements reached their final design locations in the model and fewer elements are still witnessing movements. As such, the models start converging to their final shape as the design solution is refined. Another important aspect revealed by the graphs is the rate at which each BIM model converges to its final design. For this example, it shows that the architectural model converged faster to its final design state (around 400 manhours) than the structural model (around 600 manhours). This information is important to balance the production and development of both models especially for coordination purposes.

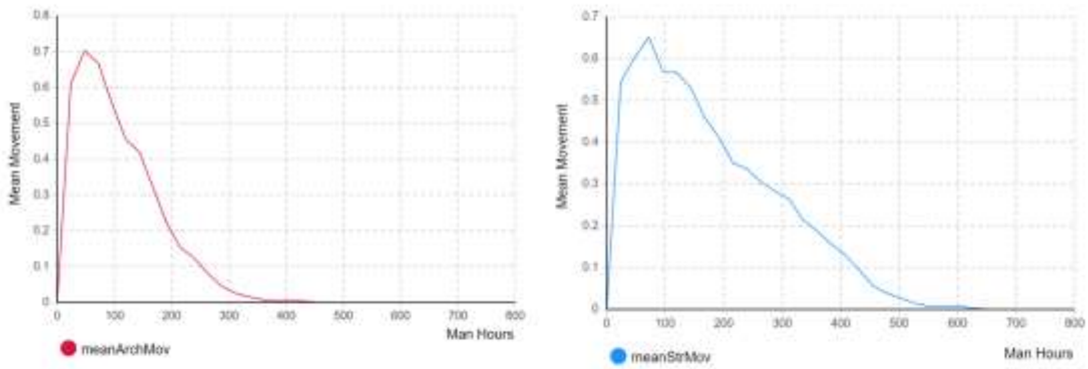

Figure 3: Average Movement of Elements (AME)

This metric also has important use at the level of BIM model categories of elements. For instance, if the design manager is monitoring the development of specific categories of elements (e.g. architectural walls and structural columns), AME can be used to track their locations changes. In this context, the design manager can wait until the architectural walls almost reach their final locations in the model, which represents the corresponding layout design, before the structural engineers can start adding the structural columns. As such, the structural designers do not have to wait for the entire architectural BIM model to be finished, thus enabling partial and continuous sharing of information among involved teams as to overlap design tasks when feasible.

At the planning level, the design manager can plan the development of different BIM model categories according to this AME metric. Collaborative planning can be done among different involved designers to plan the sequence of categories' modelling based on information dependency and model uses at each phase. The design team will have a model-based timeline showing the expected pace of BIM model development and the expected delivery of each category of elements. The design digital twin and involved metrics can be used to monitor and control the development of design with accordance to the generated AME baseline as shown in Figure 4.

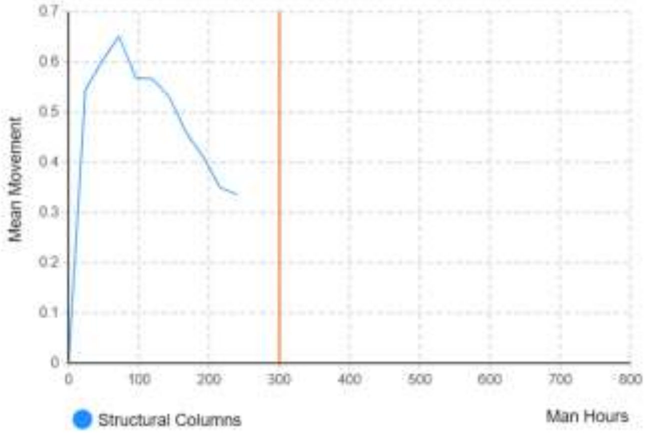

Figure 4: AME-Based Planning Example

Assume the structural columns are expected to reach their final design locations after 300 manhours (Orange Line) as per the plan. The actual movement of the elements in this category revealed by the blue graph reflects that with current development pace, the columns are less likely to reach their design state by the planned time. Based on this information, the design manager can act proactively on the situation and try to avoid the delay in delivering this category; therefore, minimizing the risk of information flow interruptions or delays for downstream activities. These expectations will be further explored in future research based on actual data.

Number of Elements Clashing (NEC)

This metric reveals the number of elements clashing in the model. Figure 5 shows the total number of elements that clash in both the architectural (in red) and structural (in blue) models. This shows that the architectural model witnessed more clashes at the beginning of the process as compared to the structural model. This can be related to the difference in production rates of both models as assumed in Table 1.

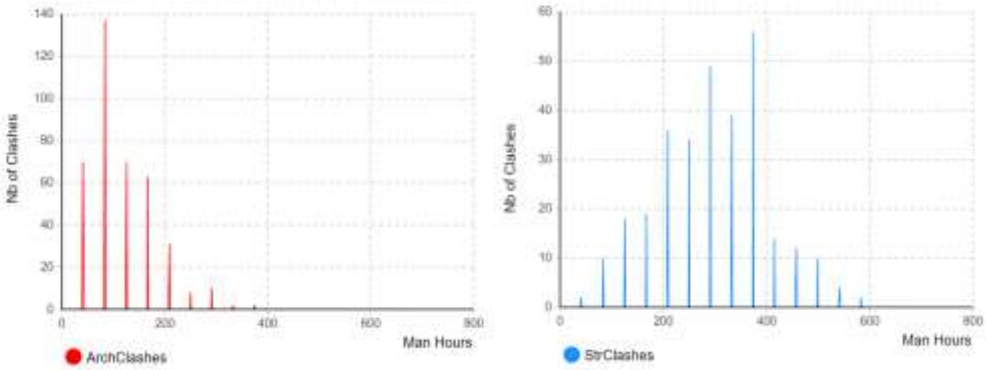

Figure 5: Number of Elements Clashing

As more elements are added to the architectural model, a higher probability of clashes is expected at the beginning of the process. More clashes would appear early, and therefore be resolved early in the process. But, as the structural production rate is relatively lower, fewer clashes are likely to appear in the structural model at the start of the process; however, more clashes will appear in later design stages as more elements are added. Comparing these two graphs shows that unbalanced model production in different design disciplines can lead to an unbalanced generation of clashes in each discipline, which can lead to continuous changes and rework throughout the process.

AVERAGE MOVEMENT DUE TO CLASHES (AMC)

These KPIs follow the specific movement of elements due to clashes. In real projects, designers sometimes need to change the locations of some elements to resolve geometrical clashes occurring within and outside their specific disciplines. Every time a clash is resolved, one or a few elements need to be moved. The AMC metric follows the average value of movement for all elements affected after resolving a clash. Therefore, the AMC values can be used to show the effects of clashes on model shape changes.

Figure 6 shows an example of the AMC graph where the average movement of architecture elements, that were moved to resolve a certain clash, is monitored. In this example, higher values are witnessed at the beginning of the process. As the design progresses, the effect of clashes reduced, and elements are therefore witnessing fewer location changes towards the end of the design process. This declining trend of the AMC graph highlights that the architecture design is converging to a final solution, where clash coordination is no longer causing big changes.

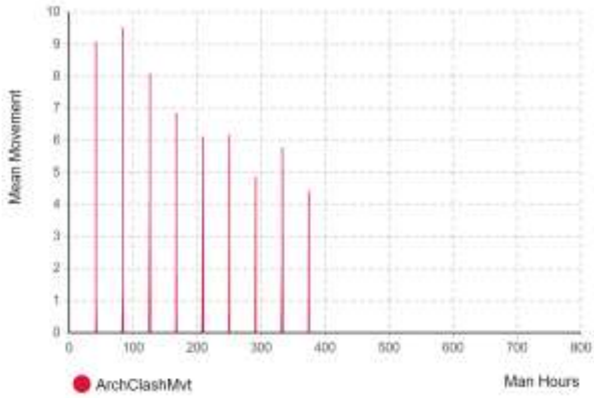

Figure 6: Average Movements of Architecture Elements due to Clashes (AMC)

ELEMENTS IN RANGE (EIR)

The last metric introduced in this study is the “Elements In Range” (EIR) shown in Figure 7. The idea behind EIR comes from the need to assess the risk of clashing among elements in the model before they occur to proactively address them. This KPI is calculated as follows; each element will have a number of elements in a specific predefined geometrical range, and then the average of all those numbers will be calculated. Therefore, this metric can reflect the congestion of elements in a specific zone or even the entire BIM model space. With enough data from real projects, a correlation can be made between EIR values and clashes, which in turn can be used later to monitor and mitigate clashing risks. EIR can also be used to assess the effects of suggested design changes in specific model zones. The effect of changes occurring in areas with higher EIR values is expected to be higher as more nearby elements can be affected. Therefore, the risks correlated with design changes can be better understood before proceeding with the change.

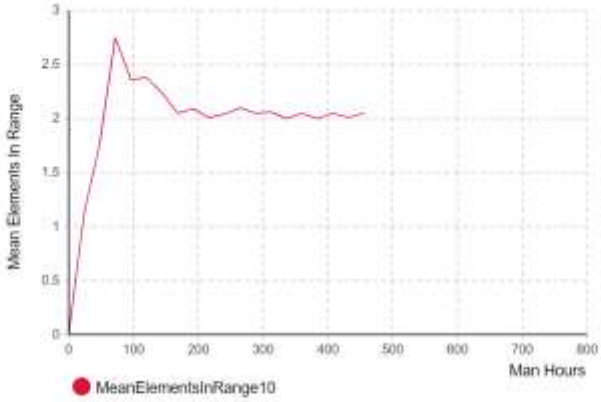

Figure 7: Elements in Range (Architecture Model)

CONCLUSION

This paper explores the concept of digital twins in the design process. Digital twins are more framed in the construction phase where a digital twin is created for an actual site; however, digital twinning in design is less intuitive where both twins are digital. Sensing is key when creating a digital twin where sensors are the source of data streaming necessary to create an informative digital replica of the ongoing project. For instance, actual sensors and cameras are installed on site as data streams for the digital twin.

In design digital twinning, sensing is also important to capture needed information about the design process. The design process has a social aspect as well as a digital aspect represented by the BIM model. This study focused on proposing sensors at the level of the BIM model to generate information that can be used for design management purposes. While actual sensing tools are not feasible in this case, some KPIs are introduced to serve as sensors to reveal BIM model dynamics. The introduced parameters reveal dynamics related to BIM model elements, and they are used to create a dashboard to visualize the corresponding data stream. The KPIs can be used by design managers to better understand the dynamics of the BIM model which can be reflected in a better understanding of the design process status as discussed in the results section for each KPI.

An important outcome of this research is related to determining the nature of the desired design digital twin itself. In this study, the dashboards created from the KPIs (model sensors) were used to analyse BIM model dynamics. Those KPIs can be directly generated from the BIM model without the need for an intermediary separated digital twin. In this context, the following questions can guide future research efforts: (1) Can the design digital twin take the shape of dashboards to monitor BIM model dynamics based on suggested KPIs? (2) Is there additional value in creating a separate digital model for the design process? Future research can update the simulation model using real data to mirror an actual BIM model into a simulation environment. Actual IFC models can be tracked and needed information can be automatically extracted to serve as input for the simulation model. The data-driven simulation model can then be tested as a design digital twin of BIM. Therefore, future research could examine the ability of a developed simulation model to fulfil the requirements of digital twinning in construction. Practitioners and design managers can play a major role in shaping the development of this digital twin and testing its value.

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