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CONTENTS

LC ³ PREFACE.....	III
IGLC PREFACE.....	V
ACKNOWLEDGEMENTS	VII
CONTENTS	XI
AUTHORS INDEX.....	XXI

PART 1

CONTRACT & COST MANAGEMENT.....	1
Discrete Costing Versus Collaborative Costing	3
Sa'id Ahmed, Christine Pasquire and Emmanuel Manu	
Impact of Supplier Evaluation on Product Quality	11
Thais Alves, Panthil Desai, Kim Needy, Ashleigh Hegwood and Sean Musick	
Testing the Value of Best Value	19
Gerald Eke and Dr. John Elgy	
Investigating Organizational Capability vis-à-vis Human Action to Minimize Post-Contract Transaction Costs in D&B Projects	27
Christy P. Gomez and Abdulazeez Umar Raji	
Design-Build and Design-Bid-Build in Construction- A Comparative Review	35
Titouan Plusquellec, Nadia Lehoux and Yan Cimon	
Applying Choosing by Advantages in the Public Tendering Procedure	45
Annett Schöttle, Paz Arroyo and Christine Haas Georgiev	

Motives for the Use of Competitive Dialogue.....53
Paulos Wondimu, Jardar Lohne and Ola Lædre

A comparison of project alliancing and lean construction.....61
Brendan Young, Ali Hosseini and Ola Lædre

ENABLING LEAN WITH INFORMATION TECHNOLOGY69

Application of BIM for Supporting Decision-Making Related to Logistics in Prefabricated Building Systems71
Fernanda S. Bataglin, Daniela D. Viana, Carlos T. Formoso and Iamara R. Bulhões

Integration of Lean Construction and Building Information Modeling in a Large Client Organization in Massachusetts.....79
Marzia Bolpagni, Luciana Burdi and Angelo Luigi Camillo Ciribini

Contribution of Information Technologies to Last Planner System Implementation.....87
Camilo Ignacio Lagos, Rodrigo Fernando Herrera and Luis Fernando Alarcón

Integration of Lean and Information Technology to Enable a Customization Strategy in Affordable Housing.....95
Eder Martinez, Iris D. Tommelein and Ariana Alvear

Development of Systematic Construction Logistics Using 'Intelligent Product'103
Saeed Mirzaeifar, Bhargav Dave and Vishal Singh

Integrating BIM and Agent-Based Modelling for Construction Management Optimization.....111
Francesco Livio Rossini, Francesco Rossini and Antonio Fioravanti

IT for Lean Construction - A Survey in India.....119
Jyoti Singh, Mohit Mangal and Jack C.P. Cheng

Lean Production Controlling and Tracking Using Digital Methods.....127
Jakob von Heyl and Jochen Teizer

LEAN THEORY135

Assessing the Impact of Lean Methods in Mining Development Projects137
Cristóbal Baladrón and Luis F. Alarcón

Ethical Dilemmas in Value Delivery: Theoretical Conditions.....	145
Frode Drevland, Jardar Lohne and Ole Jonny Klakegg	
Assessment of Performance Measurement Frameworks Supporting the Implementation of Lean Construction	153
Alexandros Hatzigeorgiou and Odysseas Manoliadis	
A Portfolio/Process/Operations (PPO) Analysis of a Meta-Project Production System in Renovation Projects	161
Samuel Korb, Rafael Sacks and Otto Alhava	
On Epistemology of Construction Engineering and Management.....	169
Lauri Koskela, Ergo Pikas, Jarkko Niiranen, Andrea Ferrantelli and Bhargav Dave	
Platform Ecosystems: Unlocking the Subcontractors' Business Model Opportunities.....	177
Enni Laine, Otto Alhava, Antti Peltokorpi and Olli Seppänen	
An Application of Control Theory to Visual Management for Organizational Communication in Construction.....	185
Koichi Murata, Algan Tezel, Lauri Koskela and Patricia Tzortzopoulos	
Hierarchy of Value Perceived by Groups of Users about Their Neighbourhood...	193
Michelle Nascimento Da Silva and Luciana Miron	
Integrating Delivery of a Large Hospital Complex.....	201
Dean Reed, Howard Ashcraft, Atul Khanzode, Martin Fischer, Leonardo Rischmoller and Peter Berg	
Removing Waste while Preserving Slack: The Lean and Complexity Perspectives	209
Tarcisio Abreu Saurin	
Application of Lean Production with VSM to the Blasting and Coating Industry	217
Wenchi Shou, Jun Wang, Peng Wu, Xiangyu Wang and Yongze Song	
PEOPLE, CULTURE, & CHANGE	225
Learning Simulation Game for Takt Planning and Takt Control	227
Marco Binnering, Janosch Dlouhy, Svenja Oprach and Shervin Haghsheno	
The Implementation of Building Information Modeling and Lean Construction in Design Firms in Massachusetts and its Correlation with Client's Requirements ..	235
Marzia Bolpagni, Luciana Burdi and Angelo Ciribini	

Features, Roles and Processes of Performance Measurement in Lean Construction.....	243
Luis Felipe Cândido and José De Paula Barros Neto	
Mobilizing BIM in a Collaborative Project Environment.....	251
William Collinge and John Connaughton	
Comparing Choosing by Advantages and Weighting, Rating and Calculating Results in Large Design Spaces.....	259
Maria Gabriela Correa Albornoz, Paz Arroyo, Claudio Mourgues and Forest Flager	
Initial Euphoria to Sustained Change - Mainstreaming Lean Culture.....	267
Venkata Santosh Kumar Delhi, Raghavan N, Ashwin Mahalingam and Koshy Varghese	
Implementation of Lean Construction in Client Organizations – An Analysis of the Status Quo.....	275
Janosch Dlouhy, Marco Binninger, Lisa Weichner and Shervin Haghsheno	
Geographical Distribution in the Scientific Field of Lean Construction.....	285
Atle Engebø, Frode Drevland, Nawras Shkmot, Ola Lædre and Jardar Lohne	
How Research Can Help Transform the Construction Industry.....	293
Fritz Gehbauer, Glenn Ballard and Margarita Leonova	
Socio-Constructivist Account of Collaboration in Concept Design.....	301
Danilo Gomes, Patricia Tzortzopoulos and Mike Kagioglou	
Building a Lean Culture.....	309
Cory Hackler, Erika Byse, Dean Reed and Thais Alves	
Cross-Functional Project Teams in Construction: A Longitudinal Case Study....	317
Jean Laurent and Robert Leicht	
Bottom-Up Strategy for Lean Construction On Site Implementation.....	325
Nero Lenotti Zanotti, Flávio Leal Maranhão and Vitor Levy Castex Aly	
Strategies that Can Help Transform the Construction Industry.....	333
Margarita Leonova, Glenn Ballard and Fritz Gehbauer	
Barriers and Challenges to Implement Integrated Project Delivery in China.....	341
Shan Li and Qiuwen Ma	
Design-Value in the Platform Approach.....	349
Duncan W. Maxwell and Mathew Aitchison	

A Lean Construction Maturity Model for Organizations	357
Claus Nesensohn	
Shared Understanding: The Machine Code Of the Social in a Socio-Technical System	365
Christine Pasquire and Paul Ebbs	
House of Cards – a Simulation of Lean Construction Principles.....	373
Paul Pollesch, Alexander Rovinsky, Raul Alvarado Iii and Thais Alves	
Re(de)fining Project Delivery with Life Cycle BIM.....	381
Adam Rendek	
Automation of the Building Information Model Breakdown Structure.....	389
Leonardo Rischmoller, Tony Dong, Martin Fischer and Atul Khanzode	
Improving On-Site Meeting Efficiency by Using an Automated Model Breakdown Tool	397
Leonardo Rischmoller, Tony Dong, Martin Fischer and Atul Khanzode	
An Exploration of Compatibility of U.S. Army Culture and Lean Construction..	405
Ralph Salazar, Zofia Rybkowski and Glenn Ballard	
Knowledge Management and Information Flow through Social Networks Analysis in Chilean Architecture Firms	413
Lluís Segarra, Rodrigo Fernando Herrera, Luis Fernando Alarcón and Eugenio Pellicer	
Implementation of Lean Practices among Finishing Contractors in the US.....	421
James Smith and Khoi Ngo	
Analysis and Assessment for Lean Construction Adoption: the DOLC Tool	429
Bruno Soares De Carvalho and Sergio Scheer	
Design Thinking as a Method of Improving Communication Efficacy	437
Laurie Spitler and Laura Talbot	
Lean Anti-Corruption Toolkit.....	445
Ahmed Stifi, Fritz Gehbauer and Sascha Gentes	
Delivery Methods and Social Network Analysis of Unethical Behavior in the Construction Industry.....	453
Muzafar Thameem, Zofia Rybkowski and James P. Smith	

PART 2

PRODUCT DEVELOPMENT & DESIGN MANAGEMENT..... 463

Design Management: Metrics and Visual Tools..... 465

Hisham Abou-Ibrahim and Farook Hamzeh

Mapping Waste in the Structural Design Process of South African Projects..... 475

Adefemi Aka, Fidelis Emuze and Dillip Das

Waiting Times in Design Process: A Case Study 483

João Bosco P. Dantas Filho, Mariana Monteiro Xavier De Lima, Luiz Fernando Mahlmann Heineck, Patricia Tzortzopoulos and José De Paula Barros Neto

A Taxonomy of Client Product Value in Construction Projects..... 491

Frode Drevland and Ole Jonny Klakegg

Virtual Design and Construction: Aligning BIM and Lean in Practice 499

Roar Fosse, Glenn Ballard and Martin Fischer

Strategic Considerations for Applying Choosing by Advantages in Design Process..... 507

Zoya Kpamma, Theophilus Adjei-Kumi, Joshua Ayarkwa and Emmanuel Adinyira

The ER Design Simulation Game: Experience and Reflect 515

Helena Lidelöw

Visual Planning in Design: The Effect of Pre-Engineering 526

Helena Lidelöw and Gustav Jansson

How BIM-Lean Integration Enhances the Information Management Process in the Construction Design..... 531

Sajedeh Mollasalehi, Anushka Rathnayake, Ahmed Aboumoemen, Jason Underwood, Andrew Fleming, Udayangani Kulatunga and Paul Coates

Design Management in a Design Office: Development of the Knowledge Base.. 539

Ergo Pikas, Lauri Koskela and Roode Liias

Design Management in a Design Office: Solving the Problem of Relevance..... 547

Ergo Pikas, Lauri Koskela and Olli Seppänen

Design Management in a Design Office: Development of the Model for 'To-Be' 555

Ergo Pikas, Lauri Koskela and Olli Seppänen

A Case Study on the Success Factors of Target Value Design 563
Patricia Tillmann, Doanh Do and Glenn Ballard

Review of Lean Design Management: Processes, Methods and Technologies..... 571
Petteri Uusitalo, Hylton Olivieri, Olli Seppänen, Ergo Pikas and Antti Peltokorpi

How Evidence-Based Design Supports Better Value Generation for End-Users.. 579
Yufan Zhang, Patricia Tzortzopoulos and Mike Kagioglou

PRODUCTION PLANNING & CONTROL 587

Project Flexibility and Lean Construction 589
Glenn Ballard and Hajnalka Vaagen

Visualizing Daily On-Site Space Use..... 597
Audrey Bascoul and Iris Tommelein

Technical Takt Planning and Takt Control in Construction 605
Marco Binnering, Janosch Dlouhy and Shervin Haghsheno

Adjustment Mechanisms for Demand-Oriented Optimisation in Takt Planning and Takt Control 613
Marco Binnering, Janosch Dlouhy, Dominik Steuer and Shervin Haghsheno

A Balanced Dashboard for Production Planning and Control..... 621
Trond Bølviken, Sigmund Aslesen, Bo Terje Kalsaas and Lauri Koskela

Lean Metric System: Proposal for a Performance Measurement System for Construction Projects 629
Juliana Carneiro, André Carneiro, Vitor Machado, Luis Felipe Cândido and José De Paula Barros Neto

Last Planner System – the Need for New Metrics 637
Ghali El Samad, Farook Hamzeh and Samir Emdanat

A Construction Delay Analysis Approach Based on Lean Principles..... 645
Huseyin Erol, Irem Dikmen and M. Talat Birgonul

Probability Density Function for Predicting Productivity in Masonry Construction Based on the Compatibility of a Crew 655
Laura Florez and Jean C. Cortissoz

Digital Kanban Boards Used in Design and 3D Coordination 663
Ralf-Uwe Modrich and Bruce Cousins

Real-Time Tracking of Production Control: Requirements and Solutions 671
Hylton Olivieri, Olli Seppänen and Antti Peltokorpi

Introducing New Capacity Planning Metrics in Production Planning..... 679
Lynn Rizk, Farook Hamzeh and Samir Emdanat

Phase Schedule Implementation and the Impact for Subcontractors 687
Flora Seixas Ribeiro, Dayana Bastos Costa and Pedro Antunes Magalhães

**Guidelines for Devising and Assessing Visual Management Systems in
Construction Sites 695**
Caroline Valente, Fernanda Brandalise, Marinna Pivatto and Carlos Formoso

PRODUCTION SYSTEM DESIGN..... 703

Comparing Production Design Activities and Location-Based Planning Tools.... 705
Clarissa Biotto, Mike Kagioglou, Lauri Koskela and Patricia Tzortzopoulos

Standardized Work: Practical Examples in a Brazilian Construction Company .. 713
Angela de Bortoli Saggin, Taynah Ramos Mota, Felipe Loiola Brito and Carlos
Alexandre M. Do Amaral Mourão

**Lean Equipment Installation - Potentials of Using Takt Planning and Takt Control
in the Equipment Installation of Industrial Buildings 721**
Janosch Dlouhy, Willem Grobler, Marco Binnerger and Shervin Haghsheno

A Framework of Five-Stream Production System for Megaprojects.....729
Michael Ibrahim, Klas Berghede, David Thomack, Panos Lampsas, Dave
Kieviet and Awad Hanna

Simulation of Production Line Improvement in Modular Home Manufacturing ..737
Chelsea Ritter, Youyi Zhang, Roger Dupuis and Mohamed Al-Hussein

Collaborative Takt Time Planning of Non-Repetitive Work.....745
Iris Tommelein

SUPPLY CHAIN MANAGEMENT & PREFABRICATION.....753

Value Stream Mapping: A Case Study in Structural Masonry755
Luane Assunção Paiva Melo, Victor França Cavalcanti de Lima and Savio Melo

Just in Time in Construction: Description and Implementation Insights763
Flora Bamana, Nadia Lehoux and Caroline Cloutier

Exploring the Application of Lean Principles to a Construction Supply Chain.....	771
Rafaella Broft	
3D Concrete Printing in the Service of Lean Construction.....	781
Fatima El Sakka and Farook Hamzeh	
Lean Opportunity Assessment of Contractors Supply Chain in South Africa	789
Fidelis Emuze, Tebatjo Masoga and Cornelius Sebetlele	
Supply Chain Design for Modular Construction Projects	797
Pei-Yuan Hsu, Marco Aurisicchio and Panagiotis Angeloudis	
Counterfeit, Fraudulent and Sub-Standard Materials: The Case of Steel in Norway	805
Nina Eklo Kjesbu, Atle Engebø, Ola Lædre and Jardar Lohne	
Optimization of Supply Logistics-Constrained Module Assembly Processes in Industrial Construction	813
Jing Liu and Ming Lu	
Value Stream Mapping: Case Study in Columns Concreting	821
Nayara Jhæssica Marques Da Fonsêca, Andrezza Vagnielly Coutinho Germando, Artur Moura and Savio Melo	
Value Stream Mapping - A Case Study of Cold-Formed Steel House Framing for Offsite Manufacturing Supply Chain.....	829
Rehan Masood, Vicente Gonzalez and James B.P. Lim	
Prefabrication of Single-Family Timber Houses - Problem Areas and Wastes.....	837
Djordje Popovic, Tobias Schauerte and Jimmy Johansson	
Lean Construction in Small-Medium Sized enterprises (SMEs): An Exploration of the Highways Supply Chain.....	845
Algan Tezel, Lauri Koskela and Zeeshan Aziz	
Development of a Materials Management Strategy to Enable Continuous Work Flow On-Site.....	853
Cynthia Tsao and Helena Lidelöw	
Flow and Resource Efficiency Measurement Method in Off-Site Production	861
Brian Wernicke, Helena Lidelöw and Lars Stehn	
Key Performance Indicator for Managing Construction Logistics Performance	869
Fei Ying and John Tookey	

Off-Site Guarding: Look-Ahead Supply Scheduling for Risk Indication with BIM.....	877
Ningshuang Zeng, Markus König and Jochen Teizer	

SAFETY, QUALITY, & THE ENVIRONMENT885

Analysis of the Influence of Lean Construction and LEED Certification on the Quality of Construction Sites.....	887
Thais Cunha and Mariana Lima	

Why Lean Projects Are Safer.....	895
Gregory Howell, Glenn Ballard and Sevilay Demirkesen	

Safety Performance Measurement Systems Based on Resilience Engineering: A Literature Review	903
Guillermina Peñaloza, Carlos Formoso and Tarcisio Abreu Saurin	

Green Building and Lean Management: Synergies and Conflicts	913
Nina Weinheimer, Sarina Schmalz and Daniela Müller	

PRODUCT DEVELOPMENT AND DESIGN MANAGEMENT TRACK

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DESIGN MANAGEMENT: METRICS AND VISUAL TOOLS

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Abstract: The iterative and multidisciplinary nature of design complicates its management. Nonetheless, the lack of adequate tools that can be used to manage design dynamics negatively affects the design process as well as the quality of the final design deliverables. In this regard, this paper introduces new metrics to measure information flow in BIM projects, and elaborates on the Level of Development (LOD) concept to reflect the design maturity of model elements in the corresponding design context. Moreover, a metric is developed to reflect the design maturity of the entire BIM model or part of it. The study also employs visual tools to plan and control design tasks based on the developed metrics. Results highlight that quantifying and visualizing the design progress helps design managers better assess the design status, streamline information flow among parties, and control the generation of corresponding design information.

Keywords: Lean design, Visual Planning, BIM, LOD.

1 INTRODUCTION

Design is a multidisciplinary process that aims to fulfil owner's needs and values by overcoming several obstacles and constraints (Cross 1984). Problems with design management can be attributed to the iterative nature of design, the involvement of different parties with different interests and mentalities, poor communication and inadequate information exchange, segregated delivery systems, and the absence of adequate metrics that can quantify design information flow using real time data (Ballard 2000, Tribelsky and Sacks 2011, Ford & Sterman, 2003).

Meanwhile, the industry is witnessing an increasing use of Building Information Modelling (BIM) as a platform for running the design process. BIM is a visual database that combines parametric design data into a centralized model. The proper use of BIM has been proven beneficial for the design process as well as the final design product (Eastman, et al. 2009; Al Hattab and Hamzeh 2016). Since BIM is object oriented, elements used in the model holds the corresponding design information either in their graphical appearance or in the corresponding attached data. Accordingly, managing design data on BIM defers from traditional 2D-CAD processes.

As research on design management is gaining momentum in different directions, visualizing and quantifying the planning and control of the design process is expected to streamline the flow of information among stakeholders, reduce waste and rework, promote coordination among involved stakeholders, and increase the quality of design for downstream and end customers.

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2 LITERATURE REVIEW

2.1 Waste in Design

An interesting study by Mazlum and Pekerikli (2016) underlines the wastes encountered during the design process, and classifies them according to Ohno's waste categories. Results show that waste related to rework is the most frequent category and has the highest cost impact. Koskela et al. (2002) refer to two main reasons that cause rework: (1) unclear definition and poor ordering of design tasks, and (2) failure to stick to the ideal order, in case planned, due to external enforcing factors. Consequently, design tasks usually suffer from a lack of timely information exchange. In this regard, Tribelsky and Sacks (2011) claim that focusing on the information flow and data sharing characteristics can reduce the generation of waste and increase the value for downstream and end customers.

To minimize rework, the Dependency Structure Matrix (DSM) tool is used to order design tasks according to the corresponding information dependency (Austin et al. 1999). Accordingly, better flow of information among design parties is expected. However, scheduling the design program resulting from the DSM requires not only the sequence of activities, but also the start/end dates, durations, and resources requirements of each activity. Accordingly, the lookahead planning technique is suggested to further detail design activities, identify constraints, allocate resources and release work packages. Nonetheless, the Percent Plan Complete (PPC) was used to manage projects during the design phase (Hamzeh et al. 2009, Hammond et al. 2000). However, the characteristics of the design process cannot be fully captured in these frameworks. For example, PPC only measures the quality of the scheduled plan not the quality of design itself. A 100% PPC does not necessarily reflect a 100% accepted design. Moreover, these techniques focus on the flow aspect of design and gives less attention to its transformation and value characteristics.

2.2 Design Information Flow

In a different direction, several studies target the definition of information flow during the design process. Note that the conceptualization of information flow during design governs to a big extent the way design is being planned and monitored. For instance, Krovi et al. (2003) compares information flow to fluid mechanics where characteristic such as velocity, viscosity, and volatility are proposed, but without being measured or demonstrated. Ballard (2000) approaches design workflow as the flow of products in manufacturing, where designers transform client requirements and ideas into product design documents. Tribelsky and Sacks (2010) further elaborate on Ballard's model and introduce metrics to quantify design workflows. These metrics help evaluate the characteristics of information flow such as work in process, cycle time, batching and other lean related concepts. However, these metrics do not reflect the quality of design itself nor its progress, they just reflect the characteristics of the ongoing process.

2.3 Level of Development (LOD)

To manage information flow in BIM, research and industry efforts created the notion of Level of Development (LOD). LOD is seen as a communication language among design participants to formalize the development of model elements and control their use by downstream users. LOD defines the minimum content requirements for an element and its authorized uses at five progressively detailed levels of completeness. Current

classification systems range from LOD 100 to LOD 500, specifying the minimum graphical and non-graphical information an element should hold at each level, and its possible authorized uses (BIMForum 2015; The American Institute of Architects 2013).

In this context, an LOD-based framework is developed by Abou-Ibrahim and Hamzeh (2016) to expand the use of LOD into design management, not just model management. The framework creates three variables to describe LOD, and introduces a matrix to relate LOD to these variables. The framework allows stakeholders to prioritize between graphics and information while deciding on modeling requirements. Also, a new variable is introduced to describe the different design checks performed on the element during the process, as a different approach to defining an element's design reliability. However, some practitioners and academics suggest abiding by the available LOD guidelines to avoid inconsistencies, especially that these guidelines are used contractually.

In this regard, a new method to plan, schedule, and control design activities is needed. This paper suggests a framework to manage design using BIM, and the objectives of the study can be stated as follows:

1. Define design workflow on BIM platforms
2. Define metrics to quantify the defined information flow
3. Visualize the planning and control of the design process

To realize these objectives, the study introduces the Design Maturity Index (DMI) that describes the design maturity of the BIM model, a discipline, or even a certain category of elements. DMI is based on the LOD concept, and expands its use for design management purposes. Thus, while LOD reflects the modelling requirements of an individual model element, DMI targets the design maturity of the entire model or part of it. An equation is developed to calculate DMI, and visual tools are used to plan and control the design process.

3 METHODOLOGY

Design Science Research (DSR) is used as a research method in this study. DSR is sometimes called “improvement research” to emphasize the problem solving nature of the activity. DSR starts by recognizing and defining the problem. Then, suggestions for a problem solution are drawn from the existing knowledge of the problem area (Peirce 1931). Afterwards, implementing the suggestions is performed under the Development phase, to be afterwards evaluated according to the functional specification implicit or explicit in the suggestion. Development, Evaluation, and further Suggestions are often iteratively performed in the course of the research effort. Conclusion indicates termination of a specific research project (Vaishnavi and Kuechler 2007).

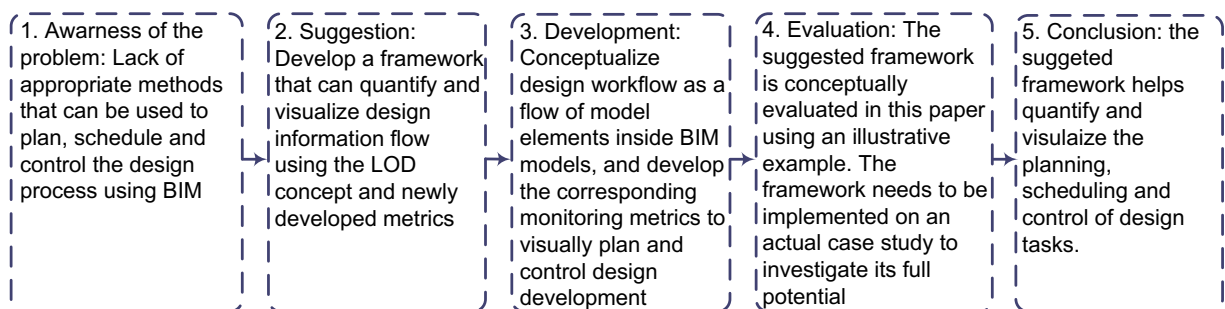


Figure 1: Research method using DSR

4 FRAMEWORK DEVELOPMENT

4.1 Conceptualization of Information Flow in BIM

When designers employ BIM during design, they actually create parametric elements in the model. These elements are classified by categories, families, and types as illustrated in Figure 2. The following are the definitions of these classes as they appear in Autodesk:

- **Category:** it is a group of elements used to model building design, for example columns, beams, walls, etc (Autodesk n.d.).
- **Family:** it is a class of elements under a certain category. "A family groups elements with a common set of parameters (properties), identical use, and similar graphical representation. Different elements in a family may have different values for some or all properties, but the set of properties—their names and meaning—is the same" (Autodesk n.d.). For example, a lighting fixture family can have pendant lights coming in different sizes and material, but having similar shapes.
- **Type:** it is a specific case of a family, where specific values are given to size, material, or any property. Every family can have several types (Autodesk n.d.).
- **Instance:** it is the actual element placed in the model and have a specific location.

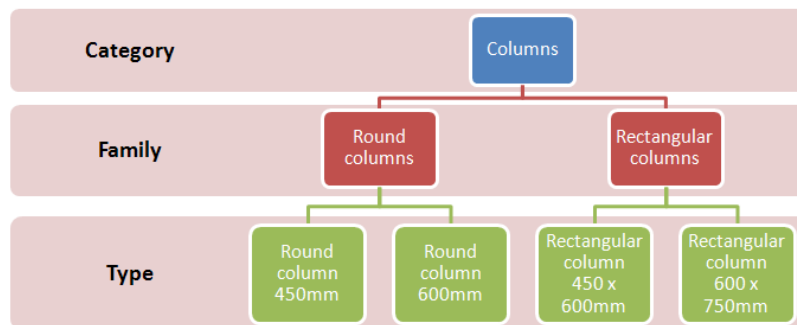


Figure 2: Hierarchy in BIM models (Autodesk, n.d.)

Design workflow in BIM projects is hereby approached as a flow of model elements. At every stage in design, some new elements are created, other elements are further developed, and some elements are deleted or changed. Thus, design dynamics among stakeholders is reflected by the generation and development of model elements throughout the process. In this regard, design information is being delivered through these elements either by their graphical appearance or their attached non-graphical data. The following is a set of notions used in this paper to describe information flow in BIM:

- **Information Package:** it can be the full BIM model, a discipline model, a category of elements or any part of the model used to deliver design intent.
- **Element:** it is the smallest model entity used to hold and deliver design information.
- **Design Information:** it is any graphical or non-graphical data attached to an element.
- **LOD:** it is the Level of Development of a model element based on its graphical appearance, attached information, and authorized uses.
- **EDM:** it is the Element Design Maturity based on the corresponding design context.
- **DMI:** it is the Design Maturity Index of the entire model or part of it.

4.2 Element Design Maturity (EDM)

The LOD classification system is currently used to describe model elements according to their graphical appearance, attached information, and authorized uses. However, current LOD guidelines are not oriented to reflect design related conditions witnessed throughout the process. For instance, at a certain stage in design, an element or set of elements in the model may be waiting for owner's approval, coordination with other disciplines, or even acceptance from concerned authorities. Although these elements might have a high LOD level (say LOD 300), their design maturity cannot be directly deduced since it is related to a bigger design context involving several stakeholders.

To account for these important aspects witnessed during design, the Confidence Index (CI) metric introduced by Abou-Ibrahim and Hamzeh (2016) is used in this paper. CI represents the design reliability of each element used in the BIM model and it is based on Gray and Hughes (2001). The design checking process can be divided into two main categories: (1) reviews targeting client needs vs. building standards and (2) reviews targeting product's in-service requirements (Gray and Hughes 2001), as highlighted in Table 1. For example, when an element is checked against client's value, the element gains C1. If in addition, the element is checked against other disciplines, it gains C4. CI can take ten different values (C1 to C10) according to each review type. The mentioned types are suggested to generally describe the checking process happening at the design stage.

In this context, a metric called Element Design Maturity (EDM) is developed to reflect the design maturity of an element based on its LOD level and CI values. While LOD reflects the level of development of an element based on its modeling characteristics, EDM reflects the design maturity of the element based on the design context. EDM has five maturity levels as highlighted in Table 2.

Table 1: Different design checks performed under CI (Gray and Hughes 2001)

Review Type	Reliability Check Type
Reviews targeting client needs vs. building standards	C1: Client needs vs. standard or innovative technical specifications.
	C2: Compliance with building regulation, planning regulations, health and safety law, national and international standards.
	C3: Building Performance under expected conditions of use.
	C4: Design validation and coordination among different trades.
	C5: Building safety and environmental compatibility.
Reviews targeting product's in-service requirements	C6: Constructability.
	C7: Permissible assembly tolerances.
	C8: Failure modes and effects, and fault analysis.
	C9: Reliability, serviceability, and maintainability of building elements.
	C10: Labeling, warnings, identification, and traceability requirements of building elements.

Table 2: Element Design Maturity Levels

EDM Level	LOD Requirements	CI Requirements	Maturity Level
EDM-1	LOD 100	C1	Conceptual
EDM-2	LOD 200	C1, C2, C4	Schematic
EDM-3	LOD 300	C1, C2, C3, C4, C5	Detailed
EDM-4	LOD 400	C1, C2, C3, C4, C5, C6, C7, C8	Shop Model
EDM-5	LOD 500	C1, C2, C3, C4, C5, C6, C7, C8, C9, C10	As-Built

4.3 Design Maturity Index (DMI)

Since EDM reflects the design maturity of an individual element, Design Maturity Index (DMI) is developed to reflect the design maturity of the entire model or part of it. DMI is the ratio of elements that reached their desired EDMs to overall modeled elements. For instance, if the planned maturity level of the architectural model is Schematic, designers need to model architectural elements according to LOD 200 requirements and check their model against client's needs (C1), planning and regulation rules (C2), and other involved disciplines at the moment (C4). Equation (1) is used to calculate the DMI of a set of model elements. DMI ranges between 0 and 100 where none or all modeled elements have converted to their planned EDMs.

Note that designers are not aware of the final number of elements to be modeled at the end of design; however, they know that all of these elements should abide by the corresponding LOD and CI requirements originally planned. This is why the percentage is used not the number of elements. Thus, DMI evaluates the ratio of elements that reached their EDM requirements based on the total number of elements modeled at the moment. Although both the nominator and denominator of the DMI equation would be continuously evolving especially at early design phases, DMI would still reflect the actual model design maturity at the corresponding moment with respect to the original EDM plan. Practically speaking, designers are not required to figure out the EDM of each element separately; however, they can benefit from the parametric structure of the model to automate this task. Rule Based checking algorithms can be developed for this purpose to fully automate the procedure.

$$DMI = \frac{\sum \text{Elements that reached planned EDM}}{\text{Total number of elements in the defined set}} \quad (1)$$

4.4 Visual Planning and Control

Using the definition of information flow provided in Section 4.1, a new method to plan, schedule, and control design development is proposed in this section. Since design encompasses a flow of elements, design managers can plan the development of these elements at each phase of the design process based on the desired maturity level. For instance, at the schematic phase of design, managers can agree to deliver architectural and structural elements at EDM-2, while designing MEP elements at EDM-1. Note that we can have elements at different EDMs at each phase of the project.

Since elements are distributed among categories as highlighted in Figure 2, practitioners can plan the progress of design using these categories as Information Packages. They can decide on the categories to be designed in each phase, the EDM requirements of corresponding elements, the sequence, the start/ end dates, the durations, and the responsible design teams. These categories are planned to reach a 100% DMI at the end of their corresponding durations, where all sub elements are required to reach their planned design maturity. Note that other Information Packages can be used to schedule the design process, for example disciplines, systems, or other parts of the model.

To visualize the planning of design, a method inspired by the Line of Balance technique is suggested. However, instead of locations, DMI percentages are used on the Y-axis as highlighted in Figure 3. This method is referred to as Design Flow Lines (DFL) in this paper. Each DFL reflects the start date of a certain design activity, its end date, the corresponding duration, and its pace. Each DFL starts by a DMI of zero and ends up with a DMI of 100 where all corresponding elements are planned to reach a certain design maturity.

5 FRAMEWORK EVALUATION

An illustrative example is used to evaluate the suggested framework at its theoretical level. Note that a real case study is needed to further evaluate the practicality and usefulness of the framework. Figure 3 illustrates the use of DFLs to plan the design process using elements' Categories. Dashed Lines reflects the original plan, whereas solid lines reflect the actual DMI values. Architectural Walls and Floors are two Categories used to design spaces, overall building shape and function. These Categories are interdependent (form a loop in the DSM), and therefore they are coupled together in one DFL. They are planned to start at week 0 and reach their desired design maturity at week 4. Rooms are another architectural Category used to annotate the designed spaces. Rooms design is planned to start one week before the Architectural Walls and Floors reach 100% DMI. The design of Columns also has a one-week overlap with Architectural Walls and Floors, and it is expected to reach 100% DMI in two weeks. Floor Openings are designed by MEP engineers while deciding on the MEP concept. In this example, their start date is planned after the architectural and structural engineers finish their designs.

Once the plan is set (dashed lines), design managers can follow up with design progress by calculating the actual DMIs (solid lines) at the end of each week. Recall that DMI is the percent of elements that reached their desired EDMs to the total number of elements in the Category. For instance, Architectural Walls and Floors failed to reach their planned design maturity by week 4, and witnessed a one week of delay. This delay affects the completion date of Columns' design where structural engineers needed to wait for architects to finalize the building spaces before they can finalize the columns' grid. Nonetheless, MEP engineers waited for one week before they could start allocating Floor Openings; however, the corresponding duration was not affected. Note that Rooms were not modeled, and the visualization made it easy to detect this deviation from the plan.

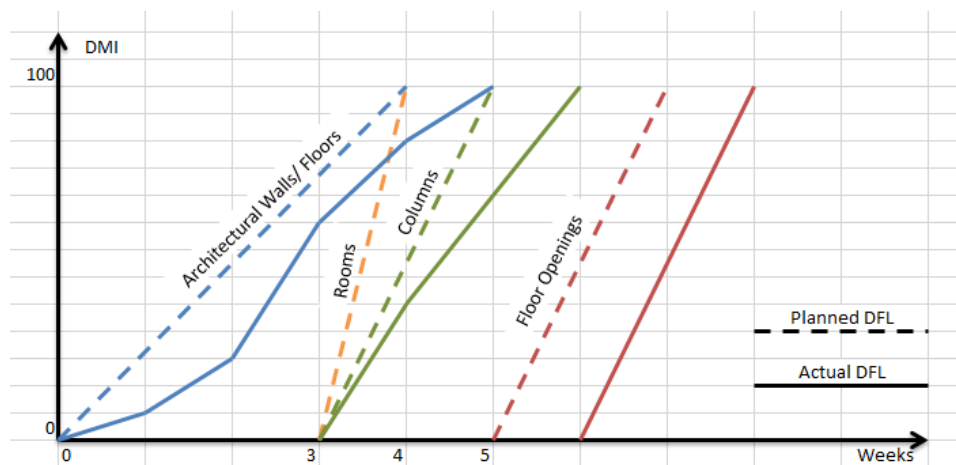


Figure 3: DFL plan for design development

6 DISCUSSION AND CONCLUSIONS

A new design management framework is developed in this study to enhance the planning and control of the design process. The framework builds upon the LOD concept, develops new design progress metrics, and uses Design Flow Lines (DFLs) to visualize the planning and control of design using BIM platforms.

In this regard, the Element Design Maturity (EDM) metric is developed to help design managers define the design maturity of an element based on its LOD level, performed design checks and reviews. In this regard, EDM completes the role of LOD, and fills the gap between modeling characteristics and design status.

Design Maturity Index (DMI) is another metric developed in this study to target the design maturity of the entire BIM model or part of it. Designers can, at any point in time, evaluate the design progress of the project by calculating its actual DMI. Accordingly, they can act upon the reasons hindering the project from reaching its desired maturity level, whether it is a modeling problem (not reaching desired LOD), or a process problem (missing design checks).

Moreover, the developed DFL method helps visualize the planning and control of the design process using the DMI metric. Each Information Package is planned to reach 100% DMI at a certain duration, reflected by a planned DFL. Accordingly, design managers can visually plan the design process by specifying the Information Packages that need to be designed at each phase, their EDM requirements, their sequence based on information dependencies, their start/ end dates, and their durations.

Once the plan is set, design managers can follow up with design progress by calculating weekly DMIs and comparing them to the plan. Accordingly, deviations from the planned progress can be visually detected using real time data. Moreover, planners can balance the production of design information by balancing the production rates of involved design teams in order to avoid waste generation.

Nonetheless, the framework is able to capture the Transformation, Flow, and Value (TFV) aspects of design that are suggested by Koskela (2000). Transformation is reflected by elements converging to their required EDMs, thus transforming client needs to actual elements having defined design maturity levels. The Flow is highlighted as a flow of model elements; planned and controlled by the the DFL method, and the value aspect is targeted by the CI variable embedded in the EDM.

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MAPPING WASTE IN THE STRUCTURAL DESIGN PROCESS IN SOUTH AFRICAN PROJECTS

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Abstract: Non-Value Adding Activities That Are Otherwise Called 'Waste' In The Lean Terms Have Continue To Hinder Efficient Project Delivery In The Construction Industry. As Such, The Types Of Waste And Their Impact Are Subject Of Many Studies. However, Much Have Not Been Done Regarding Waste In The Structural Design Process (Sdp). This Paper Reports On An On-Going Action Research Study On Waste In The Sdp. To Understand The Waste Types And Their Effects, The Lean Tool, Value Stream Mapping (Vsm), Has Been Deployed In The Doctoral Study. To Make Use Of The Tool For Sdp, A Purposively Selected Sample Of Consulting Structural Engineers, Practicing In Bloemfontein Were Interviewed In 2015. After That, A Vsm Depicting The Current State Of The Sdp And The Waste In The Process Was Compiled. The Vsm Tool Was Used To Analyze And Design The Flow Of Information. Major Waste Types Include Waiting Time, Excessive Motion, Excessive Production, And Excessive Inspection. The Eradication Of These Waste Influenced The Design Of A Proposed Future State Vsm Wherein All The Identified Problems Are Adequately Addressed. The Applicability And Usefulness Of The Vsm As It Enables Structural Designers To Perceive The Various Activities That Could Be Trimmed In Each Phase Of The Sdp Is Supported By The Results Of The Study, Although The Credibility Of The Future State Vsm Is Currently Being Examined By The Consulting Engineers.

Keywords: Construction, Design, Value Stream Mapping, Waste

1 INTRODUCTION

Non-value adding activities (NVAA) in projects are the unnecessary work done/activities and material loss in an undertaken. Such activities include waiting time, quality costs, lack of safety, rework, unnecessary transportation trips, long distances, improper management procedures, and poor constructability (Koskela 1992). The literature shows that most of the activities (waste) experienced in the construction phase (CP) of a project are due to the problems that are not discovered in the design phase (DP). To overcome this dilemma, Ko and Chung (2014) propose the use of lean concepts and a tool known as value stream mapping (VSM) in the DP of projects. It is essential to know that the idea of lean concepts (thinking) originates from production process, and can be viewed as a systemic method for the elimination of waste (Muda) within a

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manufacturing process (Womack and Jones, 2003). Womack and Jones (2003) reveal that lean thinking are based on five main principles to guide management's actions toward success. These principles include: precisely specify value regarding a particular product; identify the value stream for each product; make value flow without interruptions; let the customers pull value from the producers, and pursue perfection.

In the lean construction literature, VSM has been described as a lean tool, and a particular type of flow chart that uses symbols known as 'language of Lean' to depict and improve the flow of inventory/information (Rother and Shook 2009). VSM is much more useful as a tool, and layout diagrams that produces a tally of non-values adding steps, lead time (LT), distance traveled, and the amount of inventory in a process (Rother and Shook 2009). According to Rother and Shook (1999), one biggest problem of VSM is the inability of an investigator to adequately understand how it future state should appear when applied to a process. This makes perfection in VSM system to be solely depends on the skill of the user. Based on this dilemma, Rother and Shook (1999) suggest that a VSM team should be led by someone that can see across the boundaries over which a product's value stream flows and make change happen in the boundaries.

Based on the opinions of Rother and Shook (1999; 2009) on VSM, attempts have been made by researchers to investigate how the tool can be espoused for waste identification in projects (Alvarez et al. 2009; Goransson, 2012). However, the findings in the reviewed literature shows that the DP of projects is not adequately covered. Ko and Chung (2014) have adopted the strategy for waste identification and reduction in the construction design process (CDP), specifically in the architectural process (AP). Ko and Chung (2014) in their study show that AP is by nature a multidisciplinary effort that requires the consideration of many aspects, such as structural composition, water drainage, and many more. Premised on this contention, it can be assumed that the analytical frameworks devised by the researchers for waste elimination in the CDP may be generalized to other aspects of project design. However, the desire of the structural design team (SDT) to produce a structure that is capable of resisting all imposed load without failure during its expected lifetime necessitates that structural design be explicitly distinguished from the AP. Hence, further studies are required to expand on the existing theories and knowledge in other aspects of the CDP such as the structural design process (SDP).

2 METHODOLOGY

This research aims to identify the various waste that are significant to the SDP in the South African context. To achieve this goal, an action research design explained by Stringer (2014) was conducted in 2015. The study was carried out with groups of consulting engineers in five different firms located in Bloemfontein. The selection of the companies was based on purposive sampling techniques (Ritchie and Lewis 2003). That is, companies that have designers with extensive work experience in the SDP, and are affiliated with Consulting Engineers South Africa (CESA), were chosen. To be precise, five designers (a combination of both senior and junior engineers) and a technologist that have been working together as a team for not less than five years across the various design projects (residential, commercial and industrial) were selected in each firm for data collection. It is essential to note that focus interviews served as the main technique for data collection in the study in all the five firms. The focus interviews were used to understand the current flow of activities in the inception design phase (IDP), the predesign phase (PDP), and the detailed design phase (DDP) of the SDP. After that, VSM

proposed by Rother and Shook (2009) was depicted on the flow of the activities by the researchers to identify the various NVAA in the practice.

After the depiction of the VSM exercise, another focus interviews were conducted in each firm. The essence of the second round of the interviews was to enable the researcher and the participants in all the groups to observe clearly the various waste in each phase of the SDP and to propose for different strategies that can be adopted to eliminate the identified waste. For consistency, the focus interviews in each step of the study (diagnosing/action planning) were conducted thrice in each firm. Each focus interview in all the firms was between 60 to 80 minutes in duration. All the focus interviews discussions in each firm were recorded and transcribed (Arksey and Knight 1999). After transcription, the resultant information was analyzed using content analysis method (Krippendorff 2012). The resulting information from the interpreted data (themes) were validated using follow-up interviews, which were conducted by the researchers with the head (the chief engineer) of each group of respondents in all the studied firms.

3 RESULTANT DATA AND DISCUSSION

Non-value Adding Activities in Structural Design Process

In the study conducted, it was discovered that the current flow of activities in the IDP, the PDP and the DDP of the SDP appeared impeccable to the SDT but after the adoption of VSM, the teams in all the groups realized that several NVAA (waste) such as excessive meetings, delay to establish contract agreement between the client and the SDT, several soil test, waiting for the site report, poor site report, ambiguities in the architectural drawings, design variations/modifications, several structural calculations, wrong structural computations, excessive vigilance, and several paperwork are prevalent in the practice. These waste are clearly marked out with a VSM symbol known as kaizen burst (Figures 1 and 2). For adequate understanding, details of the waste in the PDP and the DDP are alphabetically represented in Table 1. While Table 2 presents the details of the various indispensable activities that constitute the waste in each phase. For the same reason, Table 3 provides the VSM predefined icons that are used in the two figures.

It is pertinent to know that after the depiction of the VSM tool to the various indispensable activities in each phase of the SDP, the researchers and the study participants discovered that some of the activities also required to be ameliorated. These activities are also clearly marked out with the kaizen burst in the two figures. It should be noted that all the LT and the actual process time (PT) shown in the two figures in this study were obtained from the participants in all the groups based on their experiences in the previous executed projects (residential, commercial and industrial). Hence, the LT and PT are premised to the design of any highly challenging commercial or industrial buildings such as high-rise or multi-storey structures.

Table 1: Waste in the structural design process


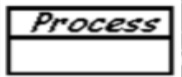


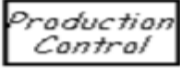
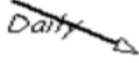

PDP	DDP
Excessive meetings among the project actors (A); several changes/corrections on the project (B); clarification of information on the architectural drawings (C);	Several consultant meetings (A); design corrections (B); redesign(C); delay in the selection of the suitable structural elements computed in the

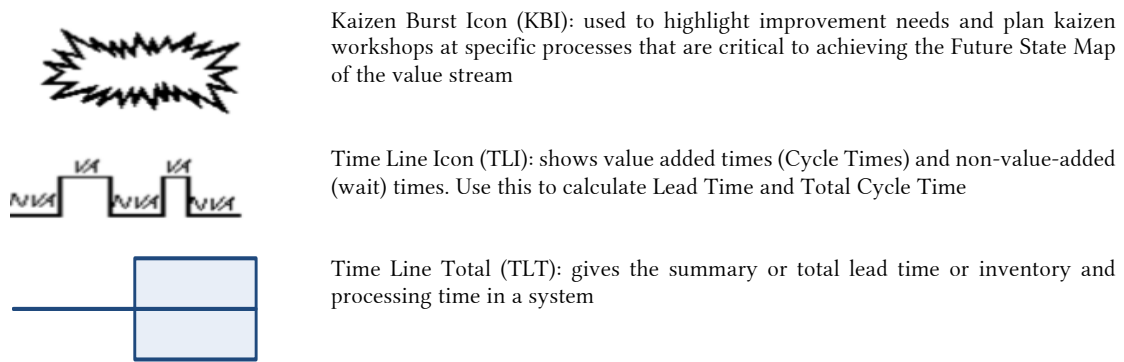
disagreements between the architect and the SDP on the critical aspects of the project (D); waiting for the modified drawings (Architectural drawings) (E); delay to establish and incorporate the necessary building requirements/codes into the project (F); several design computations (G); unnecessary mistakes/errors during the computations (H); several corrections by the senior designers during the computations exercise (I); further clarify areas that are needed to be corrected or improved (paperwork) (J), and Waiting for preliminary design documents (K)	PDP (D); delay to incorporate the observed comments into the project as earlier scheduled (E); delay to include other consultants' requirements into the project as earlier scheduled (F); several printing of the draft drawings (G); waiting for the approval of the final drawings (H); unnecessary copies of the final designs (I); delay in the production of the construction drawings (J), and slow to establish detailed design documents (K)
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Table 2: Indispensable activities in the structural design process

PDP	DDP
Attend the design and the consultant meetings (PDP-1); review the architectural drawings in details (PDP-2); modification of the architectural drawings (PDP-3); establish regulatory authorities requirements/necessary building codes and incorporate them into the drawings (PDP-4); establish structural predesign criteria (PDP-5); refine the predesign criteria to ensure conformance with all regulatory requirements /building codes and consents (PDP-6); compute the general layout, preliminary sizing and stability of the proposed structural elements of the project (PDP-7); prepare the preliminary process designs and related documents suitable for costing (PDP-8); review the overall work for approval to the next phase (PDP-9); establish initial design documents (PDP-10).	Attend consultants meetings (DDP-1); review the predesign documentation plans with other consultants that may be involved (DDP-2); select the most suitable proportions, dimensions and connections of structural elements computed in the predesign phase (DDP-3); incorporate the necessary corrections, comments and observations in the predesign phase into the work (DDP-4); incorporate other consultants designs and requirements into the work (if any) (DDP-5); prepare the design development drawings including draft technical details/specifications (DDP-6); review of the developed final drawings (DDP-7); approve the final drawings (DDP-8); produce the construction drawings (DDP-9), and establish the detailed design documents (DDP-10).

Table 3: The predefined icons for the value stream mapping process

Symbols	Description
	Customer/Supplier Icon (C/SI): represents the Supplier when in the upper left, customer when in the upper right, the usual end point for material
	Dedicated Process Flow Icon (DPFI): a process, operation, machine or department, through which material flows. It represents one department with a continuous, internal fixed flow
	Inventory Icons (II): show inventory between two processes
	Push Arrow Icon (PAI): represents the 'pushing' of material from one process to the next process
	Production Control Icon (PCI): This box represents a central production scheduling or control department, person or operation
	Manual Info Icon (MI): A straight, thin arrow shows general flow of information from memos, reports, or conversation. Frequency and other notes may be relevant
	Electronic Info Icon (EII): This wiggly arrow represents electronic flow such as electronic data interchange (EDI), the Internet, Intranets, LANs (local area network), WANs (wide area network). You may indicate the frequency of information/data interchange, the type of media used ex. Fax, phone, etc. and the type of data exchanged



(Adapted from Rother and Shook, 2009)

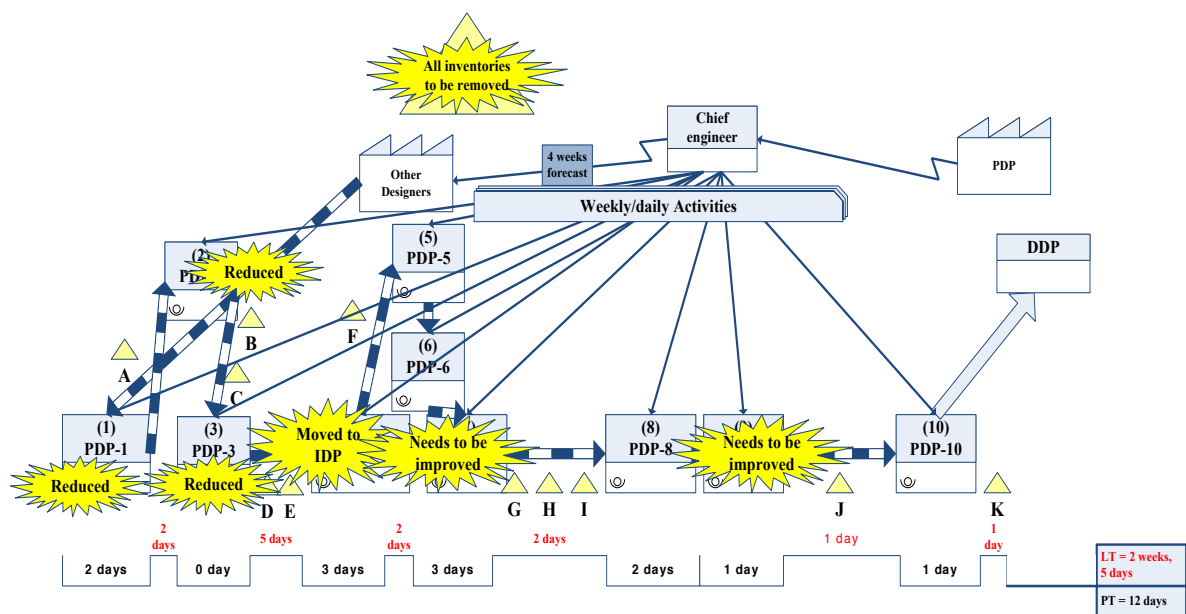


Figure 1: The current state value stream mapping in the predesign process

4 STRATEGIES THAT CAN BE ADOPTED TO REDUCE THE IDENTIFIED WASTE

Several strategies that can be adopted to reduce the identified waste in the SDP were proposed by the participants in the study. Among these strategies is adequate involvement of the SDT in the AP. The participants emphasized that the process will enable the two parties (the architect and the SDT) to detect and rectify most of the problems encountered in the SDP, and come up with an appropriate architectural drawings (AAD). Hence, activities such as several meetings and disagreements between the architect and the SDT, delay to establish contract agreement between the client and the SDT, several review of the architectural drawings, modifications of architectural drawings, and excessive waiting during the amendment exercise can be eliminated in the process. This is in agreement with the views of Forbes and Ahmed (2011), Eastman et al. (2011) regarding the application of information and communication technology platforms for waste identification and reduction in the design and the construction phases of projects.

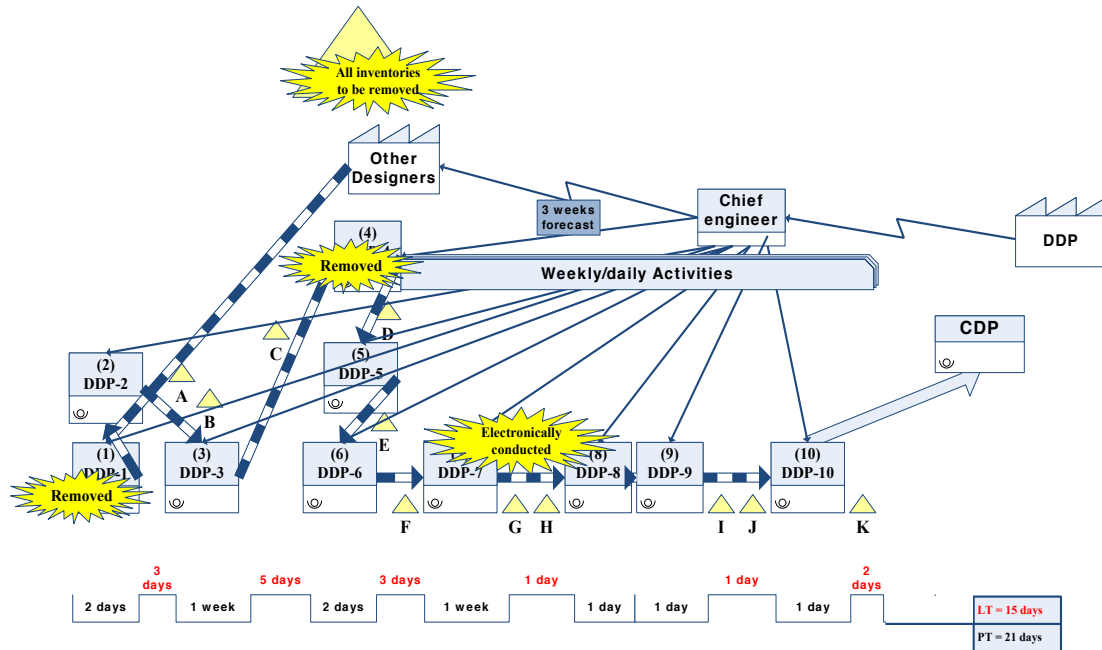


Figure 2: The current state value stream mapping in the detailed design process.

The participants further stated that the strategy will also enable the structural designers to perform some of the IDP and the PDP activities during the AP. This means that requisite activities such as attend project initiation meetings so as to implement contract agreement between the client and the designers, review of the architectural drawings, defining the services/scope of the project, give favourable advice in term of the project life cycle costs, schedule and inspect on the necessary land topographical survey/soil tests, and oversee the compilation process of site reports in the current IDP and PDP can be conducted earlier. While activities such as establish the necessary regulatory requirements/building codes and incorporate them into the project in the PDP (PDP-4) can also be performed during the AP process. Therefore, the proposed concept will not only lead to AAD, but will also avail the SDT the opportunity to reduce several waste in the IDP and the PDP of the SDP. Such waste includes excessive meetings between the architect and the SDT, waiting for site report and all other forms of delays experienced in the two phases which includes lateness to define the services/the scope of the project, give favourable advice in term of the project life cycle costs, and delay to establish the inception and the predesign documents.

Some of the participants in all the groups further stressed that structural designers should ensure that vague assumptions are reasonable and minimal during the geotechnical investigation of the proposed site, and experienced designers such as senior engineers should be adequately involved in the computation aspect of the SDP, rather than to assume responsibility for supervisions only. The participants emphasized that the above-stated opinions will enable the SDT to timely detect and rectify most of the structural computation errors/wrong computations that are being experienced in the PDP, which will consequently reduce the rate of mistakes in the DDP of the SDP. This means that waste such as several corrections/redesign, several supervisions, excessive paperwork, delay to prepare the design development drawings/specifications, lateness

in the completion of tasks as scheduled, waiting for the approval of final drawings from the senior/the chief engineer of the firm, delay to produce the construction drawings, and establish the detailed design documents, in the DDP of the SDP can be reduced or eliminated.

Based on the opinions of the participants in all the groups, the actuality/practicality of the expected (proposed) future state VSM in the IDP, the PDP and the DDP are currently being examined by the consulting engineers in the study context.

5 CONCLUSIONS

Based on the study conducted, it can be concluded that NVAA or waste exist in every phase of the SDP. The NVAA can be identified through the application of a lean tool known as VSM. The waste that can be identified in the PDP of the SDP through the application of the tool are several disagreements between the architect and the SDT; several unclear information in the architectural drawings; excessive meetings between the architect and the SDT; design modifications in architectural drawings during SDP; excessive waiting due to the modification of the architectural drawings; incorrect information in structural computations/wrong computations or computation errors; excessive printing of paperwork; excessive supervision of design activities by the chief engineer, and delay to establish the preliminary design documents by the project actors. These discoveries are also consistent with the findings of Mossman (2009) and Nagapan et al. (2012) regarding some of the waste in projects.

While in the DDP of the SDP, typical examples of the waste that can be identified with the adoption of VSM are design corrections/redesign; excessive printing of draft/paperwork; lateness in the completion of a task as scheduled; waiting for the approval of final drawings from the senior/the chief engineer of the firm; delay to select the suitable structural elements computed in the PDP; delay to incorporate other consulting engineers requirements into the project; delay to prepare the design development drawings/specifications, delay to produce the construction drawings/establish the detailed design documents, and several copies of the final drawings. These results are similar to the findings of Simms (2007) and Gatlin (2013) concerning some of the waste in engineering design. This study recommends that VSM and the five lean principles should be adopted by the SDT for waste identification and reduction during SDP. However, it has been observed in the literature that the proficiency of the future state VSM depends on the skill of the operators. Therefore, for proficient and well-organized future state VSM in the IDP, the PDP and the DDP, a more compressive VSM software that is independent of the skill or ability of the operators should be investigated or developed by future researchers.

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WAITING TIMES IN DESIGN PROCESS: A CASE STUDY

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Abstract: This research focuses on identifying waiting time in design process. This comprised the application of value stream mapping to identify existing flows and design waiting times. From this diagnosis, it was possible to propose recommendations reducing identified waste of time. This study demonstrates the viability of using the value stream mapping and to improve architectural designs process.

Keywords: Design process, Lean design, wait.

1 INTRODUCTION

Poor design management has been identified as an important factor in reducing the construction industry overall performance and efficiency (Love & Edwards 2004). Poor communication, lack of adequate documentation, lack of information input, unbalanced allocation of resources, lack of coordination between disciplines, and irregular decision-making are examples of problems associated with design, for long identified in literature (Koskela et al. 1997).

In order to reduce the problems aforementioned, studies have identified that integration between design and construction processes has become a requirement to improve construction performance. Also, lean design has been described as having potential to better integrate design and construction activities (Jørgensen & Emmitt 2009).

Lean Design deals with managing the design process complexities, aiming to reduce waste and leverage activities that add value (Rischnoller et al. 2006). Lean Design also incorporates new ways of visualizing design process and this increases understanding of how it works (Freire & Alarcón 2002). This is due to understanding of design from three perspectives: conversion, flow and value generation (Tzortzopoulos & Formoso 1999). Given this context, the question that guided this work is: How can architectural design processes be diagnosed in order to become leaner? The objective of this research is to diagnose architectural design processes, taking into account lean design perspective.

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2 LITERATURE REVIEW

2.1 Architectural Design Process

This work focuses on design process from a managerial perspective, and it does not include an approach based on the creative process.

The Royal Institute of British Architects (RIBA) promotes its RIBA Plan of Work: an important work reference and guide for better practices for buildings project and construction processes (RIBA 2013). In Brazilian context, many researchers have proposed process models to support architectural design management. Brazilian Association of Architecture Offices (AsBEA) promotes stages and sequencing proposed by Cambiaghi and Amá (2006). These activities are described in Table 1.

Table 1 - Activities performed in order to generate Architecture Design.

Activity	Descriptions	Output
Product Conception	Conception and feasibility analysis	Preliminary Study
Product Definition	Preliminary architectural solution	Legal Design
Interface Coordination	Coordination of all designs	Basic Design
Detailing	Final Solution and Constructive Detailing.	Executive Design

2.2 Improvement methodology

The introduction of lean manufacturing concepts in construction sector focuses on alleviating design and construction problems and on propagating decisions and actions efficiency (Emuze & Saurin 2016).

Lean design is a paradigm by which design process can be done more efficiently and achieving better quality results (Tilley 2005). Lean Design promotes different points of view to model, analyse and understand design process that, under this paradigm, is considered as a group of three distinct models: conversion, flow and value generation (Freire & Alarcón 2002; Tzortzopoulos & Formoso 1999). A set of Lean Design practices improved the design process as they minimized waste and maximized efficiency (Lee et al. 2010).

Reducing errors, cycle times, and part of activities without adding value, thus increasing productivity are aims of an improvement methodology proposed by Freire And Alarcón (2002) with following steps: (1) diagnosis and evaluation; (2) Changes implementation; (3) Control; (4) Standardization.

Ko e Chung (2014) analysed design processes in order to make it lean. A new stream was proposed to improve workflow, reduce errors, increase design reliability as design team members receive feedback on each design step performed allowing continuous improvement (Ko & Chung 2014).

2.3 Value Stream Map (VSM)

VSM comprises action mapping to bring a product from raw material to customer (Rother & Shook 2003). This is a qualitative Lean technique used to analyse and design the flow of materials and information needed to deliver a product, service or design to a consumer.

VSM focuses on analysing processes time and flow, from the beginning to the end of product development. Drawing current state map by collecting data in the workplace is the first VSM step. The map of the current state will serve as a baseline for drawing a future state map, that should contain ideas and recommendations aimed at improving undesirable situations identified in the current state (O'Connor & Swain 2013). The final step is to write an implementation plan that describes how to achieve such future state. VSM clearly identifies the real production process situation, indicating the main information flow and time demanded by each activity.

3 METHOD

In qualitative methodology adopted facts are observed and described without allowing theoretical preconceptions to alter their nature and importance, besides requiring the study of essential structures connections and relations with the outside (Gil 2008).

In this study, an ex post-facto research is carried out, an investigation in which the manifestation of the variables studied has already occurred and, therefore, is not manipulable (Gil 2008). The research strategy herein was a single case study (Yin 2011).

The case study company has nearly thirty years of experience in architectural design and operates in residential, commercial and public buildings market. The project analysed is a residential building with 46 apartments distributed in twenty-three floors, containing two basements, a ground floor garage, and ballroom and leisure area. The design area corresponds to just a little more than 8.690 m². The project will be built in Fortaleza – Ceará, Northeast of Brazil. The company's sum of characteristics gave basis to the study and the project, to which the studied design refers, evidences that this is a typical case in this context. Thus, the single case study is justified because it is a typical case with commonplace situation of a design firm acting for the real estate market and the lessons learned here are considered informative for many other companies (Yin 2013).

Data collection was carried out through four structured interviews. The participants interviewed were professionals who worked on case study project in the following positions: Architect Director, Architect Coordinator, Architect Collaborator and Architecture trainee. The interview script used was composed of five groups of questions designed to: (1) record participants' profiles; (2) map the value stream; (3) capture the participants' perception regarding time distribution; (4) identify performance indicators; (5) identify waste and opportunities for improvement. Data collection also included documents examining of digital folders and digital design files located in computer servers of the case study company.

The analytical procedures are of qualitative nature, and content analysis was used to analyse the interview data.

The case study protocol designed for this work (figure 1) adopts lean construction tools promoted by the book "Implementing lean in construction: Lean tools and techniques - an introduction" (O'Connor & Swain 2013). Case study protocol is a particularly effective way of dealing with the problem and increase the case studies reliability (Yin 2013).

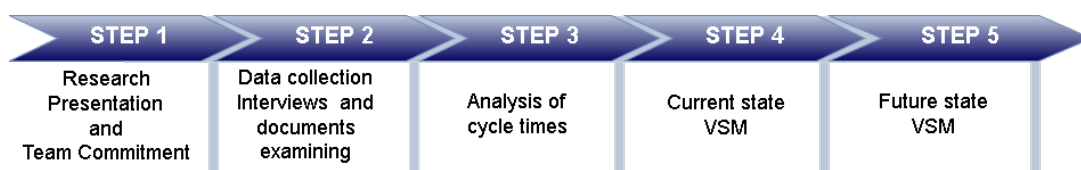


Figure 1 – Case study protocol

In step 1, a research presentation was made to the company's Director in order to obtain authorization and commitment from the design team with this research.

In step 2, interviews were conducted with professionals who participated directly in developing design chosen as the case study object. Subsequently, documents examining were conducted in virtual folder containing all design information documents. No copies of files were made because they were confidential information. The researcher had access to the documents to examine them inside the company through visits in office. While in workplace, it was possible to analyse, identify the content, and release date of design documents. The variables that were being evaluated were dates associated with stage of design process which document was related to. Documents examining based the analysis of cycle time. The documentary evidence examined was present in the folder of files loaded or downloaded from the Construmanager⁶. The use of the Construmanager platform by designers left an audit trail for researcher to trace author, action, date and time, of each document, eliminating the existence of different interpretations of "what happened." All the designers' interaction occurred by sharing online design versions in the Construmanager, and this enabled the interactive loops to be incorporated into the data collection. In this work, cycle time is understood as time required to produce a part or complete a process (Shook & Marchwinski 2014). However, an adaptation was made in the method as the cycle time is calculated. This is justified because it was not possible to calculate the cycle time making a 'real time measurement', since the facts analysed had already occurred. Thus, the sum of days elapsed from documents related to each activity is considered in this work as the activity cycle time activity.

In step 3, it was possible to construct a timeline and calculate the elapsed time between each document with DATES of each design information elaborated by designers. It was possible to perform waiting time identification and visualization of improvement opportunities.

In step 4, the current state VSM was design based on data collected in interviews with participants and on documents examining. Current state VSM shows the real process situation, especially indicating time demanded by each activity and between them.

In step 5, the future state VSM was proposed containing ideas and recommendations aimed at improving undesirable situations identified in current state. This collected and structured information was presented in a new interview with each company participating in research allowing results validation and especially of wastes and proposed improvement opportunities.

4 RESULTS

4.1.1 Analysis of cycle times

Cycle time analysis demonstrates that Interface Coordination and Detailing are activities with the longest cycle time and exceed the average time (figure 2). It also demonstrates a large amount of waiting time between activities product Conception and Definition.

Product Conception and Product Definition activities have cycle times lower than average time of process activities, but excessive waiting time between them was excessive being almost twice the average of productive activities. Two different types of waiting

⁶ Construmanager is an online platform for design and construction management in the architecture, engineering and construction sector. It is a solution to have all designs and documents in one place, connect and integrate people and ensure that everyone is always with the latest version of each document.

time were identified: (1) external wait, which occurs when Architects wait for information from other designers e.g. structure and / or MEP; (2) internal wait that occurs when Architects stop working it to complete activities from a different project (work prioritisation within the architectural firm). Long internal waitings such as those from 4 or 13 weeks should be avoided.

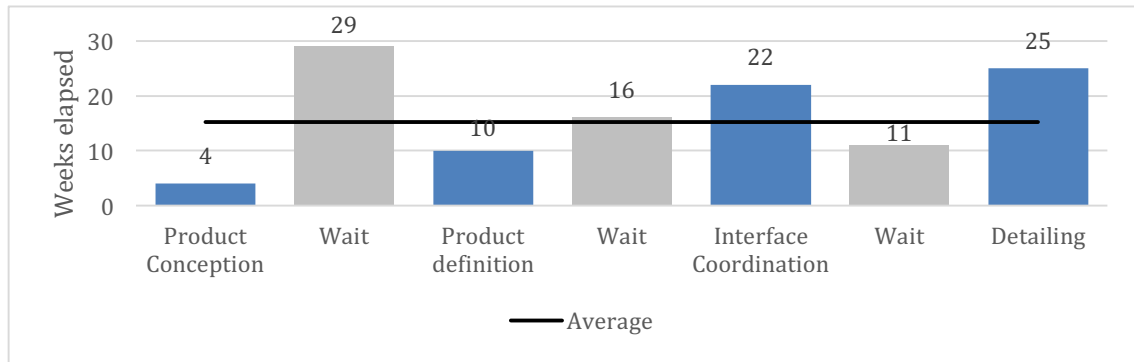


Figure 2 – Distribution of cycle times between design disciplines

4.2 Current state VSM

The current state value stream map, shown in figure 3, identifies sequencing activities of architectural process and its interactions with different designs. Out of the total of 124 weeks of design process, 78 weeks were in architectural design and 46 weeks were in external wait, when the project waited for structure and MEP designers.

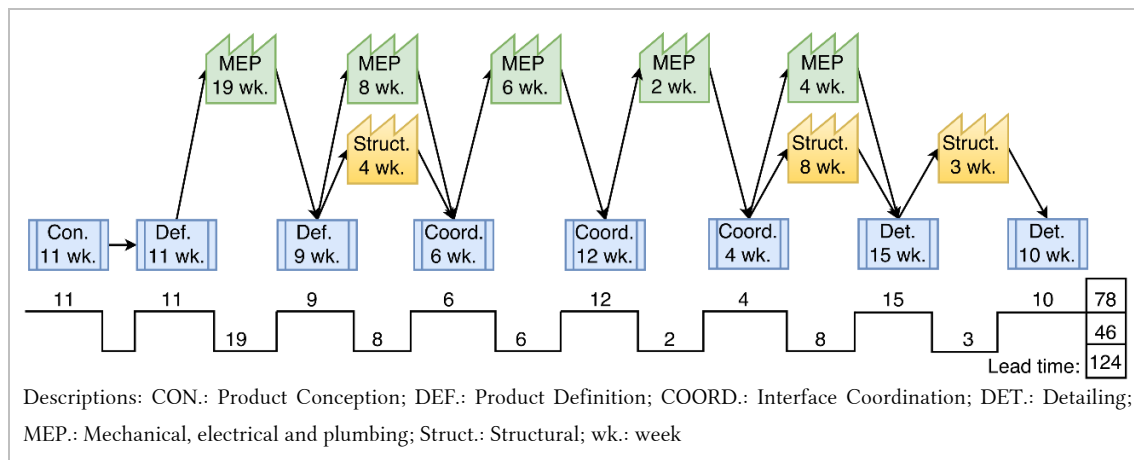


Figure 3 – Current state Value Stream Map of architectural design process

As seen in VSM shown in Figure 3, value flow follows from design conception to definition without any interaction with other designers. Therefore, an initial effort is made to Product Conception. At the end of the Product Conception and after client's approval, the design receives an effort from the Product Definition, and then only after these two steps the architectural design was sent to MEP and structure designers.

Product Definition occurs in two cycles because an interaction is performed with MEP designer. Product Definition is reviewed based on information from this interaction. At this moment, architectural design is sent simultaneously to structure and MEP. There is an interesting relationship with these designs because it allows flow in parallel. The first Interface Coordination is carried out after receipt of structure and MEP designs. Then, two exchanges information cycles are carried out with MEP designer. Again, design is sent

simultaneously to structure and MEP with modification requests for design compatibility. Then, architectural design goes into Detailing, but an information exchange is needed with structural designer due to omission of some structural information.

In activities of Product Definition, Interface Coordination and Detailing, it was verified that part of cycle time referred to time of value added in development of design and part of time referred to internal waitings that did not have an adequate management and became excessively long.

4.3 Future state VSM

Following an analysis of current state VSM there was a clear indication that benefits could be achieved by proposing a future state value map focusing on reducing waiting times, shown in figure 4.

The proposed changes focus essentially on four aspects summarized below: (1) Elaboration of structure and MEP requirements to be used as input to Product Definition stage; (2) Establish a limit of two weeks for internal waits so that architecture office return to work on the design that is in internal wait ; (3) Standardize the sending of architectural design simultaneously to the structure and MEP companies; (4) Interface Coordination made with structure, MEP and architecture designs simultaneously in order to reduce number of process steps.

The new flow makes it possible to reduce process time from 124 to 66 weeks, which is equivalent to a reduction of 47%. Note that steps of structure and MEP designs were not eliminated, but their cycle time was put in parallel because of the sending of architectural design simultaneously to the companies of structure and MEP. As a result, external waiting time is reduced from 46 to 27 weeks, which is equivalent to a reduction of 41%.

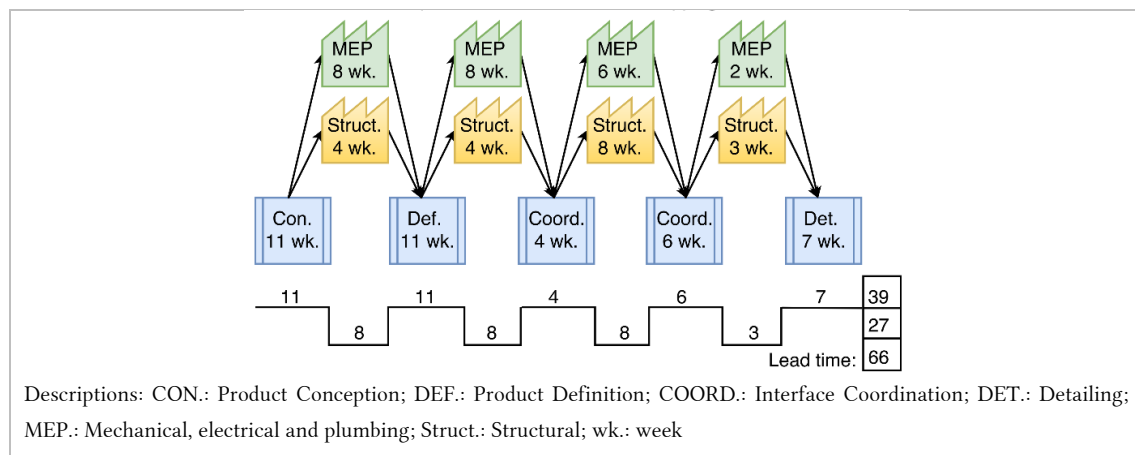


Figure 4 – Proposed Future Value Stream Mapping for architectural design process

5 CONCLUSIONS

This work illustrated the design process complexity through structuring and identification of waiting time in design process of an architectural company case study.

It was demonstrated through study that mapping and analysing value stream are viable tools for improving architectural design process. Designers can get improvements by applying these tools to their design processes. The data collected in case study illustrate that 50% of time of architectural design process is time without value aggregation and directly impact total time.

The main contributions of this work was the waiting times exposure in design process, proposing improvement opportunities for companies based on real problems identified, and structuring of methodology for application of lean diagnostic tools in context of architectural design offices.

Finally, a research restriction is that proposed modifications have not been implemented in design companies. However, the findings from this case study provide important insights that allow recommendations to be made for future successful implementations.

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A TAXONOMY OF CLIENT PRODUCT VALUE IN CONSTRUCTION PROJECTS

Frode Drevland¹ and Ole Jonny Klakegg²

Abstract: The goal of construction projects is to deliver value for the customers. In this paper, we look at what is valuable to one of those, the paying client.

Classification schemes, such as taxonomies and typologies, are in many fields used to better understand the terrain in which one is operating. We argue that having such a scheme for the client value in construction projects would be beneficial for better understanding what is valuable for the client. In this paper, we present one that has been made using abductive reasoning based on a scoping study of relevant literature.

The paper starts out by presenting different kinds of classification schemes and their characteristics. Then, a set of guiding principles for value classification schemes are introduced, followed by a critique of existing classification schemes considering these. Afterwards, a taxonomy of client value is presented with the reasons for the chosen breakdown structure. Finally, the goodness and completeness of the taxonomy is discussed.

Keywords: Lean construction, Value, value taxonomy.

1 INTRODUCTION

The goal of construction projects is to deliver value for the customers. While construction projects can be said to have many customers (Drevland and Lohne 2015), we will in this paper limit ourselves to considering value for the paying clients and what is valuable for them. However, to be able to consider what is valuable, we first need a clear notion of the concept of value.

As a concept, value is ill-defined (Salvatierra-Garrido et al. 2012) without any commonly agreed upon definition (Thyssen et al. 2010). The most common definition of value in the general literature pertaining to construction projects, is that it is the relationship between what you give and what you get (Kelly et al. 2004). However, within the Lean Construction community there is a clear tendency to use the term value referring only to the get, or benefit, side (Drevland and Lohne 2015). In this paper, our understanding of value is in accordance with Drevland and Lohne (2015). They give a comprehensive, but rather lengthy definition of value, however, the essence of it can be said to be that value is the result of an evaluative judgment of what you get and what you give.

Based on the above we will postulate that delivering value to the client in a construction project is about arriving at an optimal balance of what they get and what they give. Value is particular (Drevland and Lohne 2015), i.e. it must always be considered from the point of view of someone. This being the case entails that different clients with

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different purposes will have different things that they care about regarding what is important to them and how they weight different get and give aspects. However, there are some commonalities, e.g. construction cost will always be an issue.

Classification schemes, such as taxonomies and typologies, are in many fields used to better understand the terrain in which one is operating. We would argue that having such as scheme for the get and give factors that come into play for the clients' value judgement in construction projects would be beneficial. Partially, to further general understanding of value for both practitioners and clients, but also to serve as a foundation for developing tools for optimizing value delivery as well as for analysing current practice.

Although there does already exists some classification schemes like this, we have found them to fall short in one way or the other. In this paper we therefore set out to develop a taxonomy of client value that can serve this purpose, i.e. to create a generic classification scheme for the get and give factors that are important to client of construction projects. However, we set out to do this with some limitations.

With regard to building types, buildings broadly fall into two categories; residences and production assets (Blakstad et al. 2008). We believe that there is a great deal of overlap in the get and give factors that are considered for these two categories of buildings. However, to avoid making the discussion overly complex we initially limit ourselves to consider buildings that will be employed as production assets. Thus, our goal in this paper is to succinctly present a taxonomy of value from the point of view of clients of *non-residential* buildings. Furthermore, we also limit ourselves initially to consider clients that are building for their own use. This is again done to avoid making the explanations and discussions overly complex.

Regarding factors, we limit ourselves to considering those factors that are directly influenced by the construction project and that are tied to the product delivered. I.e. some of the get and give factors in a construction project will be tied to the process rather than the product, e.g. clients cost of staffing for managing the process, and some of the get and give consequences will be outside of the scope of the building projects, e.g. the loss of other investments opportunities. Furthermore, we do not explicitly include factors that are related to financing and taxation of the built asset, even though they might be directly influenced by the project.

2 TAXONOMIES, TYPOLOGIES AND CLASSIFICATIONS

There are several differing definitions of the terms typology and taxonomy. In his seminal work on taxonomies and typologies in the social sciences, Baily (1994) claims typology and taxonomy are used interchangeably by many people. Baily himself defines typology as being classification based on concepts while taxonomy is based on empirical data. However, these definitions do not correspond well with the different value classification schemes we have found in literature. We found definitions by Marradi (1990) to be more in accordance with these.

Classification can be said to be about ordering entities into groups or classes based on their properties (Bailey 1994). According to Marradi (1990), the difference between the types of classification scheme the lies in how this grouping is done. An adapted version of Marradi's definition is shown in Table 1.

Table 1: Classification types. (Based on Marradi 1990)

Classification type	Criteria use	Structure
Simple classification	Only one	Flat
Typology	Multiple simultaneously	Multi-dimensional matrix
Taxology	Multiple in succession	Hierarchical

3 METHOD

The problem of creating a classification scheme has been attacked using a pragmatic research approach. Within the pragmatic paradigm “*inquiry aims at utility for us rather than an accurate account of how things are in themselves*” (Rorty 1999). Thus, we have not tried to develop the one true taxonomy of value in positivistic sense, but rather to create something that is useful for our stated purposes.

To construct the taxonomy we first undertook a scoping study, as described by Arksey and O’Malley (2005), to identify relevant literature. Here, we looked not only for literature specifically discussing value in construction projects, but also for literature from other fields that deals customer value of products.

Based on the intended use of the classification scheme, as well our understanding of value grounded in Drevland and Lohne’s (2015) nine tenets on the nature of value, we set forth four guiding principles (presented in section 5).

Of the possible classification schemes listed in table 1, we considered a taxonomy to be the best model for client value factors in construction projects. The primary reason for this is that taxonomies are more flexible with regards to extensibility. I.e. it’s hierarchical nature means that the factors can always be detailed more if need be.

Based on the identified literature, the selected classification scheme type, and the guiding principles set forth, abductive reasoning was used to arrive at the taxonomy presented in section 6.

4 GUIDING PRINCIPLES FOR CLASSIFICATION STRUCTURE

We would argue that the primary benefit of having a classification of value factors is that it will ease the decision making process in projects by making it easier to understand how decisions impact the value for the client. Decisions that impact client value will tend to involve a trade-off between different get and give factors. It is therefore important that the taxonomy is made in such a way that it facilitates the consideration of trade-offs. To do so we believe that the following principles must be satisfied.

P1 The classification scheme must contain all relevant factors

P2 Factors should be mutually exclusive

P3 The classification scheme must be detailed enough for trade-offs to be considered

According to Drevland and Lohne (2015), “*get and give consequences are always in the form of gained or lost experiences, or expressed in monetary terms as a placeholder for experiences*”. What this in essence means, in the terms of a classification scheme, is that all the get and give factors must be ends in and of themselves. Therefore, a fourth principles is:

P4 Factors must be ends – not means

5 SHORTFALLS OF EXISTING CLASSIFICATION SCHEMES

The literature review identified many sources that consider mapping value in projects through workshop approaches etc. , however, few sources that proposed any kind of generic taxonomy applicable to all construction projects. It is unfortunately not possible to fully describe and critique these classification schemes within the limits of this paper. However, some general observations regarding common shortcoming are in place.

Schemes using the Vitruvian values of *firmitas* (solidity, durability), *utilitas* (utility) and *venustas* (beauty, delight) as a basis (e.g. Construction Industry Council 2002; Emmitt et al. 2005) are flawed per the third principle we set forth. This is expounded further upon in the discussion section of this paper (see also Drevland and Svalestuen 2013).

Another issue relates to not being sufficiently detailed. Examples of these are Drevland and Svalestuen (2013) and Emmitt (2005). However, it should be pointed out that Emmitt does not pretend to present a fully develop generic classification scheme, but rather a starting point for a workshop based value mapping approach.

6 TAXONOMY OF CLIENT PRODUCT VALUE

Figure 1 shows the taxonomy that was developed. The top level division is based on phases of the buildings lifecycle, originally suggested by Drevland and Svalestuen (2013). The rest of this section details each of the levels and categories, below the top level, and the reasoning behind them.

Note that for taxonomies an 'other' category is nominally present at every level. We have chosen to omit this to simplify the taxonomy for this paper. However, for practical use this should be considered. Furthermore, many of the factors included here are typically cost only. However, that might always not be the case. The building operations factors will traditionally be all give or cost related. E.g. the advent of energy-plus-houses could entail building will produce more energy than it uses, thereby energy could become a get rather than a give. For this reason, none of the factors has been labelled as cost or benefit.

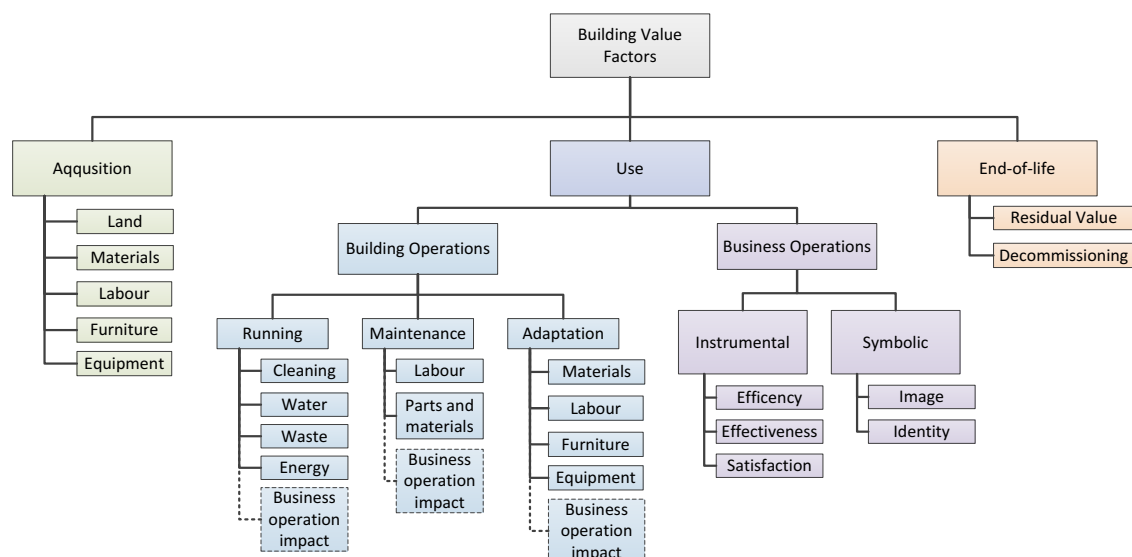


Figure 1 Taxonomy of client value in construction projects

6.1 Acquisition

During the acquisition phase, the building does not normally provide any Get or benefits for the client (Drevland and Svalestuen 2013). The Give side are related to the cost of constructing the building and acquiring the land the land it will stand on and the furniture and equipment that will be in it (Construction Industry Council 2002). Any further detailing if these factors would be dependent on the particularities of the location and the project, and are left at this level.

6.2 Use

The major distinction to be made in the use phase are the between factors pertaining to building operations and business operations. Building operations factors are related to the operation and maintenance of the building, while business operations factors are related to the operation of the business that housed by the building.

6.2.1 Business operation

From a business perspective, the purpose of a building is be an enabling infrastructure, to support the business processes of the entities they house (Mahal 2010). In this sense buildings provide both an *Instrumental* and *Symbolic* get (or possibly give) (Eikeland 1998). Instrumental in the sense that building directly supports the production process that take place in the building and symbolic in the sense that the building provides image and identity for the business that occupy the building. *Image* being how the outside world sees the business while *Identity* is how the organization and its employees sees itself.

The instrumental side of this branch is in essence about the fitness for purpose of the building, or usability, which is the term commonly used in the research literature (Blakstad et al. 2008; Leaman et al. 2010). The term originated in the ICT industry and is in ISO 9241-11 defined as the “*extent to which a product can be used by specified users to achieve specific goals with effectiveness, efficient and satisfaction in a specified context of use*” (ISO 1998). Furthermore, effectiveness is the “*accuracy and completeness which users can achieve specified goals*”, efficiency is a measure of the “*resources expended in relation to the accuracy and completeness with which users achieve goals*”, and finally, satisfaction is “*freedom from discomfort, and positive attitudes towards the use of the product*”.

6.2.2 Building operations

On the building operations side, *Running* and *Maintenance* should be pretty self-explanatory. *Adaptation*, on the other hand, warrants some further explanation.

Businesses grow and evolve while technology and society changes. With this a business’s business model and processes changes as well. This will often entail that the building enabling the business processes have to be changed as well. With the exception of the last factor, all the factors are tied to modifying the building so that it will be able to properly support the changed business model and processes.

The last factor found under all three of *Running*, *Maintenance*, and *Adaptation* is *Business operation impact*. Maintenance and adaption of a building, as well as some running activates like cleaning, will to a lesser or greater extent impact the business operations taking place in the building. E.g. a room becomes unusable while it is being worked upon. The *Business operation impact* factors are drawn with dotted lines in the taxonomy. The reason for this is that they strictly speaking overlap with the business operations factors. This discussed more in depth in discussion section of the paper.

6.3 End-of-Life

At some point in time the building will either no longer be able to support the current business model sufficiently, or the owner changes to different business model, and the building becomes obsolete. The building could then hold some *Residual value* for the owner. Either if they reuse the facility themselves for other purposes or by selling it to another party.

Decommissioning refers to all get and give that is incurred by the owner the current activity is ended. E.g. the cost of removing equipment etc. and possibly demolition of the facility if it has no other use. The latter will be substantial if the facility to be demolished for example contains hazardous waste; e.g. demolishing a nuclear power plant will be very expensive due to the requirements imposed on waste and material handling and storage.

7 DISCUSSION

7.1 The issue of time

The biggest challenge in making a taxonomy for value factors for buildings is how to handle the time aspect of value. This is something is that immensely more difficult for buildings than for most other products because of their long lifetime. E.g. compared to building a car. If someone buys a sports car when they are young, they do not try and convert it to a minivan when they grow older, get married, and have kids. They sell their sports car and buy a new minivan. Buildings, however, do get adapted over time as the needs of the owners change.

Most of the get and give of a building comes over time. Thus, each of the factors can be said to be functions of time. This is in and of itself not a problem. At least not if the factors are considered on their own in a static context. E.g. assessing the energy consumption and expenditures of building over its lifetime is relative straight forward, if we assume the same activity for all future.

The challenge comes when we have to consider how the factors correlate with or impact each other. Say we want to reduce the maintenance cost of a building by putting in more durable floor coverings. This affects not only the maintenance factors, but also the acquisition factors. However, since acquisition can basically be considered a single point in time in this context, this is still a very manageable situation. It easy to estimate and adjust the cost of labour and materials for putting the different type of floor covering at the time of construction. On her hand, it is a lot more difficult to assess the impacts to the business operations.

This is the reason why we chosen to put business operation impact factors for each to building operation branches. We believe it is a lot easier to directly estimate the impact than it is to adjust the business operations factors to take into account the impact these activities will have at certain points during the buildings life time. This, however, depends on what kinds of tools are being used. Our mind-set has been that this taxonomy should be useable in conjunction with relatively simple tools like Choosing by Advantages (CBA). Of course, if one where to develop computerized tools backed by algorithms that can abstract away the complexity of these relationships, it would preferable to not have this overlap.

7.2 Goodness of taxonomy

The taxonomy was made using abductive reasoning on the basis of a literature review. While we are reasonably certain that the upper levels of the taxonomy are good and

sensible, it might very well be that the detailing at the lower levels should be tweaked to make the taxonomy more easily usable in practice. This, however, is a question that can only be answered from empirical testing.

Furthermore, we would like to note that our purpose has not been to develop a definite value taxonomy; the end all and be all of what constitutes client value in construction templates. Rather, the taxonomy should rather be considered a starting point or template for developing tools for practical use.

7.3 Completeness of taxonomy

We initially state four principles for the design of the taxonomy. One of which was the taxonomy must contain all relevant factors. We do believe this to be the case. There is however an important caveat to this, the client's values might dictate other factors to be added. Let us consider the case were one of the core values of the client is to preserve planet earth. In this case they might want a green building even though it might be more expensive and yield no positive effect on the business operations factors. In this case the taxonomy should rightfully be expanded to take into account the client's values.

Many of the value classification schemes we came across used the Vitruvian values of *firmitas* (solidity, durability), *utilitas* (utility) and *venustas* (beauty, delight) as a basis. We believe most will recognize that *utilitas* is well covered in the taxonomy, but what about the other two aspects? The problem with including them directly is that they violate the third principle we laid down, that the factors must be and ends in and of itself.

Beauty has no intrinsic value (Drevland and Lohne 2015). The aesthetics of a building is a means to either 1) *Efficiency* – i.e. patients getting well faster in a hospital (Rybkowski 2009), 2) *Satisfaction*, – the business customers and employees become more satisfied in their interactions with the building, 3) *Image* – the outside gets a more favourable image of the business housed by the building, or 4) *Identity* – The building helps foster the desired identity of the organization it houses,

A similar argument can be made for *firmitas*. The reason for making a building more solid and durable is to make it able to support the *Business operations* over longer timespan, i.e. related to the factors being a function of time, and/or to reduce the costs of the *Running* and *Maintenance* of the building.

8 CONCLUSION

We have in this paper presented a taxonomy of client product value that has been developed from a theoretical basis. We believe it can be of help in construction projects by making it easier to understand how decisions impact the value for the client, and could provide a framework for tools used in this context. In this sense, the taxonomy should not be considered a definitive answer, but rather a template to adjusted to serve one's purpose. However, we would argue that the four principles presented in section 5 must always be observed.

With regards to further research, the taxonomy will serve as a part of analytical framework to analyse the value delivery processes in practice in projects. I.e. to answer questions such as to what extent are these factors considered, how is prioritizing between the factors done, how is the project process shaped to achieve an optimal balance?

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VIRTUAL DESIGN AND CONSTRUCTION: ALIGNING BIM AND LEAN IN PRACTICE

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Abstract: The construction industry has experienced many inspiring improvements. Especially two movements have introduced innovative design and construction practices: The advancement of lean thinking and tools and maturity in applying BIM and related concepts and technologies. Although Lean and BIM often thrive in the same culture, have many similar properties and strong potential synergies, they are often considered separate initiatives and unfortunately provide only partial benefits when applied on their own. Based on empirical findings of a general contractor, this paper shows how collaborative lean methods and BIM-related technologies can be implemented in an integrated way in practice.

Keywords: VDC, BIM, Last Planner, ICE, Big Room, metrics

1 INTRODUCTION

The construction industry has for years declined in productivity compared to other industries (Teicholz et al., 2001). One significant factor has been that other industries have proven faster at rethinking processes and applying new technology (Drucker, 2006). However, some improvements are imminent: Lean has emerged as a conceptual approach of optimizing processes, while BIM has rapidly advanced as a transformative information technology, and although conceptually independent, research has found numerous synergies between them (Sack et al., 2010).

As it is sub-optimal to implement potentially efficient technology into poor processes or to support efficient processes by obsolete tools, there is undoubtedly much potential in integrating new technology with efficient work processes. Virtual Design and Construction (VDC), a term defined by the Center for Integrated Facility Engineering (CIFE) at Stanford University, focuses on aligning new technology related to BIM with lean thinking and practices (Kunz and Fischer, 2012; Khanzode et al., 2006).

After years of success with lean and BIM as separate initiatives, several contractors have further benefitted from integrating them in construction projects. The purpose of this paper is to describe how a contractor in Norway has aligned lean practices and BIM technology. The research methods are observations by the lead author, surveys from project participants and two project case studies. Two research questions are posted:

- What are the observed project benefits from effectively combining new ways of collaboration with digital tools?
- What are critical drivers for this change and barriers against it?

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2 THEORY

2.1 Lean and BIM

The term "lean" was introduced by Krafcik (1988) and applied to construction in 1993. Lean Construction is "the application and adaptation of the underlying concepts and principles from the Toyota Production System (TPS) to Construction," (Sacks et al., 2010). Some lean principles are: Understanding value from the client's perspective (including for internal client-supplier relations in production systems and supply chains), reducing waste, improving process stability and transparency, reducing unnecessary buffers and inventory, improving flow with pull-based production, and creating a culture of continuous improvement through employee engagement and the use of metrics and benchmarking (Hines et al., 2011; Sacks et al., 2010; Modig and Åhlström, 2013).

There are several definitions of BIM, and although not conflicting, some refer to BIM as a digital product and others to the process of collaboratively making and utilizing it. BIM is a "digital representation of the physical and functional characteristics of a facility" (Smith, 2007), but also "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," (Eastman et al., 2008). Stagg (2012) defines BIM as "a method to describe the project and its spaces, structures, components and materials with their essential information and properties."

Although not dependent on one another (lean practices can be adopted without BIM and BIM can be adopted without lean practices), several researchers claim that notable benefits can be achieved by implementing lean practices and BIM functionality together (Bhatla and Leite, 2010; Khanzode et al., 2006; Khan & Tzortzopoulos, 2014). By identifying 56 interactions between lean principles and BIM functionality, Sacks et al. (2010) support the hypothesis that the full potential of BIM and lean can only be achieved when their adoption is integrated, and the paper also addresses the need for "a framework that juxtapositions BIM functionalities with lean principles."

2.2 Virtual Design and Construction

VDC can be characterized as an approach of rethinking work processes and organization in construction projects, while supporting these changes by innovative use of new technology. Khanzode et al. (2006) found interactions between VDC and the Lean Project Delivery System, stating that a key benefit is to "simulate the complexities of the construction project delivery, to understand the pitfalls the project teams are likely to encounter, to analyze these pitfalls and address them in a virtual world before any of the construction work ever takes place in the real world." For instance, 4D-scheduling, which merges a project's BIM and schedule, allows for virtual construction ahead of actual construction, which can reveal issues regarding workflow, safety, logistics, etc.

Fundamentally, a project team cannot produce great results without trustworthy information and reliable workflows. BIM tackles the trustworthiness of information and Lean the reliability of processes. Since the execution of processes both creates and depends on information, one cannot expect to improve the trustworthiness of information without improving process reliability and vice versa. By considering the contributions of BIM and Lean and by combining these with strategies for improved project team collaboration and the formal definition of expected project outcomes, VDC provides a framework to improve productivity and other construction performance objectives.

3 PRACTICAL ADOPTION OF VDC

3.1 A contractor's VDC-framework

After years of exploring lean practices and BIM technology, Skanska Norway has recently experienced notable benefits from systematically combining them. For instance, adopting Last Planner to design processes enabled efficient mapping of BIM processes in relation with other ongoing design deliverables (Fosse and Ballard, 2016). Recent development of interactions between collaborative methods and technology, combining lean methods and thinking with BIM, led to a VDC approach inspired by CIFE:

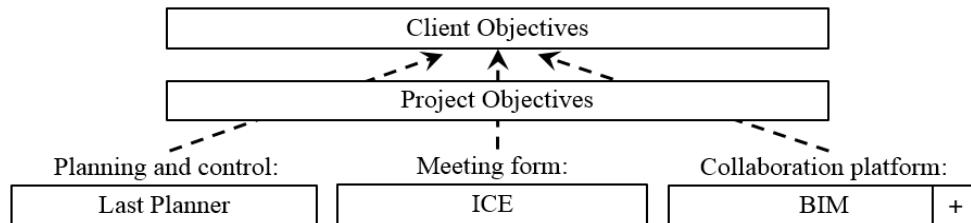


Figure 1: The VDC overview model of Skanska Norway

The lean principle of understanding the end customer’s objectives with the project is essential also in VDC, which is evident in Figure 1. The ideal is to provide customers exactly what they need in order to accomplish their purposes, and to do so with minimal waste. Project success criteria, what problem the building is solving for the client, how performance is measured and the objectives of the project team must be aligned.

The Last Planner System (LPS) is an essential collaborative method in any lean project, for mapping both preconstruction and construction activities.

Building Information Modelling (BIM) is essential to VDC. In BIM-mature projects, design coordination is model-based and geometry and object information fulfil the requirements of the Skanska Norway BIM manual. 2D-drawings still exist, but merely as products generated from the BIM. BIM+ refers to advanced BIM applications, such as 4D-scheduling, 5D-cost control, virtual/augmented reality, robotic automation etc.

Integrated Concurrent Engineering (ICE) is a method for multidisciplinary teamwork, originating from NASA's Jet Propulsion Laboratory (Kunz and Fischer, 2012). Whereas traditional meetings often suffer from vague meeting agendas, poor participant preparation and unclear logging of decisions made and follow-up work, ICE sessions counter these challenges with a clear agenda with explicit objectives, active problem-solving, precisely timed tasks and well-prepared, involved participants. ICE utilizes modern collaborative tools and technology, such as BIM on touch screens in a specially designed meeting room, so-called Big Room. An ICE facilitator ensures that the session progresses as planned, and a recorder tracks the results of the session.



Figure 2: ICE session with Tiedemannsbyen felt A (see case study 2)

3.2 Case Study 1: Gjønneshagen

Gjønneshagen is a residential design-build project of 348MNOK (\$41M), consisting of 181 living units distributed over several residential houses and two apartment blocks. The project's collaborative methods and digitalization started in 2012 with pull-planning of production work of selected phases and areas. As the project went into the third stage, several HSE and quality management processes were digitalized (Autodesk BIM 360 Field), and BIM (Solibri Model Checker) became the main tool for coordinating design and supporting production crews with geometry and information. BIM ambitions continued as a drone laser scan of the construction site was incorporated into the BIM, several materials were procured directly from BIM quantity take-offs and BIM was brought to the workplace with on-site BIM stations and tablets (Autodesk 360 Glue).

Last Planner for the design process was implemented as a continuation of the case study in Fosse and Ballard (2015). Shortly after, ICE sessions were implemented as well, after Skanska project participants had received ICE-training from CIFE.

A pilot test of a Last Planner tablet application (Autodesk BIM 360 Plan) made the production schedule accessible and fully updated at all times on all workers' tablets, allowing them to suggest changes, commit to activities and report progress on their own activities directly on their tablets. Most crews were equipped with tablets, and the few without were assisted by Skanska employees who was. With the schedule as a dynamic cloud-based document, the lead planner no longer had to update and distribute the schedule on a weekly basis, but rather spent his time handling the issues within it.



Figure 3: Last Planner System digitalized and tablet-enabled

With only a few months left, the project is on track to completion with good results on a schedule accelerated from 38 to 32 months. The project has served as a learning hub, with project participants moving onto new projects as champions for collaborative methods and digitalization. Several of the innovative practices have been adopted by other projects.

3.3 Case Study 2: Tiedemannsbyen felt A

Tiedemannsbyen felt A is a 458MNOK (\$54M) residential design-build project consisting of 251 apartments in 5 blocks. The project is a continuation of the practices from the Gjønneshagen project, and VDC implementation started in the spring of 2016. The project was rigged with an on-site Big Room, with digital touch screens and wall space for Last Planner plans. Although primarily for ICE sessions, the room has been used for several purposes within and between design, procurement and production teams. Daily BIM routines, such as model updates, clash detections and quantity take-offs, have been performed by the project team rather than a BIM coordinator from the central Skanska BIM department. This has ensured several benefits: Firstly, the project's funds for a BIM coordinator are allocated for technical support and further BIM development rather than performing daily routines. Secondly, with increased ownership and knowledge of BIM methods, project team members have replaced or supported existing tasks with BIM

functionality. Thirdly, the quality of BIM deliverables has increased, as the person performing the tasks has more knowledge of the significant issues in the project as well as more industry experience than a BIM coordinator. Metrics for Last Planner (PPC, root cause trends, task completion rate, reliability per trade), BIM clash trends per area according to the LOD-plan and ICE session evaluations (session efficiency, team preparations and involvement) have been continuously tracked and put on the wall in the Big Room, ensuring transparency and control of the project team's performance.

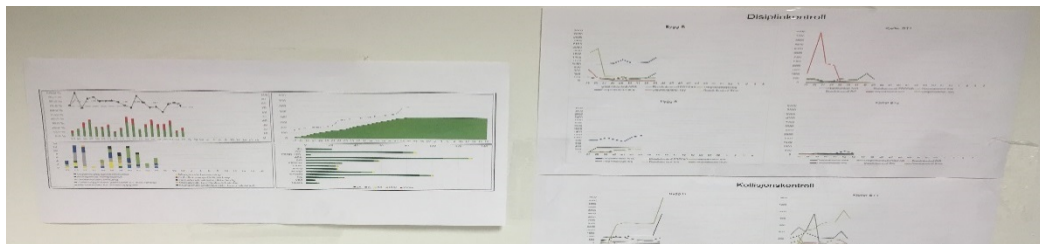


Figure 4: Last Planner and BIM metrics on the Big Room wall

A Level of Development (LOD) system, which is a status system of maturity of different objects and areas in the BIM, has been mapped on the wall with LOD-milestones as part of the Last Planner design plan. The LOD-milestones were pulled from the needs of on-site crews for a constructible BIM in time for production. The BIM has been available to all on-site crews through tablets with BIM 360 Glue, as well as in the office with Solibri. Skanska crews have also had a BIM station in a crew container, which has been especially useful for the crew that assembles rebar directly from the BIM rather than drawings. The BIM has been accessible on touch screens in the Big Room in most meetings, both for design teams and production crews. Especially in the Last Planner sessions, it has been used frequently as a discussion basis.

Everyone on the project has been offered BIM training, both for applications in the office and on-site. Every trade has also been trained in Last Planner as part of their participation in pull-planning sessions for either design processes or production work.

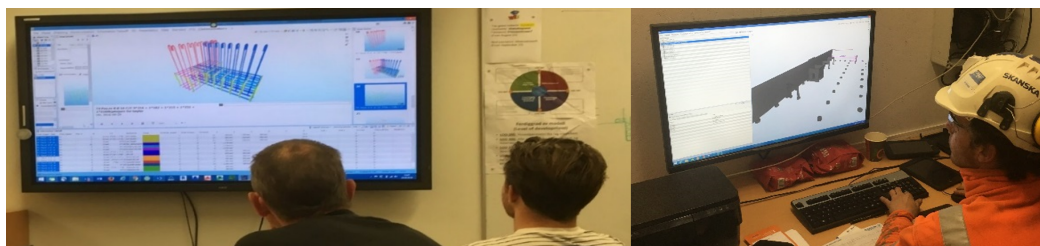


Figure 5: BIM on touch screen in project Big Room and in on-site BIM container

Although still early in terms of measuring project performance, some benefits have been observed from VDC practices. The design schedule has been reduced, allowing the senior design manager to leave the project 6 months earlier than initially planned. Members of the design team have claimed that there is a noticeable difference between the reliability and efficiency of this project compared to other projects they work with, and one major design firm has requested to adapt the project's methods to their own company. The client representative claims that the VDC methods have greatly increased the team's understanding between project team and client objectives, and has also requested training to initiate similar processes on other projects.

4 DISCUSSION

The two research questions posed in the introduction were:

- What are observed project benefits from effectively combining new ways of collaboration with digital tools?
- What are critical drivers for this change and barriers against it?

In 20 months, the first author of this paper has facilitated 59 ICE sessions, 55 pull-planning sessions and 68 plan checks for 28 construction projects, with about half of them having a holistic VDC approach as described in this paper. Although challenging to quantify the effects of VDC practices, some benefits are clearly observed. One Skanska design manager claims that VDC practices reduced his project's design phase by at least 4 months (27%), mostly by reducing waiting time and misunderstandings. In addition to measuring PPC on schedules and BIM clashes per area, ICE sessions are evaluated with anonymous survey asking the team how prepared they felt, how well they feel they participated and how efficient they feel the meeting was. The average score from a number of ICE sessions across the Oslo region indicate that ICE is beneficial:

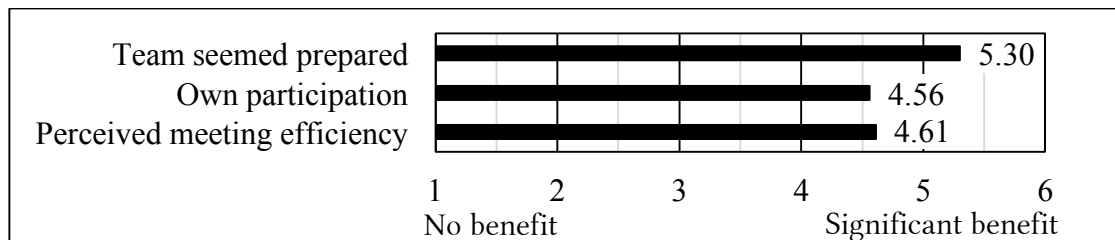


Figure 6: ICE evaluations (average team score from 5 sessions for first question and average team score from 26 ICE sessions for the other two).

A survey asked 143 participants from Skanska projects across Norway how they feel about pull-planning sessions compared to previous planning techniques, and results indicate that they feel pull-planning increased the quality of commitments within the team, resulted in a more realistic plan and a greater understanding of the planned phase:

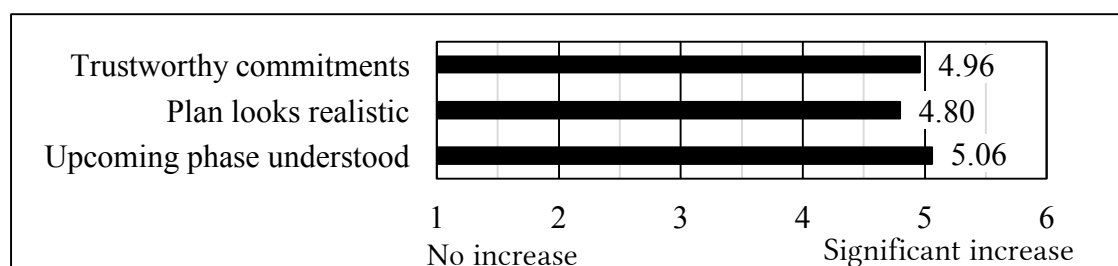


Figure 7: Survey asking 143 project participants to rank how they feel pull-planning sessions increased some key factors as opposed to traditional planning.

A key motivation for implementing VDC was to better coordinate efforts related to Lean principles and methods, especially the Last Planner System, BIM, ICE and metrics. According to the head of the BIM department of Skanska Norway, BIM is now better integrated in all project phases, and the BIM process is better understood by project teams through mapping it on the wall in the early design-focused Last Planner process. In return, the model is a central source of information in pull-planning of production, imperative to on-site production information with tablets and stationary BIM units, as well as being the

main discussion basis in ICE meetings. The plan on the wall functions as a canvas for visualizing consequences and opportunities of issues the team works on in the ICE sessions. Metrics of all three methods, such as ICE efficiency, Last Planner PPC and root cause trends, as well as BIM clash trends, have ensured control of team performance.

A lean culture is more evident in VDC projects, where project participants see each other in client-supplier relations, focus on delivering value to each other, measure and control team performance and continuously improve processes, tools, and methods.

Regarding drivers for and barriers to change, four elements have been crucial when evaluating the Skanska Norway VDC initiative recently: Knowledge of the methods and how to implement them, an innovative lean culture on a project level, proper training of key personnel and leadership that understands and promotes the approach. The first three factors have been championed by the regional lean manager (first author of this paper), alongside a continuously growing movement of project participants across the Oslo region who have participated in promoting and developing the VDC methods. Regional and national leadership has been positively outspoken about VDC as a collaboration and digitalization approach, as indicated by one Oslo district manager: “VDC increases our ability to realize lean principles, like involving people in seeing the solutions together, and use BIM and other digital tools in a sound way.”

No noteworthy barriers against change have been encountered, but some potential threats have been identified: Lack of funding for necessary tools and training, unclear goals and implementation plans and insufficient knowledge of strengths and weaknesses of methods. Funding has been solved by projects, clear goals has been achieved by putting the VDC effort into regional and national strategies, implementation plans have been developed collaboratively with project participants and substantial testing of equipment, software and methods have been done in controlled pilot tests before scaling up. Furthermore, a common barrier against change is that the time and effort necessary to achieve positive results is underestimated. This has not been observed in the VDC effort, perhaps due to the contractors years of experience implementing lean and BIM.

It has been important to "pull" innovation bottom-up, rather than "push" it top-down: VDC practices are continuously improved on a project level, and project needs regarding implementation or knowledge sharing is accommodated by management. Unfortunately, change initiatives are often implemented top-down, with new methods and tools pushed from a managerial level upon a workforce who does not want the change or see the need for new practices. Another barrier to change is to spend time and focus on working against those who do not want change. A central aspect to the VDC implementation has been to fully commit to those who want the change and not against those who do not. The belief is that those who are against the change will see the results and join the movement.

5 CONCLUSIONS

After years of exploring how to align digital tools and collaborative methods, Skanska Norway has recently benefitted from the terminology and understanding of Virtual Design and Construction. Several elements of lean construction are prevalent in the approach, and especially the combination of Last Planner, BIM and ICE sessions has been beneficial, as described in two case studies. Key drivers for positive change has been that the development of VDC practices are done on a project-level, with sufficient training provided and that leadership promotes the practices. No notable barriers have been encountered, but potential threats include lack of funding, unclear goals and implementation plans and underestimated time and effort needed for positive results.

Although difficult to evaluate the impact of VDC practices directly on project performance, there are several indications that VDC practices have had positive impact.

6 ACKNOWLEDGMENTS

The case project teams have shown a tremendous interest and willingness to adopt new practices, as well as contributing with research data in this paper. The BIM department, IT department and Digital Construction department have been crucial to the success of the methods described in this paper through their formidable efforts to collectively challenge common practice and develop innovative workflows to enable new technology. The Oslo regional management and executive directors of Skanska Norway must also be acknowledged for their immense support and encouragement of the VDC initiative.

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STRATEGIC CONSIDERATIONS FOR APPLYING CHOOSING BY ADVANTAGES IN DESIGN PROCESS

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Abstract: The design process is fraught with a myriad of decision points. The outcome of these decision points is significant in discovering and generating value in the construction project delivery process. Application of a collaborative decision system, such as choosing by advantages (CBA), on these decision points, has been established to enhance value generation by enhancing participation, transparency and respect among stakeholders. However, little attention has been given to identifying strategic considerations for operationalizing CBA application across the design process spectrum.

This paper combines knowledge from the case application of CBA, on selected design decisions, with theories on design process management and lean design in identifying these strategic considerations. Significant findings, among others, is the need to stratify the design process into identifiable decision frames to form the basis for applying CBA across the design process spectrum; the use of boundary objects to enhance communication among stakeholders in CBA application in design process; and the need for clearly established project requirements at the project definition phase to provide a sound basis for the CBA process. Findings of this study should provide a practical guide for CBA application in design process towards lean design implementation.

Keywords: Choosing by advantages, design process management, value, lean design, decision frames.

1 INTRODUCTION

Design process is noted to significantly impact the value delivery chain in construction project delivery process. Value delivered at the construction stage of construction projects is determined at the design stage (Bertelsen et al. 2002). Discovering and generating value at the design stage of construction projects requires a strong collaboration among project participants during design. Since the design process is associated with countless and expandable decision points, stimulating collaboration among participants, for value generation, requires the adoption of a collaborative decision system in design process. The Choosing By Advantages (CBA) decision system is identified as collaborative, since it stimulates an atmosphere of transparency, respect and participation among stakeholders in design process (Arroyo et al. 2014; Kpamma et al. 2016). Though several research works have established the collaborative attributes of

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CBA, little attention has been paid to identifying practical considerations to operationalize CBA application across the entire spectrum of design process.

This research, thus, set out to identify practical considerations in CBA application across the design process. Consequently, three cases of CBA application on selected design decisions were studied to obtain empirical knowledge on the functioning of CBA in design process. Empirical knowledge from the cases was further enhanced by theories on design process management and lean design in identifying strategies to apply CBA in design process. The outcome of this research should contribute to providing a practical guide in the application of CBA in design process.

2 THEORY

2.1 Choosing By Advantages

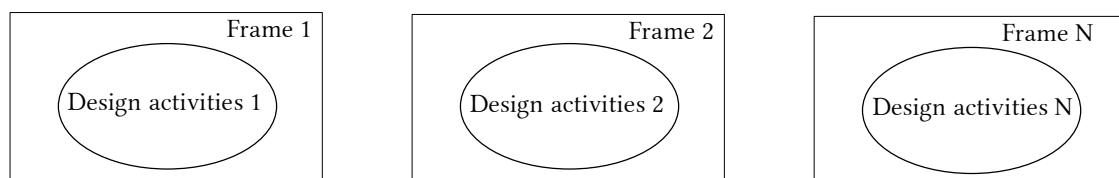
CBA is a multi-criteria decision analysis (MCDA) that, unlike other MCDAs, distinctively relies on comparing the explicit advantages of alternatives in the decision-making process (Suhr 1999). Advantages of alternatives are compared by assigning importance, using numerical weights, to the advantages. The alternative with the highest total Importance of Advantages (IoA) becomes the preferred choice. Though seminal application of CBA is attributed to the U.S. Forest Service (Suhr 1999), its prevalence in the construction industry, especially in lean construction research and practice, is growing steadily (e.g. Arroyo et al. 2014; Parrish and Tommelein 2009). CBA creates a participatory, transparent and collaborative atmosphere for auditable decisions in design and construction (Arroyo et al. 2013).

In most studies on CBA application in the AEC sector (e.g. Kpamma et al. 2016; Arroyo et al. 2013, 2014; Parish and Tommelein 2009), little attention is paid to identifying strategic considerations in applying CBA in design process. Furthermore, CBA is identified as one of the lean construction tools that are still lagging behind in terms of practice and research (Arroyo et al. 2014; SmartMarket Report 2013).

2.2 Design Process Management

One strategy for managing design process, in line with the concept of reflective practice in design process (Dong et al. 2013), is to identify decision-making frames within the design process to define the context for design activity (Zerjav et al. 2013). Frames, in this context, refer to the context of managerial decision-making which makes it possible for observable design action in the domain of design activity (Zerjav et al. 2013).

Accordingly, the design process is partitioned into recurring episodes of design activity occurring in corresponding decision-making frames (Figure 2). This approach aligns with the Group Decision Support (GDS) methodology of staging “a series of decision sessions scheduled to correspond with the decision points punctuating the building design process” (Green 1996). Consequently, a concern of design process management is to identify and enforce frames for present design activities, and anticipate subsequent frames for ensuing design activities (Zerjav et al. 2013). Anticipating decision frames for subsequent design activities provides an opportunity to direct design activities in a more informed way (Zerjav et al. 2013).



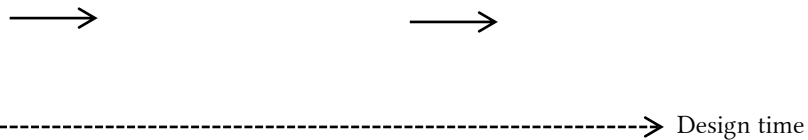


Figure 2: Decision-making frames in design process (Zerjav et al. 2013)

The design manager is expected to rely on client/user requirements to enact the decision-making frames. Even though there are difficulties in explicitly representing the frames into observable action (Stumpf & McDonnell 2002), it is also contended that managerial decision-making is based on observable action (Zerjav et al. 2013).

Beyond identifying and anticipating the decision frames in design process management is the concern of the outcome of the decision frames (Lawson et al, 2003). Consequently, as Suhr (1999) asserts, if the outcome of these design decisions matters, then the decision-making approach also matters. It is, thus, pertinent to employ a decision-making system, such as CBA, across the various frames. CBA, while ensuring that the output from each decision-making frame is sound, should also enhance collaboration and consensus building among stakeholders.

3 METHODOLOGY

The study sought to identify various strategic considerations in the application of CBA in design process. Three case studies, involving CBA application in selected design decisions were, therefore, conducted for in-depth knowledge on the functioning of CBA in design process. A case study is a research approach that intends to create detailed and concentrated knowledge about a situation or question by considering the real physical and social context of the case (Christiaans et al. 2004; Meredith, 1998; Yin 1994).

Following the action-based nature of the research in which there was the need for direct involvement of the researcher in the field (Keizer et al. 2002), a key member of the research team became an active participant in CBA application workshops for the case studies. This member participated in the workshops mainly as a facilitator, planning and moderating the processes in the workshops. The action researcher also participated in generating design options in the respective CBA applications. The use of action research afforded an opportunity for elements of CBA application process (e.g. group interaction, value concerns) to be closely studied and experienced.

The choice of three cases was based on the literal replication logic (Yin 1994). Case 1 involved the application of CBA for stakeholders to collaboratively decide on a direction of expansion of a theatre building at the Holy Family Hospital in Techiman, Ghana. Case 2 involved the application of CBA for stakeholders to collaboratively decide on a window opening system for a lecture hall complex project at Takoradi Polytechnic in Takoradi, Ghana. In case 3, CBA was applied for stakeholders to collaboratively decide on a ceiling finish for a lecture hall project at Sunyani Polytechnic in Sunyani, Ghana.

Data from the case studies was obtained through participant observation, direct observation and interviews. The use of multiple instruments for data ensured data credibility through cross-verification. The technique of pattern matching was employed in data analysis.

4 FINDINGS AND DISCUSSION

Each of the cases fundamentally involved four key sessions to discuss and establish project requirements; agree on design options; introduce stakeholders to CBA steps; and apply CBA to decide on options. Participants in case 1 were mainly two members of the design team and nine representatives of the clinical and administrative users of the theatre. Participants in case 2 were mainly two members of the design team, a window installation specialist, and representatives of the client and potential users made up of two students, two lecturers, an estate officer, the director works and the polytechnic's architect. In case 3 the participants were one representative of the design team, the polytechnic's maintenance officer, three students and four lecturers as potential users of the building.

Participants in each of the cases actively participated in the CBA process, from generating options through to the final choice. Of the two design options generated in case 1, one originated from the user-group based on prior meetings among themselves, while the other option came from the design team. The options in cases 2 and 3 were agreed upon by participants largely based on availability in the Ghanaian market. Though the process of establishing the attributes of alternatives, on which the advantages were based, also involved some consultation among participants, the action researcher, as a facilitator, played a lead role in researching to obtain, especially, technical attributes of some alternatives. In all the cases, the process of obtaining correct information for explicit description of alternatives' attributes was one of the activities that dragged process. Where attributes of alternatives were not explicit enough, it led to ambiguous advantages which, in some instances, resulted in delayed consensus on IoA.

The entire CBA process, in the three cases, generally induced an atmosphere of dialogue and consensus. This enabled stakeholders to learn and understand their respective values, needs and interests. In case 1, where the option with the highest total IoA costed more, participants still adopted it, and without regret, went ahead to implement it. This was due to clarity on this option's advantages being more aligned to the project objectives. Louvered window, in case 2, had the highest total IoA and costed least, therefore making it the obvious choice, which choice turned out to be most aligned to the objectives of the project.

Observations and interview of participants in the case studies further revealed various considerations to enhance the application of CBA in the design process. These considerations are identified and discussed below.

4.1 Pre-design activities

Preliminary design activities, such as requirements definition were identified to strongly impact the CBA process. Generating design options, in the case studies, was, for instance, guided by user/client requirements established at the project definition phase. The “ill-defined” feature of design problems and the expandable nature of design solutions particularly make the definition of project requirements useful in controlling the generation of design options.

In case 1, for instance, client/user requirements, such as maintaining a sterile work environment, and ensuring non-interference with on-going clinical activities in the existing theatre during project execution, were established at the project definition stage, and served as critical considerations for stakeholders to determine importance of advantages during the CBA process. Pre-design activities, therefore, forms a necessary foundation in the CBA application process.

4.2 Boundary Objects

Effective communication was found to be crucial in making use of the collaborative potential of the CBA process, especially when involving stakeholders in design decisions. This calls for a means for various stakeholders to effectively communicate their needs and intentions to the mutual understanding of all participants.

The use of boundary objects, in the form of animations, models or simulations, could facilitate a shared understanding when designers interact with other stakeholders at the pre-design stage or during the application of CBA at various stages of design. Animated designs could, for example, enhance a shared understanding of alternatives' attributes in the cases. An alternative's attribute is essentially the value of that alternative relative to a certain requirement; hence, a wrong appreciation of it (attribute) is detrimental to the entire value discovering process in CBA application.

4.3 Shared Mental Models

Consistent with theories on mental models and team performance (Badke-Schaub et al. 2007), mutual acquaintance among stakeholders, especially relative to their respective values, capabilities and roles, was essential in enabling the team processes in the cases. The freer and friendlier interaction among stakeholders in case 1 and 3, compared to that in case 2, were attributable to a higher level of acquaintance among stakeholders in case 1 and 3. Most of the stakeholders in case 1 and 3 had a longer working relationship and were therefore more acquainted with one another compared to those in case 2.

An open atmosphere of interaction is unrestrictive, and encourages creativity among team members. Unrestricted creativity is particularly essential at the innovation phase of the CBA process where alternative design solutions are generated to meet stakeholder requirements. Knowledge of member expertise and capabilities also enhances team confidence in the process. In the absence of previous working relationships, holding partnering/alignment meetings can help stakeholders define, as a group, the project's conditions of Satisfaction (i.e. goals). This helps create a shared mental model for the project at hand.

4.4 Combined Application of CBA with other Tools

The collaborative and value generating attributes of CBA could be complemented with the use of related lean design tools, such as A3 reports, Target Value Design (TVD) and Set-Based Design (SBD). A3 reports are employed to display relevant information on an A3 size sheet for effective team communication and collaborative decision-making based on the PDCA cycle (Sobek II and Smalley 2008). In the case studies, the use of A3 reports would be supportive to stakeholders as they explored alternatives and developed ideas for discourse in the CBA process.

The central idea behind TVD is to ensure that the design process is driven by a quest to achieve a target value in the form of a desired performance for a building project, within specified cost limits agreed with the owner (Zimina et al. 2012). TVD process, which is collaborative and starts at the early stages of design, could provide a significant guide in generating design options and deciding importance of advantages in CBA. SBD fundamentally encourages the act of considering a broad set of possible design solutions and progressively narrowing the set to a desirable solution. The design team, in SBD, is expected to postpone commitment to decisions on alternatives, to allow time to explore and evaluate as many feasible design solutions as possible (Singer et al. 2009). This identifies with the CBA process in the case studies whereby design options were

generated based on established user requirements, and commitment to them differed until they were subjected to rigorous evaluation.

4.5 Decision-Making Frames

CBA application requires a definition of a specific design problem. In the case studies, the CBA decision system was applied to precisely defined decision problems in the respective projects: “deciding on a direction of extension of an existing building”, “deciding on a window opening system” and “deciding on a ceiling finish”. This aspect of CBA application is consistent with the design process management model of identifying decision-making frames corresponding to various episodes of design activity across the design process (Zerjav et al. 2013). The GDS methodology of staging a sequence of decision sessions scheduled to correspond with the decision points which intersperse the building design process (Green 1996) also aligns with this aspect of the CBA process.

The identified decision-making frame in case 1 would be “create additional operating theatre spaces”, containing the design activity, “extend existing building in a suitable direction”. In case 2, the identified decision-making frame would be “provide window openings”, containing the design activity, “specify/design a window opening system”. In case 3 the identified decision-making frame would be “finish the ceiling system”, containing the design activity, specify/design a ceiling finish. Even though the identified frames in the case studies were from different projects, they could, hypothetically, represent a series of identified decision-making frames (F1, F2 and F3) containing various design activities (D1, D2 and D3) across the design process of one project (Figure 3).

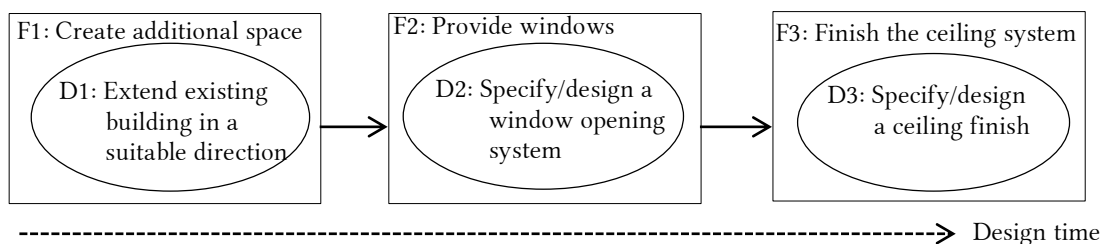


Figure 3 : Hypothetical link of Decision-making frames across case studies

The application of CBA with other lean design tools (i.e. TVD, SBD and A3) could then be decentralised across the identified decision frames. In this respect, the overall TVD for a project would, for instance, be decomposed into sub-TVDs per each decision frame. The corresponding design activity in each frame, thus, involves generating design options, in line with SBD, to form a satisfactory solution set, and the CBA process followed to rigorously evaluate and choose the desired option from the solution set. An A3 report would then be generated to provide a background to the outcome of each decision within each frame.

4.6 CBA Application Constraints

Notwithstanding the collaborative and value generating potential in CBA, it may be impracticable to go through the structured process of CBA to involve users for every design decision, and for all projects. Based on experience from the case studies, time and resource insufficiency could pose a limitation. Admittedly, it is more practicable to limit the CBA process to some category of projects and design decisions.

Projects which could possibly be considered for this process include: large and complex projects with a diversity of stakeholders who could influence and be influenced by the project; projects which lack clarity on project objectives, resulting in limited knowledge and the need for user input; projects, such as hospitals, which would eventually house specialized operations, and offer highly specialized services. In determining the kind of design decision (frames) to apply the CBA process, considerations such as, high user stake in design decision; lack of adequate knowledge for decision; and high technical complexity of design decision could also be a guide.

4.7 Facilitator

Lessons from the case studies also illustrate the crucial role of a facilitator in the CBA application process, especially when stakeholders of diverse professional and social orientations are involved. The action researcher's role as a facilitator was instrumental in the following areas of the process: training participants in the CBA process; identifying and bringing relevant stakeholders together; planning and coordinating workshops and meetings; researching for decision data, especially on the attributes of alternatives.

Proficiency in CBA application, an understanding of design process, and good interpersonal skills are essential in the facilitator role. The facilitator, for instance, based on his experience in design process and stakeholder participation, should lead the process of identifying, anticipating and enforcing decision-making frames during the CBA process.

5 CONCLUSIONS

CBA remains an emergent decision system in lean construction research and practice. Though the collaborative attributes of CBA is established in lean construction body of knowledge, strategies for operationalizing its application in design process have received less attention. Based on empirical knowledge from the case application of CBA in the design of three projects, combined with some theories in design management, a number of strategic considerations have been identified in this paper to serve as a guide in operationalizing CBA application in design process.

Among others, the findings in this paper provides a practical guide on organizing the application of CBA across the design process spectrum by relying on the concept of decision framing in design process management. The outcome of this research can help contribute to the theory and practice of lean design management. Though the findings of this study draws on empirical data from three case studies, some of the identified strategies, for CBA application in design process, are limited by the absence of an empirical evaluation of their workability.

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THE ER DESIGN SIMULATION GAME: EXPERIENCE AND REFLECT

Helena Lidelöw¹

Abstract: Most simulation games that exist are targeted towards experiencing and reflecting on Lean principles such as tact time, pull, Kanban, continuous improvements etc. The design phase in construction is characterised by information not being available, iterative work, specialized work tasks, and high uncertainty. The research aim is to develop and test a design simulation game that explains the design principles: lack of information, iterative work, and specialized work in order to let inexperienced people experience and reflect (ER) on the design phase.

The method to develop the ER design game was to alter an already existing production sequence simulation game developed to illustrate one-piece flow. Action cards were entered into the game, changing work tasks and their sequencing as the game progressed. The ER design game demonstrates the difficulties in characterising and improving the design flow, but it does not show any methods to improve it. Lack of information, iterative work, specialized work, stop-start effects, and tact time issues all surfaced during playing the ER design game. The time frame for the game set was 45 minutes, which makes it feasible to incorporate in Lean method training.

Keywords: Design simulation, Lean games, Lean simulation, Reflection.

1 INTRODUCTION

Lean principles can be applicable to many processes in construction, such as design, prefabrication, and on-site work. Experienced-based learning is a fundamental principle in Lean and this has spurred the development of many general Lean simulation games (Bicheno 2015), and also in Lean construction (e.g. Rybkowski et al. 2008, Tommelein et al. 1998). So far, there are few experience-based games that capture the discontinuous flow in construction design against the fondant of Lean principles.

The construction design phase is characterised by a discontinuous flow of information due to:

- the lack of or uncertainty in information
- iterative work flow due to new decisions by some actor
- specialized work tasks distributed on many actors preventing balancing of flow

Lean coaches are often trained in supporting either Lean production where the steady flow in a pre-set production framework is sought or in Lean construction where the temporary flow in a construction project targeted. Therefore, there is a need for a simulation game that illustrates the context of the construction design phase, while encouraging reflections on appropriate Lean strategies to improve flow in design work. The aim of this research is to develop and test a design simulation game that explains the design principles: lack of information, iterative work, and specialized work in order to let inexperienced people

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experience and reflect on the design phase. The game is named the ER design game to signal that Experience and Reflection are the targets, but also to bring attention to the urgency of understanding a process that sets the limits for downstream operations.

2 METHOD

2.1 The original game - the onset of development

The ER design game was developed as a reaction to Lean training, where all the associates at a Swedish construction contractor were given mandatory training using an experience-based game that gradually improved the precision and workflow of a production sequence. The original game had the following features:

- the production of 20-40 "products" consisting of LEGO® plates with pieces arranged in different patterns according to colour
- a known order sequence of products
- a fixed product design in five variants produced in a workflow with five stations
- the possibility to balance work between work stations

The target of the original game is to produce a set number of products (e.g. 24 pieces) within a time frame of 12 minutes with zero errors. By doing multiple rounds and reflecting between each round on the changes made in workflow, the participants experience work balancing, standardization, and continuous improvement using the Kata cycle (Rother 2009). The original game supports understanding of the workflow in a workshop environment with pre-defined products.



Figure 1: Playing the original game (Photo by Linda Rosén)

The design department who participated in the training (the author is Head of Engineering for it) collectively expressed that "this was an interesting game, but it does not visualize our reality". As a response to that, the author suggested "OK, so let us change it and see if we can illustrate our point". Five persons were up for the challenge.

2.2 The development of the ER design game

To explore how the original game could be changed, two workshops and one documentation session was held. The group of five persons participated in the workshops, while the final documentation of the result was made by the author. Finally, the ER design game was tested: once by the design team and once by the top management team of the company.

The first workshop focused on altering the game to illustrate the experience of design flow. Very early, the lack of information emerged as a topic not covered by the original game. This was illustrated by obscuring half of the variant design so that players could not see how half their product was supposed to be constructed. To unlock this information, action cards were introduced into the game releasing design information at irregular intervals during the game.

Furthermore, the notion of specialization in design (e.g. Demir and Theis 2016) emerged as a hindrance to perform work balancing. The group decided to illustrate this by only allowing certain persons in the game to mount a specific colour of LEGO® blocks. When design information was released, only the person dedicated to the specific task could perform the needed work. Finally, three scenarios of design projects were organised with different levels of complexity, where the first focused the lack of information, the second additional orders, and the last introduced alterations in the design of the products.

The second workshop started with a test round of playing the prototype ER game from the first workshop. Reflections pointed out that the roles of each participant needed to be clarified, so each role was given a separate set of instructions. Furthermore, the three different design projects were further refined by removing actions that were too elaborate and instead focus on the basic understanding of design principles. Everything was documented in an Excel spreadsheet and stored together with the original game. An invitation was sent to the top management team of the company to participate in the game as part of Lean training. The invitation was accepted.

2.3 Validation through playing

The ER design game was played by the top management team (9 persons) consisting of Head of Market and Sales, the Logistics Manager, the Chief of Factory Operations, the Chief of Site Operations, the CEO, the Head of Administration, the manager of Human Resources, and two of the three Lean coaches. The Head of Engineering, which is the author of this paper, lead the game. The game was observed by one of the Lean coaches and one member of the development team from the workshops.

Three rounds were played with increasing degrees of complexity. The results and reflections from the game are presented in the Results and Analysis section.

3 RESULTS AND ANALYSIS

3.1 Illustrating the lack of information

In the design phase, the lack of information is a constant problem. It can have several sources e.g. lack of decisions from the client, lack of a technical solution, or the solution

has not yet been developed. Whatever the cause, the result is that the work task cannot be finished. To illustrate this in the ER design game, parts of the product description was hidden to the players, shaded blue in figure 2. Each player sat down around a table with one game plan, figure 2, in front of him/her. The player should attach the blocks of his/her assigned colour and no others. The obscured information was released using an action card, issued after 3, 6, or 9 minutes into the game instructing players to reveal one or two of the hidden areas, figure 2. Therefore, the earliest finishing time for the game is 9 + a few minutes since 9 minutes is the last moment in time for releasing new information. An action card could read "We have decided that windows should have a new colour, please unlock areas labelled 1" or "The building permit is delayed, unlocking of areas labelled 2 is delayed 1.5 minutes".

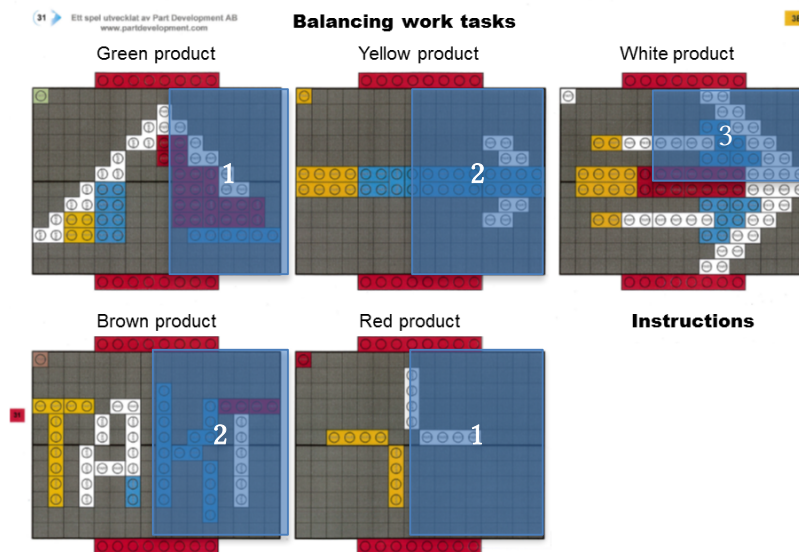


Figure 2: Game plan with obscured areas

When playing the validation round, the action cards pertaining to lack of information were read by the Head of Market and Sales as the client representative, since this emulates a realistic situation. The players' response to new information varied between the rounds. In the first round new information was needed to progress and people were eager to get new knowledge to move forward - thus giving new information fulfilled a need and was welcome. In the third and last round, the complexity was so high with iterative work being re-worked that the players met the release of new information with resistance, stating "We don't need anything more to do right now, please be quiet!".

3.2 Illustrating iterative work

Iterative work in design is often caused by changes in ideas and plans. They can pertain from the client or the designers themselves. Often iterations arise as a reaction to a design draft, which leads to a second or third draft being made. The iterations are sometimes necessary, but stifle flow of information from being smooth and predictable. To illustrate iterations in the ER design game, the action cards were not only releases of new information but also contained instructions about changes in the design. The changes were formulated as change orders e.g. by asking the team to produce something that was not originally decided or altering the design of the products by exchanging LEGO ® blocks.

As change orders were introduced some time into the game through the action cards, the game flow decreased and communication between participants increased. "If you redo your blocks, I'll go after you" was a typical comment showing the need for renegotiating the work sequence on the fly. This type of constant calibration with the surroundings is atypical for design work to avoid rework and stay tuned with the overall progress.

The resulting products of the game were approved by the client, which was an actor in the game. The client's job was to read the action cards at 3, 6, and 9 minutes into the game and accept or reject the finished products with alterations. When the client was satisfied with the batch delivery of all products, the game stopped.

3.2.1 Illustrating work interruption

In the setting of the company where the game was developed, a special circumstance occurs. The design team is given the task to support the factory production on a daily basis and if there are emergency problems, designers are summoned to the factory floor within 15 minutes to help figure out a solution to the emergency. In the game this was simulated by a factory action card entered into the game at random occasions.

The factory action card simply stated: "Emergency problem in the factory" and the instruction to the Chief of Factory Operations was to randomly remove one of the players from the game during 90 seconds to simulate that the player was now busy with something else and could not complete his part of the game. Since the game has specialized tasks (see 3.3) no other person can fill the gap during the 90 seconds of absence. When the player returned to the game, there was a start-up time for him/her to get into the flow again.

3.3 Illustrating specialization

From the validation round of the ER design game, it was clear that the restriction of specialization interacted with the iterative work. Specialization was emulated by restricting a single player to attach e.g. blue blocks. The idea was to emulate a situation where a team of drafters, structural engineers, and project leaders work together in design. If a change order in the ER design game requested that all blue blocks should be doubled, no one else in the game could complete that change order but the person assigned the blue blocks. The result was that the entire team at times was waiting for a single player to complete his/her task before delivering to the client. There were 7 appointed roles in the game, but the number of participants can be as low as 4 persons if the game leader takes on the roles of those not actually assembling blocks:

- Production preparation - starts the game by organising what products should be built according to instruction (which described a product mix, but not a sequence)
- Client - reads the action cards with new information to the team
- Production - reads the action cards where attention is taken from the team to attend to production problems
- Project leader - assembling yellow blocks
- Structural engineer - assembling blue blocks
- Designer - assembling red blocks
- Drafter - assembling white blocks

The team in the game was instructed to have a 'computer server' where the products in the game were stored while waiting for the next player to do his/her part. The server was simply a piece of paper placed in the middle of the table, emulating a computer storage

facility. It emerged very early in the course of the game that someone needed to keep track of the order of products on the server, thus unintentionally demonstrating the need for 5S.

It was the responsibility of each individual of the game to keep track of the products on the server and complete the products with the individual's specific blocks when possible. During the course of the game, much of the communication concerned quality control of the products on the server with typical statements being "You can complete that one now, it is ready for you" or "Take these two before those three, so I can work on them first" and finally "You have not completed the yellow blocks here, please redo the work". The visibility of the products as compared to the target design enabled these flow seeking communications to take place.

3.4 Experiences and Reflections

Between each round there was time allotted to reflect upon the experiences in the game. There were numerous statements that showed that the participants in the validation game actually experienced the situation in the design flow:

"How are we supposed to know what product to work on? There is no sequence."

This reflection was immediate in the first round of the game and resulted in the players inventing a system by themselves for how the products should preferably flow and be organised on the 'server'. This can be compared to the real-life situation where designers try to organise their work from conceptual to detailed questions, store their progress in predefined folder systems, and mark every drawing according to state.

"I had nothing to do, while you were struggling. Maybe I can help?"

This very kind offer was issued by one of the players sitting next to a hard working colleague. However, the specialization of work tasks prevented the balancing of work load and both of them were disappointed when they could not support each other.

"This is easy, I complete my work at even pace."

This comment was offered by the player placing the blue blocks between rounds 2 and 3. He had the role of the structural designer. During the third round, his work load was doubled through an action card never revealed before:

"I should never have said that this was easy! Now I am behind all the time."

The game plan thus illustrated that the flow in design is uneven and at times extremely stressful on single persons. While he struggled, the change order simultaneously put one of the other players out of work by commanding that his blocks were to be removed.

"What did you say? What was the change order?"

The changer orders were not issued as visual instructions showing the final product look i.e. a new game plan as in figure 2 was not issued. Instead, the change orders were written on the action cards instructing e.g. that all white blocks should be removed and all blue blocks doubled. The players and the clients had to remember these changes by heart while continuing the game. This event illustrated two things: 1. Change orders need reflection in the team before processing them and 2. Change orders are difficult to implement through the entire value chain. The work pace in the game decreased considerably after a change order.

"Well, I really think that the client can shut up now. We have enough work to do!"

This comment was offered in the last round of the game, just after a complicated action card had been entered into the game. It simulates the frustration that many designers feel

when trying to fulfil client needs while struggling with maintaining an even work flow. It also reflects the reaction to uncertainty in information that is ever present during the design stage.

The Lean coaches that participated in the game were somewhat concerned that several of the basic principles they teach are not applicable or mal-functioning in the design phase. Their background was not in Lean Construction, but in Lean Production with experience from the manufacturing industries such as Scania, Volvo, and Astra Pharmaceuticals. The ER design game thus fulfilled a second need: that of illustrating to Lean experts that there are situations when basic Lean principles must be rethought. The design flow situation is presumably better approached by Last Planner (e.g. Fosse and Ballard 2016) or Agile Project Management methods (Beck et al. 2001; Demir and Theis 2016).

4 CONCLUSION

The research has succeeded in developing and testing a design simulation game that explains the design principles:

- lack of information
- iterative work
- specialized work

The game allows inexperienced people to experience and reflect on the logics of flow in the construction design phase. The time frame of the game is 45 minutes, which makes it feasible to complete in the time allotted for most training sessions. The ER design game can be played in sequence with basic Lean training explaining flow, work balancing etc. Since the ER design game questions many of the basic Lean principles, it is wise to have a good grasp of them first, before adding the level of complexity the design flow offers.

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THE EFFECT OF PRE-ENGINEERING ON DESIGN MANAGEMENT METHODS

Helena Lidelöw¹ and Gustav Jansson²

Abstract: Several methods exist for design management such as Agile project management, the Last Planner System®, and configuration in diverse variants. Construction can be realized using different degrees of pre-engineering i.e. different production strategies, which can affect the design management method.

The research aim is to describe different design management methods and discuss their capacity to function in existing production strategies in construction. Data was collected as secondary data from earlier publications on Agile project management, the Last Planner® system, configuration, and visual planning.

Agile project management has a strong focus on customer value and lends itself well to situations with little pre-engineering. The Last Planner System® in design has a strong focus on the co-creation of flow and coordination of actions. In industrialised housing a dialect of Last Planner System® named KI-VP is implemented drawing upon predefinition of design tasks through standardized work. Configuration is the ultimate predefined design stage, where everything can be automated based on product variants.

Keywords: Agile, Last Planner System®, Production strategies, Visual planning.

1 INTRODUCTION

The design phase is characterized by uncertainty, iterative, and specialized work. Standardization and pre-engineering is argued to decrease the amount of design work. Within the Lean Construction community, several design management methods have been studied such as Agile project management (e.g. Demir and Theis 2016) and Last Planner® in design (e.g. Fosse and Ballard 2016). When using standardized products (e.g. a single-family home with product variants), the design phase is repetitive and takes the form of a configuration of pre-set alternatives preceded by a product development phase (e.g. Wikner and Noroozi 2016).

Construction can be realized through different production strategies, ranging from no pre-engineering up to fully standardized products, figure 1, (Johnsson 2013). In the situation of designing e.g. a concert hall, the level of pre-engineering is often low or zero, which means designers work directly with codes as their base going from a conceptual to a fully detailed design without the involvement of prefab suppliers, upper row in figure 1. The most common situation is row 2 e.g. the design of a multi-family building, where designers draw upon the knowledge from suppliers combining existing parts as beams, floor systems, windows etc. into a design. Row 4 captures another common situation; the standard products of e.g. prefabricated single-family homes where the design is completed

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before the customer enters the process. The customer's task is to choose from predefined variants and the design process is a pure configuration. Row 3 describes a situation in between the combination of existing parts and a selection of variants, where configuration is combined with traditional design.

The aim of this research is to describe different design management methods and discuss their capacity to function in the production strategies in figure 1 i.e. in situations with varying levels of pre-engineering. The purpose is not to advocate any design management method as superior to another, but rather to contextualize them and provide reasons for choosing between methods. The viewpoint is that the design phase is part of the production information flow (Winch 2003) momentarily setting aside design as a learning process (Kalsaas 2011).

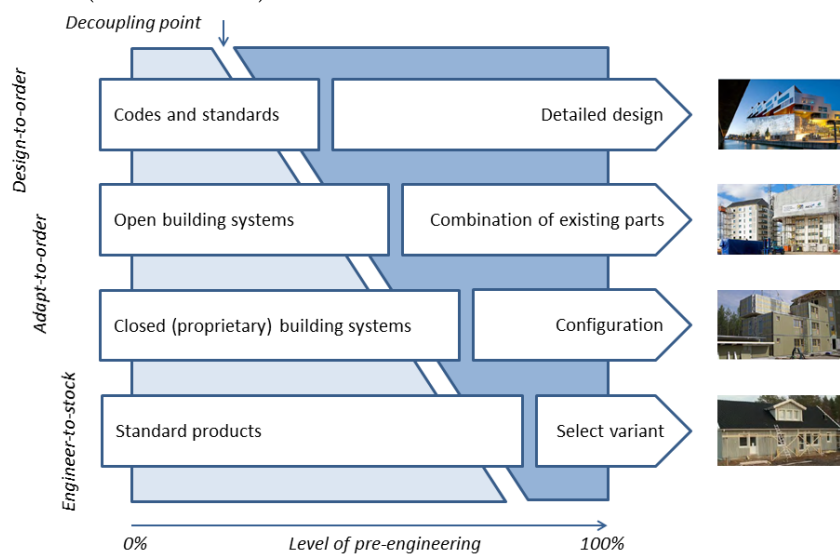


Figure 1: Different types of engineer-to-order production strategies in construction, examples from housing (Johnsson 2013)

2 METHOD

A literature study based on publications from IGLC was the onset to explain different design management methods in construction. This decision was made based on the first author's preunderstanding that IGLC is an arena where design management in construction has been vividly discussed over the years. Two major methods have been the discourse: Agile Project Management and Last Planner ® in design. A search for Last Planner within IGLC yields 224 results, which is narrowed down to 25 papers that includes "design" as a keyword, whereof 10 are case studies. Looking into Agile Project Management on IGLC reveals 24 research papers containing 4 studies in design.

Looking into the design of prefabrication, 6 papers emerge. Configuration in design reveals 4 papers. The low number of publications concerning construction design with a high degree of prefabrication motivated an additional search in other search engines.

The results from literature helps to build a basic understanding of different design management methods. Their ability to handle uncertainty, iterations, and specialized work is discussed as well as the standpoint of the method concerning conversion, flow or value (Ballard and Koskela 1998). The intention of the design management methods is contrasted with the situations in figure 1. The result is presented in figure 5 and each row in the diagram discussed and explained.

3 DESIGN MANAGEMENT METHODS

3.1 Agile Project Management

Agile project management is a software product development method suitable for situations where the requirements are partly unknown and needs to be developed during the design process, (Beck et al. 2001). While Lean focuses on efficiency and requires stability, the agile process focuses effectiveness (Naim and Barlow, 2003). Ballard and Koskela (1998) captured this through presenting design management as being captured as one of three views: the conversion of inputs to outputs, the flow of information, or the creation of customer value. The basic values and principles in agile project management is to prioritise interaction, functional solutions, cooperation with the client, and response to change as opposed to following a pre-set plan and a contract (Beck et al. 2001):

- The client representative is part of the project team, acts as the product owner
- After setting the vision, work is subdivided in cycles of 4-8 weeks - sprints
- At the beginning of the sprint, the product owner and the project team decides what client needs should be addressed and solved during the coming sprint. The client needs are often expressed as user stories and collected in a product backlog
- When the sprint ends, deliverables are presented to and tested by the product owner.
- New user stories are prioritised and the cycle starts over again.

During the sprint, the project team is ideally co-localized and meets at daily scrums managed by a scrum master. The daily scrum, which is a short daily check-up meeting, takes place in front of a scrum board, figure 2.

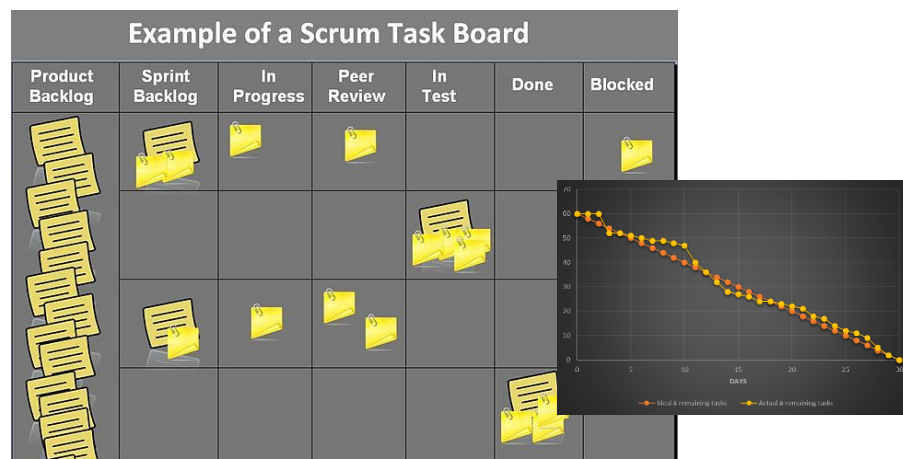


Figure 2: Scrum board (by Dr Ian Mitchell, 2016) with burn-down chart

The scrum board visualizes the product backlog, the vision, a burn-down chart, and work tasks deducted from the user stories. Every day, work task status is updated and new work tasks distributed within the team. Agile methods have no intention of finding an optimal sequence of design tasks, as opposed to Lean methods (Koskela et al 1997).

The logic in Agile project management is to temporarily freeze the uncertainty of changing requirements by asking the product owner to prioritise what user stories and requirements in the product backlog to focus on during the sprint. By asking the project owner to prioritise, customer value is ensured (Owen et al, 2006). Another priority is to

keep time and resources fixed while continuously revaluating the project goals (ibid). They further suggest that Agile should be applicable in projects where complexity and variation is substantial, where solutions to requirements evolve or are likely to change during the project, and where a considerable amount of clients are involved creating constant negotiation of trade-offs.

Demir and Theis (2016) developed Agile Design Management to adjust Agile project management to the construction design phase. This was made by clarifying who the product owner is, on what level he/she enters the process, and by adding a hierarchical structure for decision making, planning, and actual work. The VPO Lean design management model presented by Emmitt et al. (2004) resembles Agile with workshops targeted at value creation, but emphasises the connection between value, process, and operations.

3.2 Last Planner ® in Design

Last Planner ® (Ballard, 2000) has been successfully implemented and used for construction, also in the design phase (Miles, 1998). The core of the Last Planner ® system is to plan, lookahead, follow-up, and counteract problems beforehand to create a proactive work mode.



Figure 3: Pull-planning session at NCC Construction, Sweden (NCC, 2016)

Fosse and Ballard (2015) summarized the Last Planner ® system:

- Planning: Pull-planning sessions involve relevant project participants to create a plan based on needs across the team. Ownership of the plan is strengthened among participants as people can better explain and solve task sequencing of complex problems with visual post-it plans. This increases transparency of how design work must fit within the available time given by the plans for construction.
- Lookahead: In contrast to traditional planning, where problems are solved after they arise, one of the strengths of LPS is always focusing on making tasks ready in the coming weeks and solving problems proactively.

- **Checking:** Tracking PPC (percent part complete) and root causes for failed commitments provides information on how work actually is performed compared to how it was planned.
- **Learning:** Analysis of PPC and root cause analysis over time provides useful insight into plan reliability trends so that one can implement counter-measures for problems that systematically cause failure to complete tasks as planned.

In the beginning of the design phase, time is spent on capturing the client requirements as these govern what activities must take place during design. The team is not collocated, but pull-planning sessions are done with all the members of the design team present. Fundli and Drevland (2014) presented a variant of LPS in design where collocation was integrated in it drawing inspiration from integrated concurrent engineering. The pull-planning session results in a visual plan with post-its, figure 3. Meetings using the Last Planner ® system is not prescribed as daily meetings in front of the board, but rather re-planning sessions on a weekly basis. In between, the plan is frozen. Each actor can only move their own post-its on the plan.

Last Planner ® in design was extended by Kalsaas et al. (2016) through merging ideas from Agile and Last Planner ® primarily to support increased learning in the design process. Instantask is a visual communication support with an agile approach to enhance Last Planner by adding new questions to the decision flow in look-ahead planning (Daou et al. 2015). There are also tools to support the use of Kanban cards with BIM (KanBIM from Sacks et al 2011) and VisiLean developed by Dave et al (2013).

3.3 Design Management with Predefinition of Design Tasks

The Knowledge Innovation Visual Planning (KI-VP) method is based on design activities broken down into manageable tasks (Tanaka 2002). To increase design performance, predefinition of reoccurring tasks helps reduce variability, increase efficiency, minimize errors, capture, and manage knowledge. Predefinition functions as a base for continuous improvements and learning (Hoppmann et al. 2011). Being a part of Lean Product Development Flow (LPDF), the KI-VP method contains tasks that are predefined specifying what, who, when, and how the task should be operated in the design phase. Oppenheim (2004) describes that planning of the product development flow takes place in a dedicated room with magnetic planning boards where activities are mapped showing the current state of the development work. Compared to Lookahead planning in LPS, the KI-VP method contains daily meetings for fast feedback and visualisation of deviations from the takt time of the overall design plan. According to Reinertsen (2009), the management of queues in LPDF is central for balancing capacity utilisation. Queues of work tasks in product design are invisible without activity lists. Design queue inventories can quickly grow as a result of several concurrent deliveries, delayed response time, or from pauses and iterations in design work. Maximising the capacity of resources, increases the queues in design exponentially, which leads to longer cycle times, costs for delay, motivation problems, and lower quality (Reinertsen 2009). Flow efficiency is focused through visualizing daily work task queues and prioritise resources to queueing activities instead of matching work tasks to available resources.

The KI-VP concept is implemented in the design processes of industrialised house-builders to minimize throughput time, plan for takt time, hold meetings that minimize waste, and continuously improve design tasks (Jansson et al. 2016). Standard operation sheets (SOS) supporting the design tasks specify how predefined solutions and process snippets are applied in the specific construction project. In daily meetings, communication

problems, pauses or unsolved design tasks are visualised. The KI-VP plan contains a two week Lookahead plan with specified work tasks per day and a 28 weeks predefined mid-term plan with specified work tasks per week. Project specific tasks can amend the plan.

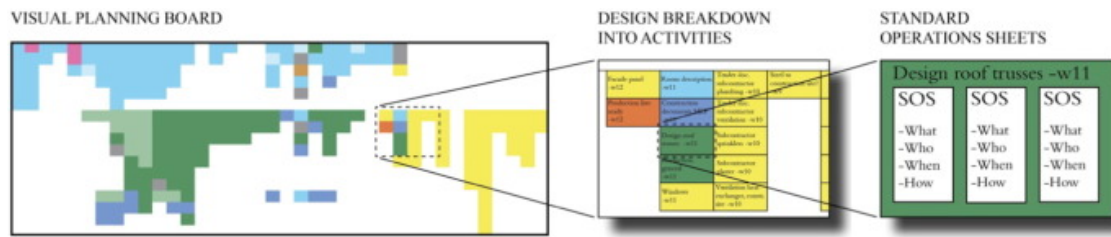


Figure 4: KI-VP board, activities and tasks with standard operation sheets.

3.4 Configuration Management in Design

When using configuration of products all design activities are executed before the client enters the process. With a high pre-engineering of the product offer, a short distance between sales and production contexts could result in benefits, but also drawbacks for the entire flow. This puts pressure on the management to schedule and coordinate orders after the decoupling point (Hines et al. 2004), figure 1. Pre-engineering contexts face the challenge of balancing the input rate of orders with the variety of product configurations. A combination of customer enquiry management (CEM) and order release management was described by Thurer et al. (2014) smoothing out peaks and troughs for a stable process of configuration before production. The planning of product configuration after the decoupling point is managed as part of the production flow (Wikner and Noroozi 2016). Further, the configuration execution is planned and controlled as production work (ibid). Visualisation methods for planning configuration of products are focused on the pre-engineering work instead of the execution i.e. there are no visual supports for the configuration process itself.

4 LINKING DESIGN MANAGEMENT TO PRE-ENGINEERING

Agile project management is suitable in projects where there are uncertainties not only pertaining to the solution, but also concerning what the actual requirements are. Therefore, it should lend itself perfectly to larger design projects with a unique character. The iterative nature of agile project management includes the client and supports problem seeking and value creation during the design process. Value creation has a higher priority than flow. Agile project management has little to do with conversion of inputs to outputs. Further, the notion of collocation of the team as a recommended ingredient in agile project management points to the fact that the method works best in complex, large projects where the team can be collocated for a substantial amount of time.

Last Planner ® is also useful in large projects where communication and coordination between many specializations are needed. However, Last Planner ® does not include the client as a default member of the project team and therefore, the requirement set should be well defined during the start-up of the design phase. Last Planner ® allows collocated teams but does not require it. This is a valuable quality in construction design as it is performed by many different firms in collaboration. LPS in design focuses the creation of flow with the underlying intent to create value.

In the specific situation of having a design process where large parts of the solution is already known i.e. in industrialised construction, there is a possibility to pre-engineer

snippets of the design process as well. This is captured by the KI-VP method, where the post-it boards used in Agile project management and Last Planner[®] are replaced by preprinted, predefined design process snippets. The order of execution is also predefined. This leads to a higher degree of predictability with the possibility to support tasks with standard operation sheets. However, KI-VP is not a method suitable when client requirements are not known or many new actors enter the design process - in those cases the power of predefinition is lost. The focus of the method lies in converting inputs to outputs and creating flow, while value creation is an underlying intention.

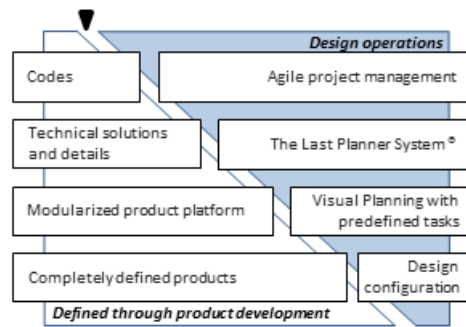


Figure 5: Visual planning methods in design in relation to pre-engineering

Configuration in design requires a fully known design solution and is thus only useful in cases where the final product is completely pre-engineered. A configuration process automates the design flow and focuses entirely on converting inputs to outputs. Value creation is ensured in the preceding product development phase.

All of the presented visual planning methods have merits in different situations and also support different underlying Lean strategies. Agile project management contains a strong focus on creating customer value, while Last Planner[®] contributes with common goal setting and letting everyone see and construct the flow. Between Last Planner[®] and Agile there have been several attempts to combine their strengths (e.g. Kalsaas et al. 2016). KI-VP is flow-oriented with predefined process flow and supports standard operations. Configuration is a fully automated, fast design flow, but the creation of customer value is pre-set and cannot change between projects - it must be made through product development.

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HOW BIM-LEAN INTEGRATION ENHANCES THE INFORMATION MANAGEMENT PROCESS IN THE CONSTRUCTION DESIGN

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Abstract: The construction industry faces significant challenges due to insufficient processes. Design phase is a key process of construction project lifecycle in which many problems and challenges occur. Most of the issues within the design process are mainly due to poor information management process. Therefore, it is important to adopt new innovative technologies and processes to improve information management. Over the last decade, the number of projects implementing innovative and technological processes such as BIM and Lean has been increased. However, rather applying BIM and Lean independently, integration of BIM features with lean principles would bring more benefits to the design process in terms of improving information management.

This paper studies the potential benefits of integrating BIM and Lean to improve information management in terms of reducing construction design problems associated with information management challenges.

Keywords: Lean construction, Building Information Modelling (BIM), Information management (IM).

1 INTRODUCTION

It is widely believed that many construction problems can be traced back to the design process due to many decision making processes and major amount of information exchange in the design process. The design process as the key process of any construction projects (Edmunds and Morris 2000) has significant impacts on both overall performance and efficiency of the project and on projects' time and cost (Formoso et al. 1998; Freire and Alarcón 2002). The success of overall quality and performance of the entire project lifecycle depends highly on the design process performance (Formoso et al 1998).

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Furthermore, it was reported by the BEDC that “the majority of construction problems are related to poor design management” (1987, cited in Austin Baldwin and Newton 1994). Also, another major problem faced by the construction industry is interdisciplinary management of design information. Similarly, it was stated that more than 50% of the construction problems, specifically on construction site, were related to poor design information management (NEDC 1987, Cited in Baldwin et al 2010). Therefore, effective design management is critically important to overcome construction problems that are associated with the design process due to poor design information management.

2 CURRENT STATE OF THE DESIGN PROCESS

Effective design management consists of various processes and strategies that aim to solve major construction problems that arise during the design process. As mentioned above many construction problems occur during the design process (Formoso et al. 1998; Austin Baldwin and Newton 1994). These problems including Lack of communication and coordination, insufficient documentation, unbalanced sharing of resources, poor or missing input information, unreliable decision making, and design changes have been described briefly in the following table (table 1). All mentioned problems would consequently result in generating waste, such as rework, waiting and over processing, in the design process and later on construction site (Ningappa, 2011).

Table 1- Construction Design Problems

Construction design problems	Description	Possible wastes
a) Lack of communication and coordination	Poor communication and coordination is a result of isolated environment where the project team do not communicate with each other to share information and knowledge. (Austin, Baldwin, & Newton, 1994).	Defects and Rework Waiting Over processing
b) Insufficient documentation	Producing inadequate documentations such as unclear drawings with errors or inadequate details and missing information on drawings or other projects documents. (Austin, Baldwin, & Newton, 1994).	Defects and Rework Waiting Over processing
c) Unbalanced sharing of resources	Sharing too many unnecessary information or lack of information. (Austin, Baldwin, & Newton, 1994).	Defects and Rework Waiting Over processing Unnecessary movement Over production
d) Poor or missing input information	Lack of sufficient information exchange is a result of poor information management. This will result in missing relevant information, excessive amount of information, duplication of information. (Austin, Baldwin, & Newton, 1994).	Defects and Rework Waiting Over processing Over production
e) Unreliable decision making	As decision making is a selection of the best solution from possible alternatives, unreliable decision making will lead to problem generating rather than problem solving. (Austin, Baldwin, & Newton, 1994).	Defects and Rework Waiting Over processing Over production
f) Design changes	Design changes may involve changes in any activity, information, order, task and any design related process which would have negative impacts on the overall design phase . (Austin, Baldwin, & Newton, 1994).	Defects and Rework Waiting Over processing Unnecessary movement Over production

3 INFORMATION MANAGEMENT

3.1 Information Management

According to Detlor (2010) Information Management (IM) is a procedure of managing “the processes and systems that create, acquire, organise, store, distribute, and use information”, which enhances the efficient and effective access, process, and use of information by people and organisations. This will result in improvement of both people and organisations in terms of better task completion and competitive and strategic operations respectively (Detlor 2010). The aim of IM is to provide the right information to the right person in the right place at the right time to support the processes efficiently (Robertson 2005; Hicks et al 2006). It is widely believed that IM is critical for projects' success as it ensures that the information value is identified and achieved to its complete level (Hicks et al 2006). However, there are many challenges within the IM that need to be addressed in order to improve the overall projects efficiency (Hicks et al 2006). Table 2 addresses the identified design challenges under four categories related to IM.

Table 2- Information Management Challenges

3.2 Information Management Challenges
A number of information management challenges have been identified in the literature, which are summarised into four main categories: systems or tools, information, people, and policy and strategy. Managing all types of documented information throughout the information management lifecycle needs an integration of policies, systems, information, and people. The relation between these challenges and construction design problems are also summarised in table 3 and 4.
3.2.1 Systems or Tools
Developed information management strategies are merged with systems and operations for a set of pre-defined or on-going actions (Hicks et al 2006). Nevertheless, most of the elements are not in line with organisations and systems (Duhan Levy and Powell 2001). Therefore, many issues related to inappropriate management systems will result in poor information management along with design problems.
3.2.2 Information
Recently with the increased amount of information generated and being available in the design process it is crucial to deal with a large amount of information (Leite et al 2016). The increased potential of creating and accessing information with various technological devices has maximised the capacity of generating information (Hicks et al 2006). Increased level of information not only effects managing the excess amount of information (Edmunds and Morris 2000), but also effects managing the possible ways for different levels of information. Moreover, construction companies require various types of rich information for managing project life cycle activities in the design phase (Pahl and Beitz 2013). Hence, increased level of information has resulted in creating many issues.
3.2.3 People
To accomplish client’s requirements, project participants work through a strategic process to achieve predetermined set of goals during the design process. The process consists of developing and sharing of relevant information. It has been identified that due to complexity of these information, effective information management is a key component in successful project delivery. Many organisations recognised that collaboration and coordination improvement among project stakeholders is a crucial need in effective information management (Peansupap and Walker 2005). Organisations should consider people with relevant skills and performance for a better information management through a process of collecting, organising and maintaining information to overcome related issues (Marchand Kettinger and Rollins, 2000).
3.2.4 Policy and strategy
According to Karimi and Konsynski (1991) “A global information management strategy is needed as a result of (1) industry globalisation: the growing globalisation trend in many industries and the associated reliance on information technologies for coordination and operation, and (2) national competitive posture: the aggregation of separate domestic strategies in individual countries that may contend with coordination.” Global strategies are linked with the involvement of coordination which includes the management of exchange sets; such as information, goods, expertise, technology, and finances (Powell 1987).

The four identified IM challenges mentioned above would result in major construction design problems as explained in Tables 3 and 4. The IM challenges are listed in Tables 3 and 4 along with their relation to the construction design problems which are categorised into six types (shown as a-f items). For example, problems associated with the information aspect, such as lack of information availability, will result in unbalanced sharing of resources (item c in Table 3).

Table 3- Construction design problems related to IM Challenges

Categories and Description	Construction design problems	Information Management challenges
Systems or Tools Developed information management strategies are merged with systems and operations for a set of pre-defined or on-going actions (Hicks et al., 2006). Nevertheless, most of the elements are not in line with organizations and systems (Duhan, Levy, & Powell, 2001).	a) Lack of communication and coordination	Large number of disparate information management systems, Little integration or coordination between information systems, Information exchange, Manual systems and data entry, Implementation and customisation of information systems, Paper based systems. (Robertson, 2005; Hicks et al, 2006).
	b) Insufficient documentation	Range of legacy systems requiring upgrading or replacement, Information exchange, Manual systems and data entry, Paper based systems. (Robertson, 2005; Hicks et al, 2006).
	e) Unreliable decision making.	Direct competition between information management systems, No clear strategic direction for the overall technology environment, Limited and patchy adoption of existing information, systems by staff, Manual systems and data entry, Functionality of information systems, Paper based systems. (Robertson, 2005; Hicks et al, 2006).
Information Increased level of information not only affects in managing and excess of information (Edmunds & Morris, 2000), but also to establish managing ways for different levels of information.	a) Lack of communication and coordination	Little integration or coordination between information systems, Large number of diverse business needs and issues to be addressed, Limited resources for deploying, managing or improving information systems, Large number of diverse business needs and issues to be addressed, Lack of clarity around broader organisational strategies and directions, Difficulties in changing working practices and processes of staff, Information exchange, Functionality of information systems, Information availability and accessibility, Information identification, location and organisation, Paper based systems. (Robertson, 2005; Hicks et al, 2006).
	b) Insufficient documentation	
	c) Unbalanced sharing of resources	
	d) Poor or missing input information	
	e) Unreliable decision making	
	f) Design changes	

Table 4- Construction design problems related to IM Challenges (Continued)

Categories and Description	Construction design problems	Information Management challenges
People Many A & E organizations identified that improving collaboration and coordination among project stakeholders is a crucial need in effective information management (Peansupap and Walker 2005).	a) Lack of communication	Little integration or coordination between information systems, Large number of diverse business needs and issues to be addressed, Manual systems and data entry, Information flow from customers and sales, Information availability and accessibility, Implementation and customisation of information systems, Information completeness and accuracy, Paper based systems. (Robertson, 2005; Hicks et al, 2006).
	b) Insufficient documentation	Large number of diverse business needs and issues to be addressed, Information availability and accessibility, Information completeness and accuracy, Information duplication, Paper based systems. (Robertson, 2005; Hicks et al, 2006).
	c) Unbalanced sharing of resources	Little recognition and support of information management by senior management, Difficulties in changing working practices and processes of staff, Manual systems and data entry, Information flow from customers and sales, Information completeness and accuracy, Information duplication. (Robertson, 2005; Hicks et al, 2006).
	e) Unreliable decision making	No clear strategic direction for the overall technology environment, Limited and patchy adoption of existing information systems by staff, Large number of diverse business needs and issues to be addressed, Internal politics impacting on the ability to coordinate activities enterprise-wide, Information completeness and accuracy, Information duplication. (Robertson, 2005; Hicks et al, 2006).
Policy and Strategy According to Karimi and Konsynski (1991) "A global information management strategy is needed as a result of (1) industry globalization: the growing globalization trend in many industries and the associated reliance on information technologies, and (2) national competitive posture: the aggregation of separate domestic strategies in individual countries."	a) Lack of communication	Lack of clarity around broader organisational strategies and directions, Information flow from customers and sales, Information availability and accessibility, Information identification, location and organisation. (Robertson, 2005; Hicks et al, 2006).
	b) Insufficient documentation	Lack of enterprise-wide definitions for information types and values (no corporate wide taxonomy), Information availability and accessibility, Information identification, location and organisation. (Robertson, 2005; Hicks et al, 2006).
	c) Unbalanced sharing of resources	Little recognition and support of information management by senior management, Limited resources for deploying, managing or improving information systems, Difficulties in changing working practices and processes of staff, Information flow from customers and sales. (Robertson, 2005; Hicks et al, 2006).
	e) Unreliable decision making	No clear strategic direction for the overall technology environment, Large number of diverse business needs and issues to be addressed, Lack of clarity around broader organisational strategies and directions, Internal politics impacting on the ability to coordinate activities enterprise-wide, Functionality of information systems. (Robertson, 2005; Hicks et al, 2006).

4 INTERACTION OF BIM AND LEAN TO REDUCE DESIGN PROBLEMS ASSOCIATED WITH INFORMATION MANAGEMENT

BIM has been widely recognised as a platform which is related to Information Management (IM), and has been defined as “not just a technology change, but also a process change” that enables “a building to be represented by intelligent objects that carry detailed information” (Eastman et al 2011). BIM has various beneficial functionalities that would improve information management and accordingly the design process. Four main

BIM functionalities that have the most interaction with Lean principles were identified by Mollasalehi et al. (2015) which can also be linked to IM. These are discussed in the following section.

According to Koskela et al (2002), “lean is a way to design production systems to minimise waste of material, time, and effort in order to generate the maximum possible amount of value”. There are many different Lean principles that are beneficial to the overall project process including information management process. Though, five key lean principles that were identified to have the most interaction with BIM functionalities which are linked to IM are: Reduce variability, reduce cycle time, increase flexibility, use visual management, and verify and validate (Sacks et al 2010).

There is a strong synergy between BIM and Lean (Sacks et al 2010). Therefore, the integration of these two approaches would enhance IM through different beneficial features that they provide as shown in Table 7. Table 7 demonstrates the benefits of integrating BIM and Lean approaches to improve information management in terms of reducing construction design problems that are related to IM challenges.

4.1 Discussion Based on Table 7

Table 7 shows four different types of linkages between IM challenges (numbers 1-4) in line with integrated BIM and Lean, and construction design problems (items a-f). Different construction design problems have been highlighted according to the previous discussion in tables 3 and 4. For example, there are only three identified relevant construction design problems (items a, b, and e), as previously discussed in table 3, which have either direct or indirect interaction with BIM and Lean in terms of IM process improvement. This has been discussed in details in Table 5 and 6 below.

Table 5- Discussion based on Table 7

Visualisation
Visualisation, as the most beneficial BIM functionality, enables a three-dimensional virtual view of the building including all the related information within the building (Eastman et al. 2011). So, all the shared information can be visualised by project participant in a collaborative environment. Visualisation is directly influencing information management as this BIM feature “helps to realise and identify any missing information or elements as well as identifying any design error” early in the design process (see table 7 type 2, items c,d,e,f)(Mollasalehi et al 2015). Therefore, design problems related to information management challenges such as poor or missing input information, unreliable decision making, and design changes can be directly improved as the project team can take any necessary actions early in the design process to resolve any identified design error or issues (see table 7 type 2, items c,d,e,f, and type 3, items a,c,e) (Mollasalehi et al 2015). Also, when the information is visualised the expected quality of information is achieved right the first time which would indirectly lead to sufficient documentation (see table 7 type 2, item b and type 3, item b). Visual management is linked closely to standardisation (Sacks et al 2010). Therefore, design problems associated with lack of sufficient systems or tools within information management that are due to lack of standardised systems would be improved directly and indirectly (see table 7 type 1, items a,b,e). For example, standardised intelligent systems or tools would assist project participants to visualise the project process in a collaborative environment to make the right decisions early in the design process (Eastman et al 2011). Also, an online object-based communication is enabled through intelligent systems which would improve the communication and coordination between different project disciplines and provide sufficient documentation (see table 7 type 1, items a,b,e and type 3, items a,b,e). Moreover, standardised systems are driven from an appropriate work strategy and policy in which the project tasks and requirements are defined for project success. As BIM and Lean provide effective work strategies (Koskela et al. 2002; Arayici et al. 2011), the construction design problems related to policy and strategy will be resolved which will then result in information management improvement (see table 7 type 4, items a,b,c,e).
Clash detection
Clash detection enables identifying and reporting of any interference and clashes between systems and objects (see table 7 type 1, items a,b,e). These improved systems and strategies allow people to take more reliable decision making through improved communication and coordination among project stakeholders (see table 7 type 1, items a,b,e and type 3, items a,b,c,e)(Arayici et al 2011). Similarly, Eastman et al. (2011) stated that “Automatic detection of conflicts is an excellent method for identifying design errors, where objects either occupy the same space (a hard clash) or are too close (a soft clash)”. Therefore, clash detection improves the richness of the information exchange reducing poor and missing input information to avoid future design changes and unreliable decision making (see table 7 type 2, items a-f). Likewise, human errors could be identified through clash detection, enhanced to improve balanced sharing of resources among project stakeholders (see table 7 type 3a,b,c,e).

Table 6- Discussion based on Table 7 (continued)

Collaboration	
<p>According to Singh Gu and Wang (2011), “the scope of BIM is expanding from current intra-disciplinary collaboration through specific BIM applications to multi-disciplinary collaboration through a BIM-server”. This will improve the communication and coordination among project participants. Effective collaboration and communication among project participants enables using intelligent tools and systems appropriately which enhances creating accurate information along with sufficient documentation (Arayici et al. 2011; Azhar 2011). Collaboration and communication allows integrated tools and systems to reduce failure which improves the reliable decision making process among project participants (see table 7 type 1, items a and e, type 3, items a,b,c,e)(Eastman et al. 2011; Azhar 2011).</p> <p>Collaboration enables project participants to share information at the same time and “adjust any changes in activities collaboratively together early in the design process” (see table 7 type 2, items a-f and type 3, items a,b,c,e)(Mollasalehi et al 2015). Also, it will allow people to have a clear understanding of the project strategy and requirements through better communication (see table 7 type 4, items a,b,c,e)(Azhar 2011). This will also improve coordination among project members. Effective information exchange among all the project team collaboratively enhances preparing sufficient documentation in the design process (see table 7 type 1, items a,b,e and type 2, items a-f and type 3, items a,b,c). Multiuser viewing and editing enhanced by collaboration reduce the unbalance sharing of information and poor or missing information from the drawings and design documents through effective visualisation of the process during the design stage (see table 7 type 3, items a,c,e and type 2, items a-f)(Sacks et al 2010). Moreover, collaboration and communication will minimise the design changes which could occur during the construction stage due to insufficient and poor information (Arayici et al 2011).</p>	
4D scheduling and construction sequence planning	
<p>BIM provides 4D scheduling and construction sequence planning through an intelligent integrated system which is driven by BIM and LEAN strategies that would enhance the design problems associated with the information management challenges. With the usage of 4D scheduling for the systems or tools, it includes information that are not only limited to a 3D model, but include parameters such as; time and cost scheduling, and thus design could be identified in an earlier stage (Eastman et al 2011), and would help to add information that could be missing, documentation that may be insufficient, enhance design making process, and help to stabilise the resource distribution (see table 7 type 1, items a,b,e). Furthermore, information within the 4D scheduling provides an overall image of projects' current situation which include activities, such as; schedule planning that would allow bridging the gaps of inadequate information, unnecessary design changes, and would deliver high quality information, and balance the information that will be shared (see table 7 type 2, items a-f)(Eastman et al 2011). Moreover, project participants using 4D scheduling would be vital in recognising current conditions of the projects and the need to outline with necessary changes that could be required (see table 7 type 3, items a,c,e)(Eastman et al. 2011; Azhar 2011). Therefore, 4D scheduling in which the time and cost planning components are linked within the 3D model would support the participants in identifying the necessary schedules required and the relevant data that will be needed in relation to material and cost information. As a result, the involvement of people in an early stage of the project shall improve the decision making process, limit the communication and coordination issues, lower the design changes, enhance the information delivery, deliver sufficient information, and manage the resources load share (see table 7 type 3, items a,b,c,e). Likewise, strategies related to 4D scheduling shall require involvement of information management challenges which are systems, information and people. Strategies such as “Construction planning and scheduling sequencing activities in space and time, considering procurement, resources, spatial constraints and other concerns in the process” (Eastman et al 2011) are examples to the requirements that will need their necessary involvement. Thereby, consideration of the required strategies will help to avoid inconsistencies related to the provided documentation, unnecessary design changes, and avoid poor information input. As a result, 4D could enhance the schedule planning reliability which will enhance the current deficiencies of communication and coordination within the projects (see table 7 type 4, items a,b,c,e) (Hartmann Gao and Fischer 2008).</p>	

Table 7- Interaction of BIM/Lean to Enhance Information Management

Interaction of BIM and LEAN		Information Management Challenges / Construction Design Problems																							
Lean Principles	BIM functionalities	1. Systems or Tools						2. Information						3. People						4. Policy and Strategy					
		a	b	c	d	e	f	a	b	c	d	e	f	a	b	c	d	e	f	a	b	c	d	e	f
Reduce Variability	Visualisation	Indirect	Indirect	N/A	N/A	N/A	Indirect	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	N/A	Direct	N/A
Reduce cycle time		Indirect	Indirect	N/A	N/A	N/A	Indirect	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	N/A	Direct	N/A
Increase flexibility		Indirect	Indirect	N/A	N/A	N/A	Indirect	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	N/A	Direct	N/A
Use Visual Management	4D scheduling and construction sequence planning	Direct	Direct	N/A	N/A	N/A	Indirect	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	N/A	Direct	N/A	Direct	Indirect	Indirect	N/A	Indirect	N/A
Verify and Validate		Direct	Direct	N/A	N/A	N/A	Indirect	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	N/A	Direct	N/A	Direct	Indirect	Indirect	N/A	Indirect	N/A
Standardise		Direct	Direct	N/A	N/A	N/A	Indirect	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	N/A	Direct	N/A	Direct	Indirect	Indirect	N/A	Indirect	N/A
Reduce Variability	Collaboration and Communication	Direct	Indirect	N/A	N/A	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	N/A	Direct	N/A	Direct	Indirect	Indirect	N/A	Direct	N/A
Reduce cycle time		Direct	Indirect	N/A	N/A	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	N/A	Direct	N/A	Direct	Indirect	Indirect	N/A	Direct	N/A
Increase flexibility		Direct	Indirect	N/A	N/A	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	N/A	Direct	N/A	Direct	Indirect	Indirect	N/A	Direct	N/A
Use Visual Management	Clash Detection	Direct	Indirect	N/A	N/A	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	N/A	Direct	N/A	Direct	Indirect	Indirect	N/A	Direct	N/A
Verify and Validate		Direct	Indirect	N/A	N/A	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	N/A	Direct	N/A	Direct	Indirect	Indirect	N/A	Direct	N/A
Standardise		Direct	Indirect	N/A	N/A	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Direct	Indirect	Indirect	N/A	Direct	N/A	Direct	Indirect	Indirect	N/A	Direct	N/A
a) Lack of communication and coordination		b) Insufficient documentation						c) Unbalanced sharing of resources																	
d) Poor or missing input information		e) Unreliable decision making						f) Design changes																	

5 CONCLUSION

It is widely believed that many of the problems faced by the construction industry are related to the design process. Some of the key challenges within the construction design have been highlighted in this paper such as lack of communication and coordination, poor or missing input information, design changes, and unreliable decision making. These problems will result in many challenges within the information management (IM) which would make the IM insufficient. This paper identified some of the key IM challenges within the design process which have been summarised into four main categories of systems or tools, information, people, and policy and strategy. These challenges have been linked to the construction design problems and it is believed by the authors that by improving those, the IM will be accordingly improved. BIM and Lean as two innovative and technological processes are believed to enhance IM. It is believed that the integration of BIM functionalities (such as visualisation and collaboration) with Lean principles (such as reduce variability, increase flexibility and use visual management) enable better IM improvement during the design process. Table 7 has been provided to show the relation between the integrated BIM and Lean and IM improvement. The interaction of BIM and Lean column in the table has been adopted from 'Interaction Matrix of Lean Principles and BIM Functionalities' (Sacks et al 2010). From the discussion of the proposed table (chapter 4.1) it can be concluded that the interaction of BIM and Lean would benefit IM in terms of reducing construction design problems that are associated with the IM problems. As this paper is based on reviewing the literature, authors would like to recommend future practical work based on the proposed table to gain more insight into this area of research.

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DESIGN MANAGEMENT IN A DESIGN OFFICE: DEVELOPMENT OF THE KNOWLEDGE BASE

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Abstract: In this second paper in a series of three, the aim is to develop a theoretical knowledge base for design science research (DSR) activity within the next paper. This is primarily a literature review based paper, inspired by the problems summarized in the first paper. The paper starts with a description and justification of the proto-theory of design and design rhetoric. It has been argued that the design science has been concerned with the artefact rather as a technical than a social phenomenon. It is opportune to propose that the proto-theory of design and design rhetoric represent different, yet related dimensions of a productive act (techne). These concepts provide the necessary prescription for the root cause analysis of the problems addressed within the first paper and practical design and design management conceptualization within the third paper.

Keywords: Design, proto-theory of design, rhetoric, design rhetoric

1 INTRODUCTION

Within the first paper, we concluded that it is the poor conceptualization of design and design management that has led to the bad consequences. Furthermore, we argue that design management cannot decouple from and ignore the fundamentally complex nature of design task; a term used to describe the invention, planning, and realization of both tangible and intangible products (Buchanan, 2001). This complexity is illustrated by the pluralism of design conceptualizations (Buchanan, 2009), including different perspectives, subject matter, strategies of inquiry and methodologies. To shed some light on the design within the context of production science, Koskela and Ballard (2013) have proposed that the two ancient methods, including the method of analysis (proto-theory of design) and rhetoric are separate, yet complementary methods for design conceptualization. Both fall into techne (Aristotle, 2001); i.e. that these are productive and creative acts of producing either geometric figure or persuasive speech.

In this second paper in a series of three, we pursue the development of a theoretical knowledge base. This would eventually be the basis for the design science research (DSR) activity, to be presented in the third paper. First, the method is described, next relevant theories are described, and interpretations and comparisons to existing design conceptualization complete the paper.

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2 METHOD

As in the first paper, also here we have adapted the DSR methodology (Kuechler and Vaishnavi, 2011), which Hevner (2007) describes as process of achieving knowledge and understanding of a problem domain by building and application of a designed artefact. Within this study, the focus is on the development of knowledge base, primarily through literature study method (Figure 1). We approach the development of knowledge base through the perspective of production science (Koskela and Ballard, 2012, Koskela, 2000), or in other words *techne* (Meos, 2011). After articulating the basic ideas of the proto-theory of design and design rhetoric, we provide an interpretation and comparison of these concepts within the context of the wider design literature.

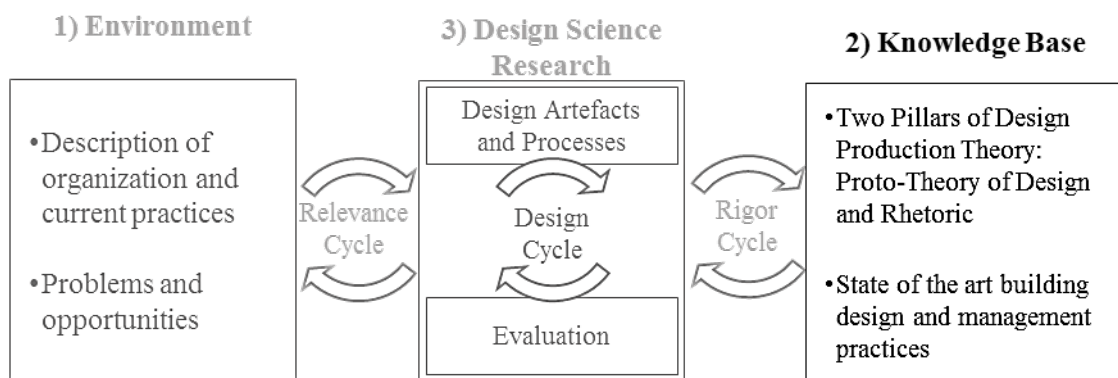


Figure 1. Design science research methodology for developing future design process and management model (adapted from Hevner (2007)).

3 TWO PILLARS OF DESIGN PRODUCTION

We start with the discussion by Kroes (2002) to justify the selection of proto-theory of design and design rhetoric as relevant prescriptions for design conceptualization. Kroes (2002) argues that Simon's view on artefact's 'inner' and 'outer' environment is limited and must be expanded. Kroes reasoned that the focus must shift from considering artefacts merely as technical to considering these also as social within the context of intentional human action. Thus, he proposed the concept of "dual nature of artefacts".

In this work, it is opportune to propose that the proto-theory of design and design rhetoric represent different but related dimensions of a productive act (*techne*). These concepts provide the explanation for addressing artefacts as technical and social phenomena.

3.1 Proto-theory of Design as Rational Reasoning

Koskela and Kagioglou argue that despite that ancient method of analysis (geometry) and its understanding was lost, including also the precise contents of analysis and synthesis, the conception of (engineering) design as rational reasoning has persisted throughout the history, to be the common assumption in contemporary (engineering) design theories (Koskela and Kagioglou, 2006). Based on the work of Aristotle and the Greek geometer Pappus, Koskela et al. (2014) identified seven key properties of the method of analysis: its start and end points, types of analysis, its stages, the types of reasoning involved, unity of two directions, the strategy of reasoning and the targeted outcomes.

In ancient method of analysis, the start and the ends points have been described to be qualitatively different. It is the movement from something given (start of analysis) to

something known (the end of analysis/start of synthesis). This stream is called analysis, including two stages, discovery and design embodiment, and three different (regressive, decomposition and transformation) types of reasoning (Koskela et al., 2014). Within contemporary design literature, two stages describe the two different time periods within the design process and/or two stages of the design reasoning.

Analysis progresses from requirements (functional and non-functional) to function allocation (concept) and from concept to design solution (structure/form) in two-step abductive reasoning (Kroll and Koskela, 2016). The progression from one to the next state is informed by continuously comparing the designs (either concept or solution) to the design goal (requirements). These concepts introduce the notions of iteration and heuristics into the analysis (Koskela et al., 2014, Ullman, 2009).

Design process is also recursive, meaning that every decision made during two-step abductive reasoning or in previous process stage, frames or constrains the subsequent decisions, including downstream design decisions (Ullman, 2009) and synthesis (making). Simply, for example decisions made in conceptual design, bound and constrain the solution space within the following design stages.

The end of analysis/start of synthesis (something known) is the beginning for another stream called synthesis (making). In synthesis, as a first step, the design solution(s) chosen are communicated/transmitted and implemented in tangible medium. From there design progresses by two different modes of reasoning, composition and deduction (Koskela et al., 2014), and activities, assembly and testing, to verify the construct against corresponding step in analysis, and to finally validate the design solution against client expectations. Verification is considered as rational and validation as plausible, subject to customer value judgment.

Thus, as opposed to dominant view in design literature (Roozenburg, 1993, Jones, 1992), analysis is creative too and concerned with devising a plan of action (means) to arrive at the desired result (ends). Synthesis is the implementation of the developed plan (Polya, 2014). Both streams of inference and action are subject to the properties of the abductive reasoning (Kroll and Koskela, 2016).

3.2 Rhetoric as a Plausible Reasoning

Partly due to the developments in the philosophy and epistemology of science, studying design as a rhetorical inquiry has captured extended attention within 20th century. Design has been considered as deliberative genre of rhetoric (Buchanan, 2001) - designers are concerned with questions of the best use of resources with the intention of the best interest of the audience (Herrick, 2015). Within this process, designers follow different lines of argumentation and pull knowledge from special and common places, similarly to the use of topoi (Burton, 1996) in classical rhetoric.

The design discourse begins with a problematic situation for new design (kairos) (Burton, 1996), a process for closing the gap between the currently unsatisfied customer needs and how things ought to be (Andreasen et al., 2015). The starting point of the rhetorical discourse is concerned with endoxa (common opinions) - the common ground about shared values, facts and presumptions between the designer and the customer/users (Koskela, 2015). Understanding the situation is necessary first step for designer to adapt to his/her audience by selecting the intention (Herrick, 2015). According to Perelman (2012), the four types of audiences include: universal, particular, audience of one; and oneself. For example, the society as a whole or the local government could represent the universal audience; customer and (potential) users the specific audience; colleague as the audience of one; and designer as an audience to oneself.

As conceptualized by Buchanan (1985), a designer is not creating an object or a thing, but developing a persuasive argument for creating an effect on the audience. The object of communication, the design artefact, facilitates the engagement of the designer and its (potential) users into dialog. This rhetorical dialogic has several dimensions (Herrick, 2015): it requires forethought/planning/deliberation to adopt to audience/users/customers; it is guided by intention to receive compliance; and it invites response to test the ideas. Rhetorical process is a deliberation and weighing of alternatives, not proofs of the type of mathematicians use. Aristotle states that to deliberate is to reason through alternatives, no one does this when things cannot be “other than they are” (Perelman, 1971, Kennedy, 2007). Thus, rhetoric is a model for the plausible reasoning.

The original concept of rhetoric and rhetoric in design by Buchanan (2001) are concerned with rhetoric as practiced by an individual/designer. However, the division of labor and work have introduced the need for collaboration in design and making (Koskela, 2015). In design practice, design is to a large extent co-created by different specialized disciplines developing persuasive means for meeting the ends (Andreasen et al., 2015, Koskela, 2015). It is the intention embedded in the design object that links designer to users (potential users), but also designer to designers and/or makers (contractors). Thus, the design product/object becomes a common denominator for everybody involved, either as an objective or work at hand within the conversation.

This principle of intention effectiveness connects other elements, including the transmission of rules (transferring best practices and patterns from previous experience to new one); usage of the fundamental arguments (lines of argumentation, *topoi*); and invention and development of alternatives, requirements, issues, and ideas. Transmission of rules (solution principles and methods) from previous work and experience to new work is thus an essential dimension of design.

The need to persuade, but also to judge emerges from the fact that design deals with the probable and particular (Koskela, 2015). In design, it is not possible to attend all the possible future conditions in use that prevent the causal relationships holding. Therefore, design requires reasoning concerning probable (Koskela, 2015).

Furthermore, it is the user/customer's subjectivity of changing values and needs related to the artefact that are limiting the applicability of necessary reasoning, drawing knowledge solely from the episteme (Rittel and Webber, 1973, Buchanan, 1992). The establishment of design criteria is a problem of competing values and priorities. Thus, it is the limited predictability of all future circumstances and “wicked” nature of design problems that makes studying rhetoric as method for plausible (particular and probable) reasoning compelling.

The object of the design communication is subject to three different appeals, involving interrelated qualities of useful (*logos*), desirable (*ethos*) and usable (*pathos*) (Buchanan, 1985). Designers must skillfully blend these three elements in design argument (artefact), to gain compliance to their ideas. For developing the design argument, Buchanan (2001) proposed a set of “fundamental arts of design thinking” for diffusing the appeals, form and medium. These are somewhat in parallel to traditional canons of rhetoric, including (Kennedy, 2007, Koskela, 2015): *Inventio*, (invention) is concerned with the design circumstances and common ground, audience, intention and invention of requirements, issues and ideas; *Dispositio* (arrangement) is concerned with decomposition and composition; *Elocutio* (style) refers to the communication (embodiment) of design information into medium throughout the design stages; *Memoria* (memory) is concerned with design artefacts, representations of accumulated design knowledge; and *Actio* (delivery) is concerned with the delivery of designs.

In summary, rhetoric is an art of inventive and persuasive communication forming a common system for setting, content, aim and means (Joost and Scheuermann, 2007). It is essentially the relationship, interaction between rhetor and audience, brought together in variety of objects (medium) of communication. This link is best described by Burton (1996) who states that the central rhetorical principle requires rhetor's words and subject matter be aptly fit to each other, to the circumstances and occasion (kairos), the audience and the speaker.

3.3 Interpretation and Comparison of Two Design Conceptualizations

Table 1 summarizes the different dimensions and aspects of the proto-theory of design and rhetoric. The starting point for proto-theory of design is a given design problem, while for rhetoric it is the given context/situation for understanding the particular and probable. If in analytical design problems or design requirements are assumed to be given (Vermaas, 2013), then in rhetoric only the design situation is given and requirements, issues and ideas need to be invented. For example Jensen (2011) and Emmitt and Ruikar (2013) have developed dynamic briefing method for continued customer/user involvement for understanding the design situation and customer values. The same briefings are used for evaluating the proposed designs too, representing the rhetorical dimension of design communication. On the other hand, the quality function deployment could be considered as a systematic study of user needs and requirements (Akao, 2004), guided by the necessary reasoning.

In both design concepts, there are two time periods in design, namely analysis and synthesis in proto-theory, and invention and delivery in rhetoric. These two time periods are proposed for example in an integrative design model, including discovery and design embodiment/construction (Reed, 2009). According to proto-theory, designers progress through two step abductive reasoning (Kroll and Koskela, 2016): from requirements to concepts and from concepts to structure/form; and in rhetorical design from invention (*inventio*) to arrangement (*dispositio*) to embodiment (*elocutio*). Within these two concepts, different modes of reasoning are used, in the proto-theory designers use transformation, regression and decomposition in analysis; and deduction and composition in synthesis. In rhetoric designers use argumentation and abduction (experience and intuition). Methods such as integral morphological charts (Zeiler and Savanovic, 2009), building information modelling, drawings, specifications, unit tests, checklists and quality management techniques have been used for systematic decomposition of requirements, concepts and solutions, and composition and deduction for assembling and testing more holistic solutions.

Analytical design and rhetoric represent necessary and plausible reasoning, respectively, the former based on the universal and certain, and the latter based on the probable and particular. Designers draw from common and specific places (*topoi*) to invent means for ends and advance towards different appeals in necessary (useful) and plausible reasoning (desirable and usable). However, the two step abductive reasoning in the proto-theory of design also involves drawing from experience and intuition when developing and selecting between alternative means (Kroll and Koskela, 2016). Zeiler and Savanovic (2009) proposed to use the integral (collaborative) and morphological CK theory for multidisciplinary building design, requiring designers to carry out all modes of reasoning.

The relation between parts and whole is unproblematic (a whole can be divided into parts, and parts can be put together into the whole) in analytical design, while problematic in rhetoric. Within the latter the focus is on the whole, requiring also assembling partial wholes (Koskela and Ballard, 2013). This means that the design and making are

cyclic/repeating within all the stages of design process. However, in the different stages of design, the focus is on one of the four domains, including activity, organ, parts and process (Andreasen et al., 2015). This is an important and valuable insight to production science, meaning that rhetoric proposes building artefacts (representations as physical or digital models) already during the design for the purpose of testing ideas on design audience.

In terms of collaboration, the proto-theory of design is more focused on the internal argumentation of individual designer. Rhetoric on the other hand lends itself to the service of planning and coordination as design is to large extent co-created by different specialized disciplines developing persuasive means for meeting the ends (Andreasen et al., 2015, Koskela, 2015). People need to work together because of the common objectives, interdependent activities and parts that must fit together to function and behave as required (Koskela, 2016, Pikas et al., 2016).

The targeted outcome in the proto-theory is the proof that the targeted technical artefact can be constructed with intended functions and behavior, while in rhetoric it is the persuasion of audience and their judgment (validation). As summarized by Buchanan (2001): "If a product is persuasive in the debate about how we should lead our lives, it is so because a designer has achieved a powerful and compelling balance of what is perceived to be useful, desirable and usable."

Table 1. Summary and comparison of the two design conceptualizations.

Characteristics	Proto-Theory of Design	Rhetoric in Design
Starting point	Given design problem	Given situation (common ground, audience, intention and ideas)
Time Periods	Definition and embodiment/construction	Invention and delivery
Stages	Two step abductive reasoning: function to concept to structure/form	Invention (inventio) of issues, ideas and requirements, arrangement (dispositio) and embodiment (elocutio)
Modes of Reasoning	Necessary reasoning (certain and universal)	Plausible reasoning (probable and particular)
Types of Reasoning	Transformation, regression and decomposition in analysis; and deduction and composition in synthesis	Argumentation and abduction (experience and intuition)
Types of Activities	Communication, assembly, testing, verification	Delivery, Validation
Persuasion Strategies (Appeals)	Useful (Logos)	Desirable (Ethos) and usable (Pathos)
Creativity	Finding alternative means or chains of means	In inventing topics and in composition
Whole and parts	Simple, tractable	Complex, intractable
Representation	In the thing (artefact) itself	Physical and digital models
Social Interaction	Internal argumentation	Communication as a means for collaboration
Standardization	Elements, parts and methods	Reuse and transfer of experience and methods
Output	Proof of product (useful)	Persuasion of customer, user and judgement (desirable and usable)

4 CONCLUSIONS

Within this study, we have developed a theoretical base for the design science research (DSR) activity to be carried out within the third paper. The two complementary concepts of the proto-theory of design and design rhetoric provide the necessary prescriptions for understanding the nature of the design task. The latter implies that artefacts are not merely static things, but rather have an active role in shaping the human (customer's and users') context. In rational reasoning, we ascend from given premises to conclusions that directly derive from these. The proto-theory of design is concerned with the design and making of

the artefact itself. In design rhetoric, premises are not assumed to be given and the design inquiry commences with the identification of the common ground, selecting the intention and the invention of means contributing to the three appeals of “useful, desirable and usable”. As a result of the theoretical investigation to develop the knowledge base for design management, several aspects of the design get clarified, including design inferences (modes and types of design reasoning), processes (types and modes of design activities) and strategies. We also most consider that the creative nature of the design process sets extra challenges to managing design.

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DESIGN MANAGEMENT IN A DESIGN OFFICE: SOLVING THE PROBLEM OF RELEVANCE

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Abstract: In this study we contend that the conceptual foundations of conventional construction design and design management are obsolete, and these need to be substituted by a more comprehensive theoretical basis. As the first paper in the series of three, the main objective of this study is to justify the research by determining the significant problems and challenges related to the design management in a case study organization. Design science research methodology is chosen to develop a scientifically grounded solution with practical relevance. Based on surveys, interviews, database analysis and observations, we conclude that there are significant problems with the design management practice. The major issue with design management is related to the poor and simplistic conceptualization of the design task. The problems summarized in this study facilitate the quest for the proper theoretical understanding and developing a knowledge base for designing a new process model.

Keywords: Design, design management, design science research, design management problems

1 INTRODUCTION

In this work, we contend that the conceptual foundations of conventional construction design and design management are obsolete (Ballard and Koskela 1998), and these need to be substituted by a more comprehensive theoretical basis. The narrow view of design management is founded on the conceptualization of design production as a transformation of inputs to outputs (Koskela 2000). Design managers focus on managing projects, tasks, resources and contracts (Howell et al. 2010) and less on managing people, processes, environment and technology. This has led to bad consequences (Arnell et al. 1996, Ballard and Koskela 1998, Fosse and Ballard 2016, Koskela et al. 2002, Pikas et al. 2015a, Freire and Alarcón 2002), including but not limited to: Disjointed management, operations and contracting methods; management by deliverables, focused on producing models and drawings, while needs, requirements and alternatives are poorly specified and studied; process and product uncertainty by designers/engineers on what, when and by whom must be designed; misalignment between different design flows etc.

As the first paper in the series of three, within this study the aim is to solve the problem of relevance or in another words, to justify the research purpose. For that, the current state of the practice of design and design management in an Estonian case study design office is analyzed. In following the research method is explained, results of the study are outlined, and conclusions are drawn on significant problems and challenges.

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2 METHOD

Within the domain of productive sciences, using methodologies addressing how things are is not fit to answer the questions of how things ought to be (Koskela 2008). Thus, in this work a constructivist research approach is used, namely design science research - learning through making (Kuechler and Vaishnavi 2011). The goal is to develop scientifically grounded solutions that are able to solve problems with practical relevance (Rocha et al. 2012).

For the methodological framework, we have adapted the DSR model (see Figure 1) from Hevner (2007), which is the embodiment of three closely related cycles of activities: relevance cycle between environment and design task (understanding context and requirements, and testing of developed constructs); design cycle within DSR domain (building design artefacts/processes and evaluation); rigor cycle between design science research and knowledge base (grounding in theories and methods, domain experience and expertise but also developing new knowledge generated by the research).

As part of this first article (environment in Figure 1) the current situation or “as-is” was analyzed. This stage was divided into three steps and in each of these several methods were used to study the current state of the design and management practices: 1) surveys and interviews for understanding designers and engineers’ views on main challenges; 2) database analysis based on the data from enterprise resource planning (ERP) system; 3) observation of one design project for gaining contextual understanding of the problems and challenges.

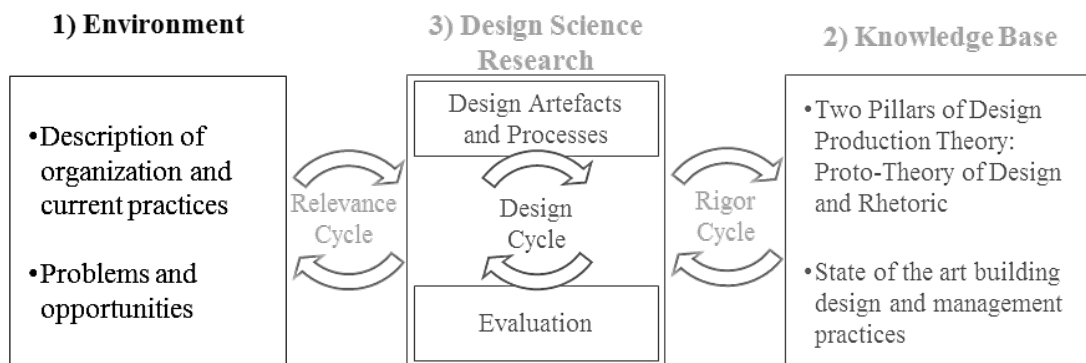


Figure 1. Design science research methodology for developing future design process and management model (adapted from Hevner (2007)).

3 PROBLEMS AND OPPORTUNITIES FOR IMPROVEMENT

The Estonian design office founded in 2005 provides multiple design services, including all services of building design and design project management except for the electrical engineering. In 2015, half of the projects were public Estonian projects, and another half were private design projects either in Estonia or in Scandinavian countries, mostly Norway. Company has been using Building Information Modelling (BIM) for the last eight years, and today all projects, no matter the size, are completed in BIM. They have around 40 people working in different departments of the organization. The primary way of standardizing and controlling the quality of the work is the usage of quality system based on ISO9000 quality management standard.

3.1.1 Survey and Interview Results

A survey, compiled in Google Forms, was sent to 34 designers, including architects (10), engineers (12 structural and 8 building services engineers) and project managers (4). Altogether 24 people responded, making the response rate 70.5%. Within the survey, respondents were asked to assess the design management and organization issues statements on five-level Likert scale from strongly disagree to strongly agree. Results were also analyzed according to the disciplines (6 architects, 7 building services engineers, 7 structural engineers, 4 project managers) and years of work experience (three <2 years, ten 3-5 years, four 6-9 years, four 10-14 years, four >15 years).

As for the general problems, the main ones were considered to be poor coordination, intrinsic uncertainty with information flows and clients' lack of timely response. However, the answers varied with respect to respondents' years of experience and discipline. The more experienced designers/engineers did not emphasize the importance of technology, in contrast to the less experienced ones. They also seemed to be more confident regarding knowing where, when and why projects go wrong. For experienced designers, engineers and projects managers, the biggest problems were related to the late changes and lack of information flows and communication.

For project managers, IT solutions played a crucial role and the main issue for project managers was the limited resources for doing the project. For building services engineers, the main problems were related to changes and poor coordination as they are typically at the end of the design production line. The results were confirmed during the group discussion, and designers added that limited time to analyze, plan and also do work is actually one of the major issues.

3.1.2 ERP Database Analysis

The case study organization has been using an ERP system for the last seven years. Thus, it was a useful resource for doing a retrospective analysis of completed projects. For conducting a database analysis, the following questions were posed: What type of projects and how successfully has the design office completed? How well are they capable of planning and executing their projects? Where in design process is the time spent? How much resources are spent on fixes, changes and meetings before and after the project contract deadline?

For querying the database, the following criteria were selected: The design office had at the minimum two disciplines working on the project; at least two stages out of typical four (schematic design (SD); preliminary design (PD); design development (DD); and Construction Documents (CD)) were done; projects were executed between January 2014 and September 2016. Altogether, data about 28 projects were analyzed, including 10 housing buildings (35%), 5 industrial and warehousing buildings (18%), 4 office and 4 public buildings (14%), 2 commercial and 2 infrastructure (7%) and 1 industrial and office project (5%). Altogether 13,421 data points (activities) with the total time of 51,357 hours were exported to Excel for statistical analysis.

The first thing analyzed was the difference between the planned hours of project work and actual hours of project work. According to the data the design company planned 50795 hours of design work and spent 50,051 hours. This is excluding the sub-contracting hours as there is no actual data about these. Thus in total absolute numbers the difference was -1%, meaning that little less time was spent on work than planned. However, the problem is not in total hours, but in the difference between planned and actual hours within a project, which according to the following building categories were 17% in Office building, 23% in Housing, 38% in Infrastructure, Commercial -6%, Industrial and Warehousing -

10%, -9% in Industrial and Office, and -136% in Public Buildings. The variance between estimate and actual was 33% and standard deviation 58%. Thus, although overall the projects could be considered successful, on the level of individual projects there is a great variance between the planned and the actual. This means that the company has a lot of variability in projects, and the success of any individual project is uncertain.

The total average of design time consumption in all 28 projects per typical project stages within three different disciplines was calculated. Much time is spent in the DD and CD stages. Little time is spent in SD (2.9% all together) and PD (9.2% all together), where the most important decisions are typically made. Moreover, in these early stages, structural and building services disciplines were involved only minimally. However, not all projects had all four stages. For comparison, 12 projects that had at least SD, PD and DD stages were filtered out and in that case the total time spent in each of these stages was 6%, 17% and 77% respectively. Thus, much time is spent on producing drawings, but not for example working through alternatives for delivering the best value to the customer.

Figure 2 illustrates the total time expenditure with respect to project duration. The same 12 projects with three stages out of 28 were analyzed. For calculating the distribution, all project durations were normalized into 5% duration increments (thus there were 20 increments) and the curve was produced by using the fourth order polynomial. Projects were divided into two categories, profitable (blue lines) and non-profitable (gray lines). The average contract deadline was determined by adding up all project's end dates in specific increment and divided by the number total number of increments. For example, if one project ended in fourth, the second in ninth and third one in sixth, then the average is 6.33 (calculated as following $(4+9+6)/3$). The figure illustrates that projects where the resource peak fell around the middle of contract duration tend to be more likely profitable. The non-profitable ones had a much flatter resource curve throughout the entire project lifetime. Additionally, all projects within this case study organization had very long tails, including time spent on changes, design fixes and meetings. These tails are the reason for non-profitable projects as most of this time and resources spent are often not reimbursed by the customers due to the type of contracts. Therefore, the conclusion from the figure is that more focus should be put on doing the right things earlier in the project to prevent the loss-causing tails. For metaphorical purpose, if one would compare the two curves to the famous McLeamy curve (McLeamy, P. 2004), clearly the profitable one is closer to that ideal.

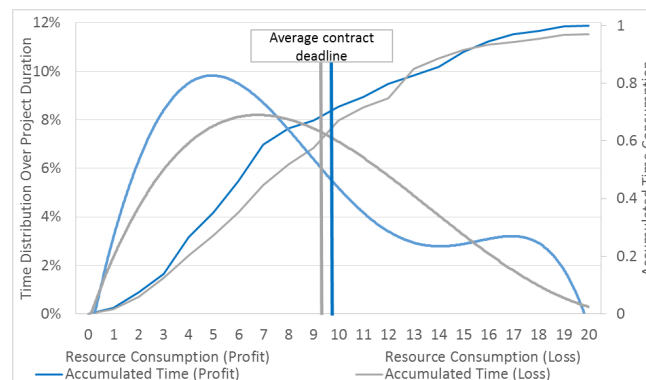


Figure 2. Time consumption over the lifetime of a design project on left and accumulated time consumption on the right axis.

Figure 3 represents the time distribution over 14 different types of activities in all 28 projects for involved disciplines. As the data show, little time is spent on activities such as

controlling and supervising work inside the discipline, which could be the reason for little control over projects, design problems and errors leading to many fixes. Also, based on the observations and interviews, it is not unusual that projects fall behind the schedule by months without anyone even noticing it. Under control, we do not mean just an inspection of completed work, but a process of making sure that right things get done right at the first time. That is, everybody understand the scope and flow of work, hand-offs, quality criteria and have all necessary inflows to commence and complete the work successfully. Thus, the lack of design production control can be considered one potential cause for project failure.

Based on the classification system of activities used within the company and assuming that design work is value adding and the rest is either non-value adding or other, designers or projects managers spend on average 52% of all time on design activities, 39% on non-value adding and 9% on everything else. However, this assessment is a black box as we do not exactly know on what this 52% was spent by designers and projects managers. For that reason, one project design development stage was observed over eight weeks.

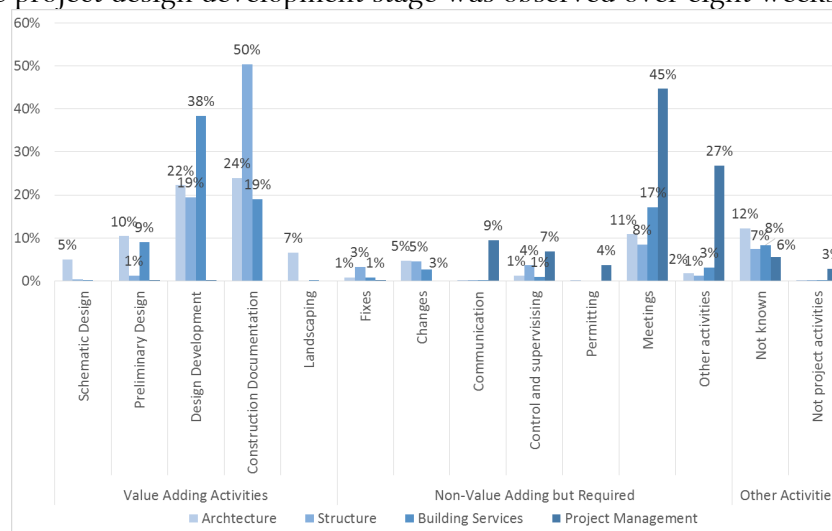


Figure 3. Average activity time distribution per discipline over 28 projects.

3.1.3 Observation of a Project's Design Development Stage

The aim of the observations, conducted over eight weeks, and two days in a week between 5.7.2016–1.9.2016, was to get contextual understanding of design and design management problems. Few interventions were introduced to meaningfully collect data, including the co-location of 9 out of 10 (3 architects, 4 structural engineers and 3 building services engineers) design team members from different disciplines and using twice a week stand-up meetings with sticky note Kanban boards. Observations were conducted on days when the team had stand-up meetings (every Tuesday and Thursday) from morning to evening sitting together with design team members and protocolling all the events of working and communicating with each other.

During eight weeks, the planned work, progress and problems discussed at the stand-up meetings were used as an input for recording tasks and for observations. Altogether 154 events were recorded during eight weeks and divided into three categories (activities 57%, exchange of information 20% and problem-solving 23%). The exchange of information and problem-solving per discipline, such as 3% exchange of information and 9% of problem-solving in architecture, show intra-disciplinary communication events. Out of 154 events, 20 were interdisciplinary events: 1 (ca 1%) activity of a total of 89; 9 (ca 29%)

exchanges of information of a total of 31; and 10 (29%) problem-solving events of a total of 35.

Only 1 event out of all 89 events was recorded as collaborative work. This occurred when the architect and the building services engineer discussed what should be the elevation of ceilings from floor level in order to provide adequate space for the building services behind it, before the actual design of the ceiling. The data show that even when co-located, the designers worked together only for the reason of exchanging information and problem-solving. Despite for co-location, design process was still fragmented and driven by partial designs. Designs were prepared primarily from the perspective of individual designers first and coordinated only retrospectively. This lack of collaborative working on activities, could be seen as a source for late fixes and changes discussed within section 3.1.2.

Altogether 89 activities were recorded, out of which 58% were design and engineering activities (calculations, drawings, specifications and model coordination), 28% changes, 6% waiting (that means designers had to stop working on an activity and do something else due to a missing input), 5% control activities and 3% other activities. Of all the 89 (57%) activities, out of 154 events recorded, only 58% could be considered directly value-adding and the rest non-value adding. Thus, based on anecdotal evidence, one could argue that the proportion of work directly adding value in design was only around 33%. This is the time when design decisions are converted into design specifications, drawings and calculations, assuming that for example exchanging information or working on the problems, though necessary, are not directly value adding.

Next, problems were analyzed to understand their source. Altogether 35 problems were recorded during observations, of which 9% were architectural, 20% structural, 43% building services related and 29% interdisciplinary. The problems within disciplines were caused by lack of information, changing requirements that rendered already developed solutions useless, conflicting needs and legislative requirements, faulty input information, and coordination issues between disciplines. For example, a client did not want to have a separate toilet for people working within the kitchen, which however according to legislation is required. Another example is changing equipment technology that required all new building services solutions. Interestingly, 26% percent of the problems were related to the usage of ICT systems. Either something could not be modelled or there was a lack of knowledge on how to use the application for a specific situation.

As the last step, communication or information exchange practices were also observed. Altogether 33 communication events were recorded. These could be divided into five categories: 29% was intra-disciplinary communication and consulting on solutions; 26% interdisciplinary coordination; 23% software training; 16% intra-disciplinary coordination; and 6% related to drafting conventions. When design team members communicated with each other, almost always some tool or object was used as a reference for communication. Out of 31 communication events, in 55% of the cases some sort of computer drafting or modelling application was used; in 21% of the cases designers used sketches either on drawings (mostly related to discussing changes) or on blank paper (mostly for drafting structural connections); in 18% of the cases, designers did not use any specific tool but communication was verbal; and in 6% of the cases something else was used (e.g. excel or project documentation server).

Before and during the project, interviews with team members were conducted for evaluating the effect of interventions. The main benefit of co-location, according to team members, was the reduction of time spent on problem-solving. The observations agree

with their assessment as several problems were solved on the spot, when they had emerged.

Based on the observations, other conclusions were drawn. The level of task break-down or resolution differentiated between different disciplines. Co-location improved the reaction speed and efficiency of problem-solving. On the other hand, the focus was on problem-solving instead of avoiding these in the first place as there was little discussion on how something should be designed. It was observed that the architect who sat separately in her department did not participate that much in different conversations, indicating that physical distance can play an important role. Experience but as well as social skills played a crucial role in initiating and facilitating discussions.

3.1.4 Summary and Generalization of As-Is Situation

This study approached the design management from a design office's perspective, not commonly adopted in the lean construction community. However, it is important that design offices have capacity to manage their internal processes as any project delivery is as successful as its weakest link. Designers have an important role to play within building projects, they are the mediating actors between customer and the contractor.

Based on the surveys, interviews, database analysis and observations, several conclusions were drawn on causes that make projects and project results highly unpredictable. Design management has focused on planning projects, tasks and resources, but not on managing the design process and value.

Design management control is primarily based on the thermostatic model of control (Koskela and Howell, 2002), monitoring deviations between planned and actual resource consumption and task completion during design meetings (e.g. 45% of project managers' time is spent in meetings). The process of making work ready is carried out in a short term perspective and motivated by urgency within weekly meetings. Much time is spent on producing drawings, but not working through alternatives for delivering best value to the customer. Based on database analysis and observations, only little time is spent on controlling and supervising work activity at the unit level (1% in architecture and building services engineering, 4% in structural engineering and 7% in project management). There is no reason to assume that the whole will work if one or several elementary units do not.

The study results support the findings of other studies discussed in the introduction. However, we hypothesized that it is the poor understanding of design and design management that have led to the bad consequences. Indeed, the evidence in this study show that design management is narrow-minded and founded on the conceptualization of design production as a transformation of inputs to outputs, missing flow and value views (Koskela 2000). Traditional project management was the only visible method/framework in use, and the outcomes corresponded to what critical accounts of it have argued to occur due to poor conceptualization.

4 CONCLUSIONS

Any act of design requires understanding of the current environment and situation to close the gap, or, in another words, how things are and how they ought to be. Within this article, the aim was to solve the problem of relevance, and for that relevant practical but also theoretical problems were articulated. In summary, the main problems observed within the case study organization include: poor conceptualization of design task; focus is on production of drawings and models; late changes and patching; unaligned work scope; unpredictable projects and plans; and poor design quality. Traditional project management

was the only visible method/framework in use, and the outcomes corresponded to what critical accounts of it have argued to occur due to poor conceptualization. This becomes the material for defining the requirements and carrying out the subsequent DSR stages for developing a proper theoretical knowledge base in the next paper, and for developing the theoretical as well as practical design management model within the third paper.

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DESIGN MANAGEMENT IN A DESIGN OFFICE: DEVELOPMENT OF THE MODEL FOR 'TO-BE'

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Abstract: As the third paper on design management in a series of three, design science research activity was carried out. Based on the problems identified within the first paper and the knowledge base established in the second paper, theoretical and practical design process and management models were developed. Within the language of two-step abductive reasoning, the theoretical model served as a solution concept for developing a practical solution. This research reports the first cycle of design science research. The result is the description of "to-be" to facilitate the change management within the case study organization.

Keywords: Root causes, design model, design management

1 INTRODUCTION

Within the first paper, problems were addressed and the conclusion was drawn that the design management of the case company is focused on the transformation view (Koskela et al., 2014). Essentially, this means that the company's interpretation of design task is too simplistic. In the second paper, we addressed the literature from the perspective of productive science (techne) to develop the theoretical knowledge base. Thus, the problems, the nature of the case study design organization and the knowledge base served this work as requirements and the source for developing a generic and practical new process and design management models. However, we must note that this work reports the first cycle of design science research. In the following, the method is described, the problems to be solved are outlined and the theoretical as well as the practical models are developed.

2 METHOD

Within this research, the design science research methodology is used (Figure 1). Within this last paper, in the series of three, first, a new theory based design process and management model ("to be") for systematically managing three complementary dimensions in a case study organization is developed. As the last step, the main author designed together with the members of the design office a new high level and second level process models. This became the basis for change management, which is a process too. Also the new models provide a framework or container for incorporating several methodologies, methods and tools to be used for better design management. The development of the design office design production and management model was carried out using the following steps: Forming an organizational product-process quality

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management team, including board members (two), heads of functional departments (altogether three, one from architecture, structure and building services each), project manager (one) and senior architects/engineers (one architect and one engineer). As the first step, every member of the team developed their own view of the design process and his/her sketches with the rest of the change management team. After that the first meeting was held to discuss different views on the design process and to develop an organization wide design process model on a high level. The latter was carried out based on the two conceptualizations of design proposed in the second article. Subsequently, three value stream mapping events for devising a new second level process model was carried out. Every meeting concluded with the discussion on the lessons learnt. Several weeks after the design science research sessions, semi-structured interviews with quality management team were conducted to evaluate the effects of the proposed models.

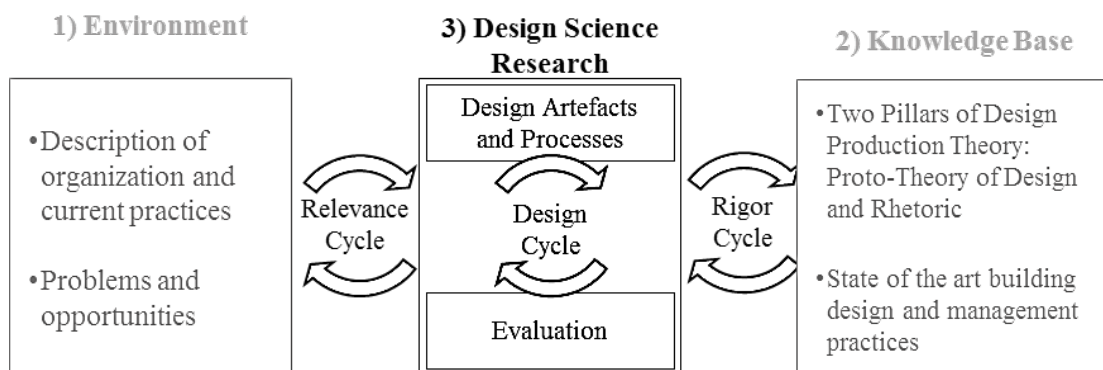


Figure 1. Design science research methodology for developing the future design process and management model (adapted from Hevner (2007)).

3 DESIGN SCIENCE RESEARCH

3.1 Problems, Requirements and Countermeasures

First, a summary of problems to be addressed within this work is outlined. Within this process, we had to take into account the needs of the company because DSR is always contextual. For example, the development of a company-wide process model required analyzing the sales process; i.e. the time period before the design contract. Analyzing sales was important because of the commitments made to the customer. Secondly, the company does not have all the building design services in-house, which means we had to explicitly include the sub-contractors into the process description as well. In Table 1, problems discussed and analyzed within the first paper are outlined with respective root causes. Additionally, we have proposed a list of countermeasures (means) based on the second article and other practices relevant to solve the problems. The idea is that the process model would become the container for the proposed means.

3.2 Theoretical Solution Concept for Process Model Development

Based on the proto-theory of design as well as design rhetoric and inspired by the "Vee" model (Forsberg et al., 2005) from systems engineering, first a theoretical high level process model was developed (shown in Figure 2). This includes two time periods (discovery and embodiment/construction) and two stages (planning/programming and concept design in discovery; design embodiment and production planning in embodiment/construction) within both periods. Within each stage the focus is on the

particular aspect/domain of the artefact (Andreasen et al., 2015): activity – analysis of the use functions and properties (objectives, criteria and programming); organ – strategic selection of systems and sub-systems for design conceptualization; parts – design embodiment, an instantiation and materialization of selected concept(s), typically from schematic design through construction documentation; and process – design of the production system. With the exception of process domain, these could be considered also as environment, function/purpose and structure in Simon's (1981) analytical design science model.

Table 1. Summary of problems, root causes and possible countermeasures.

Problems	Root Causes	Possible Countermeasures
Design management is concerned with task and resource management	Oversimplified conceptualization of design task	Proto-theory of design and design rhetoric for explaining the design process and thinking
Focus is on producing drawings and models	Assumption that the customer and users know what they need and want	Design rhetoric, design briefing, quality function deployment, level of development and customer/user involvement
Late changes and patching (creative workarounds) as the wrong thing was done or the thing was done wrong (errors)	Poor and unsystematic specification of customer/user needs and requirements	
	No systematic investigation of design alternatives	Morphological charts, Choosing-by-Advantages, Building Information Modelling and A3-s for reporting and documentation
Unaligned work scope, uncertainty of information flows, poorly coordinated work and assumption-driven designs	Poor design process management	Last Planner System, design structure matrix, dialogue matrix and the rolling wave concept
Unpredictable and unreliable plans, resulting in unpredictable projects	Design production control as thermostatic model (planned versus actual)	Pull planning and make ready process on phase, lookahead, weekly and daily (huddle meetings) levels, design process metrics and Plan-Do-Check-Act cycle and A3-s for reporting and documentation
Poor solutions and/or design errors	Poor design quality management	Unit control/testing, checklists; BIM based design coordination for integration and coordination; prototypes, simulations, design of experiments, Taguchi methods and life-cycle optimization for verification; and customer design reviews and briefing for validation; A3 for problem-solving

Rhetorical design assumes constructing partial wholes, either building physical or digital models to be tested on the different audiences (e.g. users or potential users, but also contractors, maintainers and public representatives). Thus, each stage has the two directions of the proto-theory of design, analysis and synthesis, or the two stages of rhetoric, invention and delivery.

Additionally, in a rhetorical discourse, every stage should start with studying and analyzing customers, their intentions, needs and values to be translated into requirements, typically including functional (e.g. number and areas' of spaces, indoor climate control) and non-functional requirements (e.g. facility must meet nearly Zero Energy Certification requirement). Every stage should finish with the customer/user value judgment (indicated with the diamond symbols in Figure 2). For the latter, customer design reviews and/or briefing sessions should be used. Using building information modelling and its functionalities allows the intermediate virtual construction of artefacts to facilitate the evaluation process by the relevant audiences (Eastman et al., 2011).

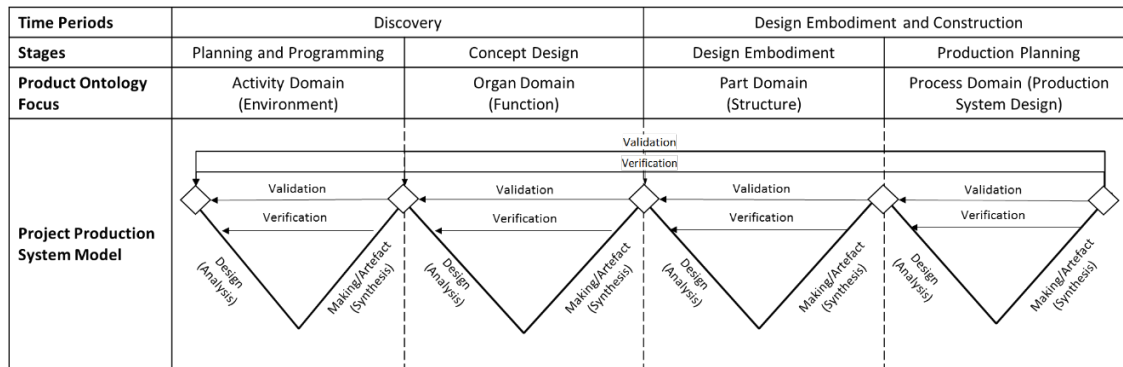


Figure 2. Design project delivery model based on the interpretation of proto-theory of design and rhetoric in design.

In Figure 3, the content of each "Vee" model with steps, reasoning modes and types of activities of design are represented. Rhetoric is concerned with the 'outer' (users, goals, resources etc.) and proto-theory with the 'inner' (function, behavior and structure) environment.

In the left leg of the "Vee" model (analysis), design rhetoric requires designers to study the situation, users and their needs, to invent requirements, issues and ideas. This is the transformation from 'outer' to 'inner' environment, into the functional and non-functional requirements. In following, the first step in two-step abductive reasoning is the requirements loop, which is the movement from requirements to concept, and design loop is a movement from concept to design solution. This process is not a linear (from step to step) and mono-directional process, but can and typically includes iterations within designers' heads. For example, it has been studied that expert designers tend to propose a solution straightaway and then try to show that it fulfils all the requirements. On the other hand, novice designers try to derive a solution proceeding logically from what is required to meet the ends (Ahmed et al., 2003). These have also been described as solution and problem-oriented strategies (Wynn, 2007).

The right leg, the opposite direction to analysis, of the model is synthesis, which is about working towards the proof and demonstration. The two types of reasoning, deduction and composition, and two types of activities, assembly and testing, are used to move the design forward (shown in Figure 3). Within synthesis, the design information created in analysis is communicated to be implemented into/in a medium (e.g. calculations, drawings, specifications, BIM models), and later composed into partial or final wholes (e.g. BIM models) to be verified for example through tests, reviews and/or simulations (Fujimoto, 2007). As a last step in synthesis, the design solution is delivered to the customer/user for validation (Buchanan, 2007). Validation is the evaluation against customer and end user needs and expectations (desirability and usability). Thus, this process is ideally symmetrical, for every step in analysis there is a counter-activity in synthesis. Within each step of the design synthesis, the design output is verified against the counter step in analysis.

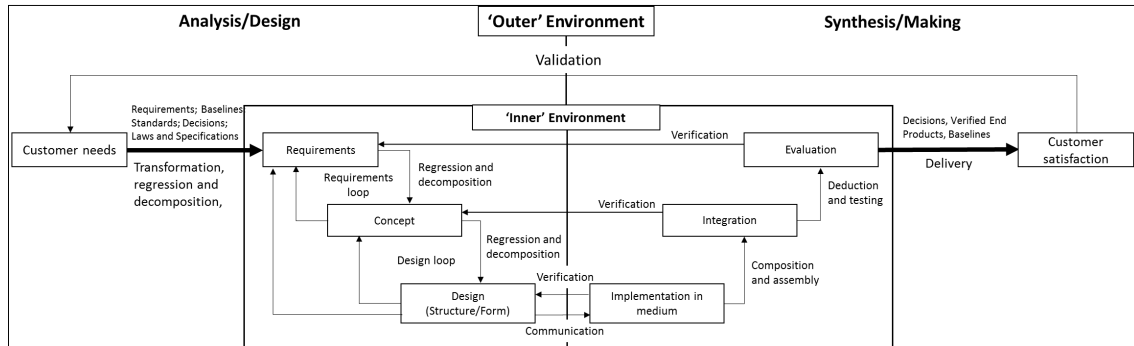


Figure 3. Design synthesis process with reasoning modes (partially adapted from Kapurch (2010)).

In Table 2 we are juxtaposing the design cognitive and process steps illustrated in Figure 3 with different methodologies, methods and tools to illustrate how and when the different methods and tools could be used. As the last step we have added the layer of design process management. This essentially means that design inquiry is almost always a collective activity. Thus, we have included collaborative methods such as the Last Planner System (Hamzeh et al., 2009), design structure matrix (Huovila et al., 1997) and some other process management related applications.

Table 2. Juxtaposition of the design cognitive and process steps with contemporary applications.

Step	Explanation	Methodologies, Methods and Tools
Transformation	Transformation of customer needs, requirements and baselines to functional and non-functional requirements	Design briefing, quality function deployment, level of development and customer/user involvement
Requirements loop (regression and decomposition)	From solution concept to design solution, a second step in abductive reasoning	Morphological charts, Choosing-by-Advantages, Sketches and/or A3-s for documentation
Design loop (regression and decomposition)		
Transmission to medium and verification	From design regression and decomposition to design implementation in medium	Building Information Modelling, drawings, specifications, calculations etc. and work unit control/testing, checklists and client reviews for verification
Composition, assembly and verification	From units of work to integrated whole	Building Information Modelling, drawings, specifications, calculations etc. and work unit control/testing, checklists and BIM based coordination and client reviews for verification
Deduction, testing and verification	From partial and final wholes to the evaluation of design solution	Building Information Modelling, A3 documentation, prototypes, simulations, design of experiments, Taguchi methods and life-cycle optimization for verification
Delivery	From evaluation of artefact functioning and behavior to the judgment of objective worth	Customer design reviews and briefing for validation
Overall Process Management	All the design cognitive but as well as process steps, which are the tasks types should be managed from the collective perspective as almost any design is carried out by several complementary disciplines	Last Planner System, design structure matrix, dialogue matrix, the rolling wave concept, pull planning and make ready process on phase, lookahead, weekly and daily (huddle meetings) levels, design process metrics and Plan-Do-Check-Act cycle

3.3 Design Cycle for Developing Case Study Organization Process and Design Management Model

Within this stage, the researcher together with the members (CEO, owner, heads of the departments and project manager) of the design office, designed first the high level

process model and then the second level process model. The high level process model shown in Figure 4 was developed based on Figure 2. In this work we have excluded the stages related to sales. Besides the milestones and the division of the design embodiment stage into four phases, other aspects have been already described in section 3.2.

Milestones represent the larger deliverables, which essentially form a baseline for subsequent stages and phases. At every milestone, which is the start and the end of a design stage and phase, there is a meeting with a focus on understanding the customer priorities, needs and requirements and/or evaluating the outputs of respective stage or phase. These could be considered design briefings and/or client review meetings, proposed to have a standardized structure (objectives, participants, typical agenda and expected outputs). The aim of the standardized meetings is to facilitate teams focusing on the content rather than on the process – thus applying the principles of rhetoric, including the situation analysis, common ground and intention selection.

The first milestone is the signing of the contract. The second milestone requires the delivery of project requirements and program, including the description of project objectives - aspirations about quality, project outcomes, sustainability, budget, feasibility, site conditions and other parameters or constraints to develop the project initial brief and criteria for measuring project success (Sinclair, 2013, Ballard, 2000). At the second milestone, a project start-up meeting should be held for all the relevant stakeholders to create a common ground about the design task. The purpose of the start-up meeting is to answer two questions: what are our objectives and how are we going to work together throughout the entire project lifetime? The next milestone is the delivery of a general concept, typically including decisions about the selection of systems and solution strategies. At the meeting the proposed concepts will be assessed by the customer and other designers. We do not go into the details of the other milestones as these are typical to most project delivery models.

Time Period	Design Project Realization							Project Completion
Stages	Discovery			Design Embodiment				Project Closeout
Phases	Planning/ Programming	Conceptual Design	Schematic Design	Preliminary Design	Design Development	Construction Documentation		
Milestones	Contract	Program/Requirements Start-Up Meeting	Concept	Program Fixed	Building Permit	Bid Package	Handover	

Figure 4. First level company process model.

Within Figure 5 we have outlined the design steps of Figure 3 with practical model steps of the generic design phase (similar process in whole design embodiment phases). Similarly to the theoretical model, the steps can be categorized into two: design/analysis/invention and synthesis/making/delivery, as shown in Figure 3. Within each stage and phase, the ‘outer’ environment (customer voice) is translated into ‘inner environment’ and back to ‘outer’ environment for validation either through design briefing sessions or evaluation meetings. This concept of translation between the two (inner and outer) helps a designer working on the inner functioning and structuring of the system while also involving users and customer into the active dialogic of pros and cons of designs. Within this process, designers and engineers collectively or individually carry out reasoning and types of activities as proposed in proto-theory of design and design rhetoric.

Inside design phases, we have described the weekly or bi-weekly Plan-Do-Check-Act (PDCA) cycles and daily cycles (indicated with light blue and transparent orange in

Figure 5). It is a generalization of the repetitive weekly PDCA cycle, describing the planning meetings with client and team, work execution and control, and the coordination (synthesis) of work-in-progress through model coordination and resolution, feeding back to team planning sessions. During the progression of a specific stage or weekly cycle, work-in-progress results will be shared with clients as well, to get early feedback on design solutions.

After the process model development, it was introduced to the whole organization by respective participants from the model development meeting; i.e. the head of the structural engineering introduced to structural engineering department, the head of architecture to architectural department etc. The proposed model became the basis for developing further improvements, including but not limited to: checklists, meeting templates and structures, new classification system for design activities, BIM execution plan etc. Finally, a process for implementing a process was developed too. Every Wednesday, the CEO of the company checks with all projects managers and heads of the departments, if things outlined in process model are followed or not.

After several weeks, semi-structured interviews with persons who participated in the new design model development were conducted. Despite it being the first cycle of design science research, the main conclusion was that the development of the model and its introduction to people in company has helped to clarify the overall process. The new process model with new methodologies, methods and tools have significantly changed the way of working in the company. The next design science research cycle is planned for July 2017.

Transformation Requirements Loop (Regression and decomposition)		Design Loop (Regression and decomposition)		Communication	Composition and/or assembly	Deduction and/or testing	Delivery	
				Verification	Verification	Verification	Validation	
Milestones/ Stages	Contract Start	Preparation and Planning	Initial Meeting	Conceptual Design	Concept Selection	Design Staging/Phasing and Production		
Inputs	Decision to sign the contract from both sides	Signed contract; client initial information (requirements); surveys and studies	Assigned project head designers; project initial information and requirements; contracts with sub-contractors; project program; meeting agenda	A3 on general project information (objectives requirements, criteria etc.); A3 on design management plan; A3 on communication and collaboration standards	Coordinated concept(s)	A3 Concept Paper describing a selected single or set of alternatives being pursued in design process	Phase schedule; Score task list	Progress, completed and work-in-process
Main Activities/ Meetings	Signing a contract	<ul style="list-style-type: none"> Assigning project manager (involved already in sales) Assigning head architect and engineers Collection of initial project information Familiarizing with project information and discussing with client Estimation of sub-contracting need Negotiation with sub-contractors and contract signing Preparation of project program and quality management plan, including BIM requirements following standard layout 	<p>Meeting Objectives: Create a common ground among all stakeholders about the design task.</p> <p>Participants: Customers, project manager, head designers, sub-contractors and other relevant stakeholders</p> <p>Typical Agenda:</p> <ol style="list-style-type: none"> Getting acquainted: organization, roles and responsibilities Common ground on a design task (objectives, criteria, constraints, possible challenges and the expected results) Design management plan: how and quality management plan, including Collaboration and communication principles: BIM, meetings' structure, communication principles, channels and tools 	<ul style="list-style-type: none"> Every discipline developing and studying alternative concepts Concept coordination and evaluation Assessment of amount of work and resources needed per stage and trade 	<p>Meeting Objectives: Evaluate different ideas and decide about the solution strategy and direction(s)</p> <p>Participants: Customers, project manager, head designers, sub-contractors and other relevant stakeholders</p> <p>Typical Agenda:</p> <ol style="list-style-type: none"> Introduction of different ideas Evaluation of benefits and challenges with each concept Selecting a Solution Direction Deciding about the design criteria for measuring project success 	<ul style="list-style-type: none"> Preparing a list of tasks based on the expected outputs of specific stage (LOI) Phase pull scheduling meeting Preparation of phased schedule based on information flows Add tasks to Score information system for tracking and assigning to persons 	<p>Weekly/By-Weekly PDCA Cycles</p> <p>Weekly/By-Weekly Customer Meetings: Progress, plan, problems, task prioritization, decisions and client input, providing and pulling information</p> <p>Weekly Design Work Planning Meeting: Weekly work planning, task coordination, commitment making</p> <p>Work execution and control: Work processing, control, progress monitoring and tracking</p>	<ul style="list-style-type: none"> Weekly or By-Weekly Model & Design Review and Coordination Client Work-in-Process Reviews Change & fixes analysis and plan
Typical Meetings	Contract signing	Project program coordination	Initial project meeting	Concept coordination and evaluation meeting	Concept(s) Selection Meeting	Pull scheduling meeting for phase	Weekly/By-Weekly Customer Meetings; Weekly Design Work Planning Meeting; Daily Huddle Meetings	
Outputs	Signed contract	Assigned project head designers; project initial information and requirements (including building program); contracts with sub-contractors; project program	A3 on general project information (objectives requirements, criteria etc.); A3 on design management plan; A3 on communication and collaboration standards	Coordinated concept(s); resource estimation	A3 Concept Paper describing a selected single or set of alternatives being pursued in design process	Phase schedule; Score task list	Decisions, required actions for constraint removal, Weekly Work Plan, work in process and completed	Required changes and fixes; change plan; work-in-process or completed

Figure 5. Comparison of the theoretical design process steps on top and practical model steps below.

4 CONCLUSIONS

Studying and developing a specific method or process model with the aid of a theory (proto-theory of design and rhetoric) is common in design research. In the given context it has allowed us to investigate the current situation and to devise a new theoretical and

practical process and design management model for the case study design company. However as design is a premediated creative act, it sets extra challenges for design management, which need to be taken into account. Despite it being the first cycle of design science research, the main conclusion was that the development of the model and its introduction to people in company helped to clarify the overall process. Also, this model has been a catalyst for developing further improvements, including but not limited to: checklists, meeting templates and structures, new classification system for design activities, BIM execution plan etc.

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A CASE STUDY ON THE SUCCESS FACTORS OF TARGET VALUE DESIGN

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Abstract: Target Value Design (TVD) has extensively been adopted in Integrated Project Delivery (IPD) environments in the U.S. Drawn from a profit planning approach used in the manufacturing industry called Target Costing (TC), TVD supports integrated project teams to plan and deliver projects for an agreed target cost. Research on TVD has revealed the success rate for delivering a project at or below the agreed target varies, and the results does not always meet expectations. Therefore, the aim of this paper was to report on lessons learned from an in depth case study that can contribute to advance the knowledge and improve the practical application of TVD on IPD projects. The research reported in this paper is part of an overarching research effort to improve the adoption of lean construction methods in the context of IPD-ish type of projects for the public sector in California. As multi-party agreements is not an option available for organizations in the public sector, this research effort focuses on understanding the underlying mechanisms of IPD in addition to contextual elements that can influence the successful application of TVD.

Keywords: Target Value Design, Target Costing, Integrated Project Delivery

1 INTRODUCTION

Target Value Design (TVD) is a lean construction method that has gained increased popularity over the years in the U.S., especially in Integrated Project Delivery (IPD) type of projects. The origins of TVD can be traced back to Target costing (TC), a practice used in new product development and popular in the car manufacturing industry. One fundamental principle of this method is viewing cost as an input to the product development process, instead of an output. Coupling this principle with transparency and cost tracking, TVD supports integrated project teams to plan and manage production costs in a setting where risks and rewards are shared (typical characteristic of an IPD environment).

The first successful TVD application in construction was reported by Ballard and Reiser (2004) in a Design-Build project in the USA. Since then, owners adopting TVD in IPD type of projects have reported significant improvement in performance (Conwell, 2012). However, a recent study based on the experience of a poll of practitioners from California reveals that even with the support of IPD principles, e.g. early involvement of participants, multi-party agreement, and shared risk and reward structure, project teams are not always successful in delivering the project to an agreed target cost (Ballard et al. 2015).

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The research reported in this paper is part of an overarching research effort to improve the adoption of lean construction methods in the context of IPD-ish type of projects for the public sector in California. As multi-party agreements is not an option available for some organizations in the public sector (and against the policies of some organizations in the private sector), this research effort focuses on understanding the underlying mechanisms of IPD in addition to contextual elements that can influence the successful adoption of TVD. Within this context, the intent of this paper was to describe and discuss the findings of a case study in which the final cost of the project exceeded the target cost established by the integrated team. Findings are then compared to another case study in which the target cost was also exceeded. Lessons learned from both cases aim to contribute to the advancement in knowledge and to improve the adoption of IPD and TVD principles.

2 LITERATURE REVIEW

The origins of Target Value Design can be traced back to Toyota's Target Costing approach. Originally introduced in Japan under the name of Genka Kikaku, Target costing is an approach to reduce the overall cost of a product over its entire life cycle, with the help of a multidisciplinary team, formed by the different departments of a company and the active contribution from the supply chain (Kato, 1993). Target costing has been defined as a "system of profit planning and cost management that is price led, customer focused, design centred, and cross functional" (Ansari et al., 1997). In target costing, market price for a new product is not determined by adding a profit margin to cost (e.g. cost-plus approach); instead, an allowable cost is determined by a target price less an appropriate profit margin (Kato, 1993).

The major contribution of TC is that it shifted the understanding of "production cost" from a fixed value (with profit and market price as variables), to production cost being variable (with profit and market price established upfront).

$$\text{Market price (fixed, determined 1st)} - \text{Target profit} = \text{Production cost (result)}$$

In the construction industry, the first effort to implement target costing was in the UK, on two military housing projects (Nicolini et al., 2000). The same authors observed several challenges to implement such an approach in the construction industry, including the industry-level fragmentation, the culture of companies being "adversaries" and the traditional cost-plus approach used in the construction industry.

The first reported successful case of TC adoption was in the construction of St. Olaf's College in Northfield, Minnesota, completed in 2002 (Ballard and Reiser, 2004). As the popularity of this approach increased in the construction industry, new reflections about its meaning and application emerged. In 2007, the term Target Value Design was coined and replaced the name 'Target Costing' (see Macomber et al. 2007). Since then, several projects in the U.S. have adopted TVD, and the lessons learned from this experience has led to the publication and periodic revision of a benchmark to support the adoption of TC in construction (e.g. Ballard 2005; 2008; 2011).

Although TVD can be implemented in any type of project, it is common practice to adopt such method in IPD type of projects. Through multi-party agreements that prescribe desired means and behaviours, IPD provides the contractual support for project teams to align their commercial interests, achieve organizational integration (i.e., downstream players involved in upstream processes and vice-versa), adopt lean management

philosophy and methods (including TVD), and use appropriate technologies that support integrated work, dissolving silos.

However, even with the supporting environment of IPD, sometimes project teams have exceeded the target cost at the end of projects. On a study done in retrospect with a project team, Ballard et al. (2015) highlight some of the difficulties faced by the team in delivering the project for an agreed target cost, including:

- Difficulty of tracking changes in scope during design with associated impact on costs;
- Reducing escalation to zero and reducing estimates too early during pre-construction;
- Collaboration issues with consultants not on the risk pool;
- Design problems cascading into execution delay and impact on interdependent systems;
- Extensive use of overtime to recover from delay;
- Lack of a transparent and shared productivity measuring system;
- Contingency set too low for the complexity of the building; and
- Drastic increase in general conditions towards the end of the project.

The same authors highlight major concerns for the success of TVD and IPD, including: (a) teams setting up fair deals with the owners upfront; (b) being able to choose their partners in the risk pool; (c) tracking and controlling costs throughout project execution (and not only design). This paper expands on that discussion and presents another case in which the target cost was exceeded, identifying similarities and differences to the case reported.

3 RESEARCH METHOD

IPD and TVD have been popularly prescribed together for the success of projects. Both approaches are based on various managerial principles, that together support project teams to generate optimal project results. However, in practice there are contextual factors and nuances on how these approaches are implemented that affect expected results. In order to refine the understanding of these factors and improve the application of TVD and IPD principles in practice (allowing it to be transferred to contexts where full IPD is not possible), a design science research approach was chosen.

Design science research supports not only the creation of new artefacts to solve problems but also the refinement of existing ones through the evaluation of their implementation. The focus of this research is not on devising new artefacts but on evaluating the adoption of TVD and IPD principles to confirm their intended consequences, identifying factors that contribute for their success.

The typical research strategy adopted in design science research is multiple case studies (Van Aken, 2004). To date, the authors of this paper collected data on seven TVD and IPD projects, two of which have exceeded the target cost. One of the cases was described in Ballard et al. (2015), the second one is the focus of this paper.

The project reported on this paper was a ~500, 000 sq ft Hospital project, that took 10 years to be delivered - from conceptual design to execution, and did not achieve the desired target cost.

The project was observed for one year and data was collected through observant participation, interviews and focus groups. A total of (a) 17 decision-making meetings and 14 meetings with the IPD team were attended, (b) 15 interviews with project team members were realized and (c) three focus groups to generate lessons learned were facilitated. Follow up interviews were also realized with key stakeholders after the project was delivered.

4 CASE STUDY

In this session, empirical observations are presented in a chronological manner, according to distinct phases of the project: early design, design development, construction documents and construction administration.

4.1 Early design phase

The project submitted their preliminary application to the city in 2003. The integrated agreement was signed in 2006 and the project continued until mid-2009, when it was partially suspended due to capital funding constraints, a consequence of the 2008 economic downturn in the U.S.

As a result, the project team had to carry out a validation study to assess the feasibility of the project within the new funding constraints. It was the interest of all participants to move the project forward and the team worked hard to make the project economically feasible by adjusting project scope and exploring ways to reduce construction costs. Through this effort, the team was granted authorization to re-start the project in mid-2010 and a revised integrated agreement was signed.

At this stage, the close participation of owners as part of the integrated team allowed a better understanding of their business case and funding constraints, helping the team to design solutions that would make the project feasible again. According to project team members, this resulted in a very challenging starting point for TVD. With an aggressive allowable cost, the team decided to set a target cost arbitrarily 5% below the allowable cost to spur innovation.

4.2 Design development phase

During design development, the project team was organized in multidisciplinary clusters, and each cluster worked within an allowable cost and towards the established target cost. As design progressed and multiple stakeholders got involved, the project scope and estimated costs of construction varied drastically and an effort was made to maintain design within the allowable costs. Interviews with project team members illustrated the difficulty to track the evolution of scope and costs during that phase, highlighting three key factors. Firstly the presence of an owner represented by two organizations with different priorities: one organization responsible for managing the funds for construction and another organization that will occupy the building. This resulted in the need to negotiate many decisions, sometimes taking longer to achieve a conclusion. Secondly, a change in key decision-making stakeholders from the users representative group. New stakeholders came with a different mind-set, causing more changes than the project team had expected. Thirdly, the fact that the architects were part of the integrated team but were not co-located in the same office space. That made it more difficult to track the evolution and costs of design development in a more integrated manner because design changes would be incorporated in the drawings without a prior assessment of their impact. Finally, the fact that not all trades were part of the risk pool. The team perceived that it was harder to collaborate and get updated estimates of those companies that were not in the risk pool.

The changes in scope and the need to revise the original design was the reason for the architects renegotiating their fees in the project. During the interviews with team members it was observed that opinions were distinct about whether or not this negotiation was justified. As part of this negotiation, the owner decided to audit the design consultants' fees, which also increased the costs of the project.

The opinion of some interviewees is that the risk pool and shared profit affects companies in different ways, depending on how their fees are set and how they traditionally make profit in projects. While there is a big incentive for general contractors to work in such terms, for companies that have their profit based on the amount of work they do, the benefits of shared savings must be higher than the profit opportunity based on amount of work.

Another aspect that was revealed during the interviews with the team was the lack of common understanding regarding how the decision making process within TVD should work: how the ideas should be vetted, who should approve them, how to better filter ideas that will impact the costs of the project and so forth. Team members joined the project in different points in time and the ideas of IPD and lean were new to many of them. The level of expertise with TVD varied greatly among team members and the project did not have an on-boarding process or formal training specific to those lean methods and techniques.

Despite these difficulties, during that stage, the co-location of GC and trade partners, the multi-disciplinary cluster organization, training on lean production principles and extensive use of BIM was very positive to stimulate project team members to find creative ways to reduce project costs. Based on their technical expertise, team members were able to explore design alternatives with similar performance but that would cost less to produce. A few examples of value engineering ideas resulting from an analysis of building configuration included:

- Changing the configuration of interior partitions to an alternative that presented an equal acoustic performance but would be less expensive to install
- Pre-mounted sink, involving multi-disciplinary components reducing field installation hours
- Modularizing and optimizing the design of glass panels to avoid waste of material

In addition, as design progressed, project estimators started to produce estimates with greater accuracy based on detailed information about building components. Greater accuracy of estimates and allocation of reduced escalation were two components that contributed to reducing expected costs and getting close to the target cost.

4.3 Construction documents phase

As the team approached the end of the design development phase and scope changes were stabilized, it was time to agree on an estimated maximum price. In that stage, the team made a commitment to deliver the project for an agreed target, setting the basis for a risk and reward distribution at the end of the project.

The cluster organization and collaboration among trade partners also contributed to designing a production system that would generate savings for the project team. Those savings were not only a result of designing multi-disciplinary and pre-fabricated solutions to increase productivity but also by coming up with efficient ways to install interconnected systems, sharing the savings from reduced field hours.

By using lean principles to achieve simplification through pre-fabrication and continuous flow, the project team was able to achieve efficiencies during the construction phase. A factor that has contributed greatly for the team's ability to design an efficient production system was training and a shared understanding among trade partners about lean construction principles, methods and tools. A few examples observed include:

- Developing an integrated logistic plan to share and therefore reduce the costs of expensive rental equipment and machinery

- Creating interdisciplinary plans that optimize the sequence of installation of interdependent building systems
- Pre-assembling building components to reduce man-power efforts in the job site
- Defining a material staging and tool distribution strategy that will reduce transportation effort

4.4 Construction administration phase

During the construction administration phase, the main focus of TVD was in tracking productivity and schedule. The team started to observe that one of the trades in the risk pool was falling behind and underperforming in terms of costs and schedule. At the end of the project, the team could not achieve the agreed target cost and the main reason was associated with the challenges faced by this particular trade during construction.

5 DISCUSSION

The observations made on this empirical case brought new insights to the success factors of TVD. The discussion is organized in chronological order and based on the formula previously presented:

$$\text{Market price} - \text{Target profit} = \text{Production cost}$$

5.1 Market Price

One important success factor of achieving a target cost seems to be tied to decisions made in the beginning of projects about market price. Uncertainties related to market fluctuations and how escalation will play throughout the years seems to be the first challenge for teams implementing TVD. In the analysed project, the team waited to commit to a target cost as much as they could. That way, they could understand how escalation would play during the construction period.

The benefit of IPD in this context is that the integrated team will bare together the uncertainty related to escalation. However, as observed by Ballard et al. (2005), a shared risk and reward structure by itself does not assure that the challenges related to escalation will be solved. A plan for managing and mitigating risks needs to be in place.

The shared responsibility of risks also supports teams to be less conservative about their estimates. As observed in this case study, during design development phase, the gap between expected costs and the target costs was reduced due to the refinement of estimates. The comfort level brought by sharing risks seems to be an important component for the success of TVD.

5.2 Target Profit

It was observed in this case study (which resonates with the findings in Ballard et al. 2015) that companies do not seem to be only after a profit. They seem to seek a long-term partnership with their clients or avoid the cancellation of the project (especially during market uncertainties), therefore willing to work around client's constraints to make the project feasible, accepting a stretched starting point for a target cost. This will influence the baseline to which final costs will be compared to and this baseline is set partially based on external factors that are out of the project's control.

Also, in construction, projects are temporary organizations formed by a group of companies, which sometimes may have different strategies for making profit. It was

observed in this case, that for companies that have their profit based on the amount of work they do, the benefits of shared savings must be higher than the profit opportunity based on amount of work. Although the multi-party agreement of IPD intends to create a better alignment among these companies, it seems that there is still some work to be done in regards to creating incentives that are perceived as equal and fair by all team members.

In this case study, it was also observed that perceived the shared savings as an incentive, were able to shift scope of work not only during the design phase but also during construction. This resulted not only in better design solutions but also in gains to field productivity during construction.

5.3 Production costs

Based on the findings of this study, production costs in TVD seem to be determined by three major components: (a) product design - costs associated with how the building is designed, (b) process design - costs associated with the production system, and (c) service design - costs associated with maintaining a temporary organization.

Product design influences the costs associated with scope, spatial configurations, modularization, systems and material performance, etc.. As observed in this case study, IPD brings downstream players to upstream processes and integrates team players that would traditionally work in silos. Such integration allowed the project team to understand better the client's business case and avoid the discontinuity of the project, as well as improve the constructability of design solutions (noting that companies that were not collocated or not contractually integrated, were not as collaborative as the ones in the team).

Production system design influences the ability to gain savings during project execution due to greater efficiency. By sharing resources, focusing on multi-disciplinary collaboration and applying lean principles, the integrated team was able to achieve significant gains in productivity. However, in this stage, companies that might bring major risks to the project need to be incentivized to collaborate in identifying and managing risks - independently if they are signatory of the multi-party agreement. This includes tracking, reporting performance and collaborating to mitigate risks.

Finally, costs of services are related to the costs of maintaining a temporary organization. If those are not agreed and made transparent from the beginning of the project, it can result in distrust among the integrated team members later on and undermine the performance of the team as a whole.

6 CONCLUDING REMARKS

The aim of this paper was to describe and discuss the findings of a case study in which the final cost of the project exceeded the target cost. The intent was to understand factors that influence the success of TVD and IPD and in the future understand how to create a similar environment in non-IPD projects.

This case brought insights about external (little control over) and internal (the team has control over) factors that influence the ability of a team to deliver a project to a target cost. Achieving an agreed target cost, seems to depend on: (a) how the market price and target cost are set; (b) how shared profit is agreed upon and made transparent; and (c) how production costs (product-process-service) are steered towards the target cost and tracked, so risks can be identified and mitigated.

The next steps of this research will be to further understand the influencing factors for the success of TVD and IPD on other case studies and explore the adaptation of these principles to a non-IPD environment.

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REVIEW OF LEAN DESIGN MANAGEMENT: PROCESSES, METHODS AND TECHNOLOGIES

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Abstract: Lean Design Management (LDM) has been used by lean practitioners to manage the design process in construction. Several methods, processes and tools have been successfully implemented, such as the Last Planner System (LPS), Target Value Design (TVD), Set-Based Design and Design Structure Matrix. However, despite the increased use of LDM, many attributes are still applied in an isolated manner. Thus, there is a lack of an integrated framework which takes into account possible combinations of LDM methods, processes, and technologies used by designers and construction companies.

The aim of this paper is to analyse design management attributes based on a literature review, case studies and interviews with practitioners, in three countries (Finland, Norway and United States), which have previously reported advanced lean design management implementations. Three new attributes were identified based on the case studies and interviews: Location-Based Design Management, Level of Detail and Real-time cost estimation. The completed list of attributes was presented to three Finnish contractors, and each selected a different combination of tools for their project which will be used as case studies in future research. Future research will test new combinations of LDM tools and evaluate their interactions and benefits to the project teams.

Keywords: Lean Design Management, Lean Construction, Last Planner System, Virtual Design and Construction, Collaboration

1 INTRODUCTION

Design in construction has been explored by lean practitioners through the concept of Lean Design Management (LDM, Koskela et al. 1997), transforming customer needs into engineering specifications and outputs (Ballard and Koskela 1998). Regardless of project delivery method, many methods, processes and tools have been used to support LDM, such as Last Planner System (LPS, Ballard 2000), Target Value Design (TVD, Ballard 2006), Set-Based Design (Lee et al. 2012) and Design Structure Matrix (Huovila et al.

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1997). In addition, the use of Virtual Design in Construction (VDC) in association with LDM is an emerging area and is being developed rapidly by both academia and construction industry (Khanzode et al. 2008, Bølviken et al. 2010, Franco and Picchi 2016). Lean and Building Information Modelling (BIM) are known to have interconnections and significant synergies between them, but both are still independent from another and can be used separately (Sacks et al. 2010). However, despite the increased use of LDM, many processes are still applied in an isolated manner. Thus, there is a lack of solutions which include the most relevant processes, methods and tools in an integrated framework.

To promote the understanding of the integration of design and production, this research examines design management concepts, tools and methods focusing on the detailed engineering and document production phase. The goal of this paper is to analyse design management attributes based on a literature review and an interview study of practitioners in countries which have previously reported advanced lean design management implementations. Our hypothesis is that to fully control the reciprocal link between design and production, companies are implementing only a part of the lean design management toolkit and so far, no company has mastered them all in an integrated system.

2 BACKGROUND

LDM has been explored in literature mainly through different social processes, methods and technologies. In this chapter, we briefly summarize each based on literature.

LPS has been studied a lot by the lean community, reducing waste and process variability and getting stakeholders more committed to the project (Koskela et al. 1997, Bolviken et al. 2010, Fosse and Ballard 2016, Franco and Picchi 2016). Collaborative Planning in Design is an adaptation of Last Planner System to design management which has been developed by the Norwegian construction company, Veidekke. The method focuses on the collaborative design production and decision-making processes (Bølviken et al. 2010). Thus, in addition to technical planning and coordination, LPS and Collaborative Planning in Design introduce the need for social processes management.

Related to social processes, there are several approaches have been developed to improve collaboration between stakeholders. Big Room is an on-site space that enables designers, builders and owner to work together and solve issues that need close participation of everyone. The main aim is to improve team collaboration through higher integration (Khanzode et al. 2008). Co-location brings all the team members together to the same physical space. It is best used by having team members from different organizations who have interdependencies within the product and between the tasks, to work close to each other in the site office in clusters (Thompson and Ozbek 2012). Big Room meetings are held only periodically but co-location is an essential part of team members' every-day activities. Continuous co-location is closely related to Big Room, but it enhances the project team information flow by reducing the time wasted while searching up-to-date information. Integrated Concurrent Engineering is a form of extreme collaboration and simultaneous engineering, where usually highly motivated team members solve interdependent design issues in a good and productive environment with a pre-planned agenda and clear objectives (Ballard and Koskela 1998, Kunz and Fischer 2009, Knotten and Svalestuen 2014).

Several methods and tools have been developed to support Lean Design Management. TVD is a model for collaboration where the designing process starts from customer's business case and the cost estimation and the design is driven by the value which the owner has defined (Ballard 2006). Target is to maximize the produced value by paying attention to cost, time and other limitations. Set-Based Design is a method which can support TVD, where issues are solved by having several possible design alternatives in play. Different alternatives are narrowed out while adding detail. Finally, at the last responsible moment, the best design solution or alternative is chosen (Lee et al. 2012). Another concept which can support TVD is Choosing by Advantages, which is a method where advantages of design alternatives are considered and used to make comparisons to choose the best design alternative (Munthe-Kaas et al. 2015).

Design Structure Matrix is a tool where tasks are defined, their relation and information need from other tasks, and from that information an optimal task sequence is indicated in the matrix (Huovila et al. 1997). Dialogue Matrix is a good tool to structure design meetings. The matrix is based on questions to other designers and answers are pulled from other team members (Bølviken et al. 2010). A3 Report is a tool, originally developed by Toyota Motor Corporation, which is used for problem-solving and it streamlines the design process (Sobek and Jimmerson 2004).

In terms of technologies, the key technology for LDM is VDC, which is a more advanced form of BIM. VDC is more than just coordination of Mechanical, Electrical and Plumbing (MEP) systems. The whole building and its technical systems are parametrically modelled in three-dimensional environment which enables the model to be used for different analysing and production planning needs, four-dimensional scheduling being a good example (Khazode et al. 2008). BIM is closely linked to lean construction (Sacks et al. 2010).

3 METHOD

First, a literature review was carried out, aiming to investigate the concepts related to LDM. Second, a series of small international case studies (mini-cases) and face-to-face company-level interviews were done, aiming to find out the main concepts, systems and tools used by the companies. A standard list of 25 questions was prepared and 12 semi-structured interviews were done in three countries (Finland, Norway and United States/California). Norway and California were selected because several case studies had been reported in lean construction literature (Ballard 2008, Khazode et al. 2008, Kunz and Fischer 2009, Knotten and Svalestuen 2014, Fosse and Ballard 2016). Finland was selected because Finnish contractors have formed a Vision 2030 consortium which explores LDM as a topic in their research program. The case study and interview findings were categorized in three groups of attributes: 1) Social processes, 2) Methods, and 3) Tools and technologies. Finally, the combined list of attributes was presented to three Finnish companies and future action research was proposed, based on case studies implementing different combinations of LDM attributes.

4 RESULTS

4.1 Concepts, systems and tools used by companies

Veidekke previously documented use of Collaborative Planning in Design (Bølviken et al. 2010), a system based on the LPS concepts, applying the same techniques used in

production to the design process. The main elements of Collaborative Planning in Design are: 1) The start-up session, aiming at a common understanding of the project scope through the perspectives of the designers and stakeholders; 2) The scheduling system, which starts with a master schedule and then applies the phase scheduling process, detailing the activities through the look ahead and weekly schedules; 3) Constraints removal, using tools such as Dialogue Matrix to improve communication among designers and project teams, and; 4) Meetings structure, where standard topics are used to guide the biweekly meetings. The interviews at Veidekke helped the research team understand Collaborative Planning in Design better but new design management attributes were not found.

Ramboll is an engineering, design and consultancy company founded in Denmark in 1945. Aiming to overcome the typical challenges in design management, such as the coordination of designers and the management of resources, combined with LPS the company uses Scrum in their design management (Cobb 2011). Underlined by pull principle, it is an incremental and iterative design management methodology, often used together with Kanban boards. It is a workflow management tool to enable pull-based design production, limit the work-in-process and prevent overdesign. For that, activities are prioritized in order of relevance, and then managed through the backlog for later follow-up, or inserted in a sprint screen, where project teams can follow the status of every activity. Scrum was originally developed to be used in agile software development projects. In construction projects, it is used as a designer's tool to improve predictability and to control risks (Owen and Koskela 2006). Backlog is a tool to prioritize design tasks and short sprints are used to effectively to finish those tasks.

Skanska Norway is the largest construction company in Norway. Skanska has implemented a CIFE certified VDC (Kunz and Fischer 2009) approach for design, planning and execution of building projects. LPS, Big Room and Integrated Concurrent Engineering sessions are also used in Skanska's projects. Like Veidekke in Norway, Skanska is using Dialogue Matrix in their design meetings and metrics are used to follow progress.

Skanska USA has been in the United States market since 1971 and it is the 3rd largest building contractor by revenue. Skanska is a founding member of Lean Construction Institute and it uses Lean approaches in their projects such as Big Room, LPS and TVD. VDC is also part of Skanska's project delivery. For managing complex design prioritizing, Design Structure Matrix is used with the software called ADePT (Choo et al. 2008).

Suffolk Construction, founded in 1982, is based in Boston, Massachusetts. In Suffolk's 24 story high-rise building project at 340 Fremont in San Francisco, California, VDC is used extensively with all the major trades and their multiple drawings and models are coordinated into one federated model. That model is also used for cost estimation purposes. Real-time cost estimation in construction is a difficult task that has been difficult to resolve (Lai et al. 2006). BIM-based real-time cost estimation is based on the link between model components and cost line items. This is an effective way of giving almost instant cost feedback of the design changes.

Suffolk uses a milestone driven pull plan to manage design. Differently from other reviewed case studies, they explicitly manage the Level of Detail of models based on milestone requirements. Different milestones are set for the permitting requirements, the coordination requirements, setting the Guaranteed Maximum Price, procurement requirements, construction start and long lead-time items. With each milestone, the level

of detail rises for each system. Suffolk used an excel-based tool to manage different designers and their outputs. Leite et al. (2011) defined Level of Detail as a process where building information models and the complexity of their components progress from the lowest level of conceptual representation to the highest level of detail based on component's use, for example for fabrication or installation needs. Suffolk is helping the designers focus on the deliverables of current design phase by giving them a requirements list so they can pull information and commitments from other project parties. For design, pull plan meetings were typically held once per milestone.

Sutter Health's Hospital project at Van Ness and Geary Campus is an Integrated Lean Project Delivery with Sutter Health, SmithGroupJJR architects and a partnership of Herrero Builders and The Boldt Company. The companies are all working together under an Integrated Form of Agreement which includes an integrated team of equal partners. All the stakeholders were brought on early to develop the project using TVD (Hamzeh et al. 2009). VDC is highly used in the project and some of the modellers doing the detailing are former installers. This arrangement lowers the risk of possible constructability issues. BIM is also used to plan production and visualize the design. Teams are co-located in clusters and each discipline related to the cluster (for example designers and sub-contractors related to MEP rough-in phase) are in the same physical location with regularly scheduled meetings. Detailed design is done in these clusters and is managed by location. LPS is used to manage design hand-offs. LPS pull scheduling is implemented so that milestones are formed by every location and a location-based production schedule is driving the design so that modelling and document production is using the same locations as construction and they are sequenced in the order of construction. This method to manage detailed design driven by a location-based schedule can be called Location-Based Design Management. To shorten response time, the Owner has provided five or six people full time right in the project office to shorten the design decision lead time. A3 reports and culture of learning and continuous improvement are used in the project.

All the attributes identified from the literature review, interviews and mini-cases are listed in Table 1. Combining interview and mini-case data with literature review, we formed an idea of what are the current best practices globally. Each company or mini-case has an "X" in the cell if they are applying the method or tool in their current projects. Circled X's are those new attributes, that are less documented and were discovered from the mini-cases or interviews.

4.2 Proposed combined model

To select a combined model (which includes methods, processes and tools) for testing in future research and case projects, a workshop was held with Finnish construction and design companies participating in the Vision 2030 consortium. They selected the combination of tools and methods for testing in case study projects presented in Table 1.

In addition to Company One's (Case 1 in Table 1) current attributes in use, they chose Design Structure Matrix as a method for prioritizing the design tasks and to reveal those tasks that require Integrated Concurrent Engineering sessions to complete them. Set-Based Design was chosen because the Company One needed a tool to help manage design options for example on parking garage decks. To support that method, Choosing by Advantages was also chosen in the toolbox. Dialogue Matrix was chosen with the idea that it would replace Company One's current design meeting structures with the goal of diminishing or eliminating design meeting minutes and memos. Company Two (Case 2 in Table 1) chose to test Big Room and study it to see if it could be applied virtually

because of the long distances between their project parties in their normal project. They selected Level of Detail as a method to be accompanied with Real-time cost estimation, for example pricing the change orders from the owner.

The difference separating Company Three (Case 3 in Table 1) from the two other companies, is the fact that Company Three is construction management consultant and not a General Contractor like Companies One and Two. Company Three chose Virtual Big Room to their toolbox to test on the next project. TVD is chosen because of the normal role of Company Three in construction projects. They are typically hired by the owner and TVD is natural choice in the toolbox which supports the company’s collaborative approach to projects. Both Companies Two and Three wanted to research more about VDC. Their goal is to develop a standard network of design dependencies for their projects.

Table 1: Attributes of Lean Design Management.

Attributes of Lean Design Management	Veidekke	Skanska Norway	Ramboll	Skanska USA	HerreroBoldt	Mini Case 1, Suffolk	Mini Case 2, Suffolk	Case 1 to be tested	Case 2 to be tested	Case 3 to be tested
1. SOCIAL PROCESS										
LPS	X	X	X	X	X	X	X	X	X	X
Big Room	X	X		X	X	X	X	X	X	X
Co-location					X					
Integrated Concurrent Engineering (ICE)	X	X						X		
Collaborative Planning in Design (CPD)	X									
2. METHODS										
Level of Detail (LOD)							(X)		X	X
Location-Based Design Management (LBDM)						(X)				
Target Value Design (TVD)				X	X					X
Set-Based Design (SBD)			X	X				X		
Choosing by Advantages (CBA)								X		
Real-time cost estimation							(X)		X	
3. TOOLS / TECHNOLOGIES										
Virtual Design and Construction (VDC)	X	X	X	X	X	X	X	X	X	X
Design Structure Matrix (DSM)				X				X		
Dialogue Matrix (DM)	X	X						X		
A3 Report					X					
Scrum			X							

5 CONCLUSIONS

The contribution of this research is to review different social processes, tools and methods based on the literature and evaluate their use within different companies by using interviews and mini-cases. In addition to the LDM tools reported in literature, we found three new ones in the interviews. All the social processes, tools and technologies form a toolbox of design management. Some of the tools, for example LPS and BIM/VDC, have been studied more than others, but different combinations and how they generate positive

interactions and outcomes have not received the attention they deserve. Projects are unique and design is a complex art of producing engineering outputs of customers' needs. Finding the optimal balance between people, process and technology, is hard because different companies use different attributes, as we found from the interviews and mini-cases. Thus, in our future empirical research we attempt to test the proposed models and combinations to find out how they affect the project teams and design management results. Performance measurement metrics to evaluate the results of case studies also need to be developed.

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HOW EVIDENCE-BASED DESIGN SUPPORTS BETTER VALUE GENERATION FOR END-USERS

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Abstract: Interest in evidence-based design (EBD) has been growing extensively. Proper design decisions can, not only maximise the occupants’ health benefits, but also, improve service delivery. There is a clear link between the concept of EBD and that of value generation to guide decision-making for better healthcare design. Through an extensive literature review, a conceptual framework is presented, illustrating important decision-making steps, considering EBD as a means, with an emphasis on how it helps increase the end-user’s value generation. The paper concludes by identifying limitations and potential future studies.

Keywords: value, healthcare building, evidence-based design

1 INTRODUCTION

A growing body of evidence indicates that physical environment affects patient and staffs well-being, healing processes, stress reduction, safety and quality of care provided in healthcare buildings. Basing healthcare design decisions on this evidence and generating actionable advice to achieve the best possible patient, staff and operational outcomes, is what evidence-based design (EBD) is all about. However, information on the effect of the built environment on end-users’ health and well-being is still very limited and difficult to establish, especially as regards how well a positive environment could be. It seems premature to formulate EBD guidelines for decision-making and is an area in need of further research (Tzortzopoulos et al.,2005, Dijkstra and Pieterse 2006).

This paper explores how EBD supports better value generation for end-users. It is structured as follows: it begins by describing value in general and healthcare building specifically in literature and practice, followed by interpreting the research problems and method. The paper goes on to present the review findings, illustrating important steps used for decision-making in a given setting when using EBD as an intervention, with an emphasis on how EBD helps increase end-user generation. The paper concludes by identifying limitations and potential future studies.

1.1 Value in Healthcare Buildings

Improving performance depends on having a shared goal that unites the interests and activities of all stakeholders. In most fields, the pre-eminent goal is to reach the best possible value from the point of view of the customer (Shewhart, 1931). Nowadays, the emphasis on ‘value’ and how it can be generated and maximised, is growing in

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popularity. One of the essential issues is how to define and measure it (Koskela, 2000). For example, 'value' in project management can be defined as meeting the original design within cost, schedule and quality limits (Koskela et al., 2002). According to Zeithaml (1988), 'perceived value' is the consumer's overall assessment of the utility of a product, based on perceptions of what is received and what is given.

In healthcare, stakeholders have myriad, often conflicting, goals, including access to services, profitability, high quality, cost containment and safety (Porter, 2010). Achieving high value for end-users (patients) becomes the overarching goal of healthcare delivery; as value improves, patients, providers and suppliers can all benefit while the economic sustainability of the healthcare system increases (Porter, 2010). Within this context, value can be something tangible, such as recovery time, staff absenteeism, medical errors, falls, budget plans, service costs, energy consumption and so forth. For example, Walch et al. (2005), found that patients staying on the bright side of the hospital unit (46% higher-intensity sunlight exposure on average) took 22% less analgesic medication per hour and had 21% less pain medication costs. Raanaas et al. (2012), carried out a longitudinal quasi-experiment and found a blocked window view appeared to negatively influence changes in physical health for women and mental health for men ($p < .05$), when compared to the patients who were assigned to the room with a panoramic view.

On the other hand, the value can also be intangible, such as comfort, satisfaction, quality of sleep and working efficiency. In fact, patients are particularly affected by the intangible aspects of the building. For example, Kaldenberg (1999), discovered that patients in private rooms were more satisfied with their hospital stay, including their communication with staff members, than were patients staying in multiple-occupancy rooms. Freedman et al. (2001), concluded, in a review of current knowledge about sleep in the ICU, that noise was a notable contributor to sleep disorders.

It can be seen that value is measured by outputs, not inputs (Koskela, 2000). Hence, value in healthcare depends on the actual patient health outcomes because it is what ultimately matters for customers (patients) and unites the interests of all system actors (Porter, 2006). Like Stichler once argued, healthcare building is: "A physical setting ... that supports patients and families through the stresses imposed by illness, hospitalization, medical visits, the process of healing ..." (2001).

1.2 Summary and Focus of this Paper

From the introduction and a brief review above, it can be anticipated that: (i) the value generation process needs to identify effective and efficient design solutions so that the customer's perception and experience are optimized; (ii) the built environment of healthcare building can, not only maximize the occupants' health benefit (Salonen et al., 2013) but also, improve the service delivery (Grazier, 1999). This research is an attempt to link the concept of EBD, and that of value generation, to guide decision-making for better healthcare design.

This paper acts as a follow-up to initial preparatory work (Zhang et al., 2016). Through an extensive literature review, two research questions are addressed: (i) How can EBD be used to support design decision-making? (ii) What is the value of EBD from the patient's perspective? In other words, what does it bring to the end-users of healthcare building? The purpose of this paper is to identify the starting point of these two research questions and to establish the vision to which the questions are directed.

2 METHOD

A synthesis of the literature is performed to explore current research on EBD with respect to process (evidence generation) and output (value generation). It was carried out, not only to collect the evidence that relates to value generation, but also, to explore how practical options/interventions help increase the value generation. The literature search employed a three-step strategy. Firstly, a wide range of key words and phrases associated with healthcare, building and environment and user experiences were identified from a framework initially built up from previous work (Zhang et al., 2016). Then, the evidence was reviewed by seeking detailed descriptions of how the studies were carried out and how their key findings contributed to value generation. By reviewing the EBD process and output, a conceptual framework was developed to facilitate decision-making in terms of supporting it. In total, 30 papers, reports and books (seven review papers) written in English were included in this paper. It has to be mentioned that this review focused on ‘how well a positive environment’ can contribute to health benefits, therefore, the evidence of negative impact (e.g. noise) was not included.

3 RESULTS AND DISCUSSION

3.1 Framework

Figure 1 establishes the links between design decision-making (EBD means) and value generation (value output) in a given setting/project by illustrating how EBD can be applied to support design decision-making with four steps. Firstly, when evidence is identified as a potential for implementation, collecting relevant sources available will be very important, to not only accurately reflect the most up-to-date information, but also, to reduce bias and acknowledge uncertainty. Nowadays, the evidence that supports healthcare building design has been accumulated extensively from scientific research, statistics and many other sources being used in practice. The Cochrane Database of Systematic Reviews (CDSR), Pubmed (Medline), Jstor and Scopus are a few common databases used to find relevant information.

EBD draws on knowledge from a multitude of disciplines with varying approaches to knowledge generation and therefore, it is difficult for implementation in practice due to the different level of credibility and also the fact that not all of the design elements collected are equally positive (step 2). This has also been discussed by a few previous studies using a different approach. For example, Pati (2011), proposed a framework for evaluating the degree of credibility of a specific (or a body) of evidence, separating the strength and quality from the evaluation of appropriateness and feasibility in a specific application context. The assessment of the evidence’s credibility will help the stakeholders understand it and treat it with a different level of confidence, avoiding the inappropriate usage (DiCenso et al., 2009).

As most studies attempt to develop one specific evidence to address specific health outcomes, it is important to realise that the benefits generated from EBD depend on how it is applied. The evidence synthesization (step 3) will create a new understanding of EBD by analysing findings from different sources of evidence, with a focus on the same topic of interest, and integrate the best evidence that fits into a given situation (Popay, 2005). A few works also explored the potential solutions to create a manageable framework that integrates varied design features together, for example, Durmisevic and Ciftcioglu (2010); Rybkowski and Ballard (2008). Special attention has to be paid to those

conflicting evidences, for example, in the current debate of physical size, is bigger better? The implementation has to be carefully considered in the given setting/project.

The central part of this framework in this paper is the ‘value generation’ analysis (step 4) which is an essential tool for the early design stage when developing an EBD implementation. It is obvious that the more valuable a piece of evidence, the more confidence one has in the findings for application in building and environmental design, regardless of its source: scientific journal and/or practice. To clarify it, the next section assesses the current state of development in detail.

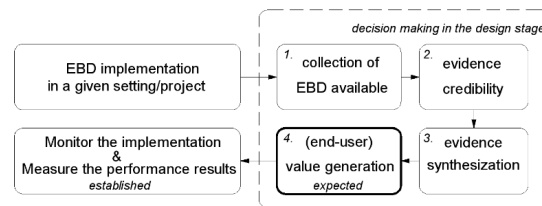


Figure 1: links between design decision-making (EBD means) and value generation (value output)

3.2 End-users’ Value Generation

The findings of the literature review were organized with the same structure in the following format: **EBD foci** were firstly categorized into four groups that relate to end-users’ experiences when they are in the immediate building space. How EBD adds value for the end-user is also presented in brackets: [a] Improves patient safety and stress level; [b] Improves staff working efficiency and reduces staff turnover; [c] Decreases the need for medication and length of stay; [d] Promotes efficient workflow and quality care. *Practical options* are then specified with a number from I to IV indicating the level of credibility: [I] systematic review; [II] experimental studies; [III] quasi-experiential studies; [IV] consensus and expert opinions, followed by a few relevant case studies that could link EBD and value generation for the end-users.

Positive Perception [a, c]→

Links to nature [II~III]: Indoor courtyards and atria with greenery (Dijkstra et al., 2008); window view of natural scenery (Raanaas et al., 2012) and well-designed gardens with easy entry, sitting areas (Cooper-Marcus and Barnes, 1995) provide calming and pleasant views of nature which is effective and beneficial for stressed patients and staff.

Natural light [II~III]: Large glazing area without obstruction allows the room to receive abundant daylight. Patients had shorter hospital stays when receiving abundant daylight (Raanaas et al., 2012) and took less medicine (Walch et al., 2005).

Colour and art [III~IV]: Calming and restoring colours (e.g. blues, greens and violet) (Fontaine et al., 2001); art content (e.g. blue waterscapes, green landscapes) (Daykin et al., 2008) are recommended for high-stress areas and also, areas that require concentration and visual acuity.

Manual control [IV]: Patients have a choice with manual control of room temperature, ventilation rate, lighting level and/or sound when these fall into unacceptable levels (Ulrich et al., 2008). This will be an efficient way to give a familiar and less overwhelming feeling to patients.

Privacy [III~IV]: High level of privacy and confidentiality improves communication efficiency (Kaldenberg, 1999), infection control and satisfaction (e.g. single patient rooms) (Kirk, 2002). Patients perceive significantly less auditory and visual privacy in areas with curtains, compared to a room with solid walls (Barlas et al., 2001).

Flexibility usage [b, d]→

Nursing station [III~IV]: The 'hybrid' nursing station may strike a balance between the increase in computer duties and the ongoing need for communication that addresses the conflicting demands of technology and direct patient care (Zborowsky et al., 2010).

Personalized functional zone [III~IV]: It provides a certain level of flexibility for alternative activities and service efficiency (e.g. family zone) (Douglas and Douglas, 2004) breakout area for nurses (Sheahan et al., 2016) and therapy garden (Marcus and Barnes, 1999).

Patient room [III~IV]: Single patient room (NHS Estates, 2005) acuity-adaptable rooms (Hendrich et al., 2004) improve the flow of patients and delivery of care. However, few reliable studies were found to evaluate the value of single patient rooms thoroughly (Glind et al., 2007).

Accessibility [a, c, d]→

Location [IV]: A well-structured path, clear and few choices in navigation (Carpman & Grant, 2002), unique identification at each location and abundant area for car park (Arthur & Passini, 1992) can improve the overall user flow.

Signage [III~IV]: Typography, colour, pictograms and icons are all elements that can be used in order to offer as much information as needed (Uebele, 2007).

Closeness [IV]: Delivering healthcare services closer to home and nearer to people, alongside work on other solutions, avoids emergency admissions to acute hospital, for example, health and social care centres, community care centres and specialist care centres (Monitor, 2015)

Facilities and Maintenance [a, b]→

Surface [II~III]: Carpets reduce falls, resultant injuries, noise levels and glare disturbance (Crane et al., 2014) while hard materials (matte, vinyl-covered surfaces) are easy for maintenance and cleaning (CDC and HICPAC, 2003). Soft flooring is more cost-effective for initial purchase and installation, equipment assets and maintenance over the time of facilities (Harris & Fitzgerald, 2015).

Ergonomics [I]: Ergonomic chairs and desks, adjustable and movable furniture reduce falls, back pain, and increase social interaction (Ulrich et al., 2008). Incidence of falls is improved by reducing the design faults, for example, slippery floors, inappropriate door openings, poor placement of rails and accessories and incorrect toilet and furniture heights (Springer, 2007).

Mechanical control [I]: Mechanical ventilation provides a comfortable environment by controlling the air movement, dust, smell, relative humidity and air quality, which reduces the infection risk that is spread through airborne transmission (Li et al., 2007).

This section first presented a framework indicating an information flow from design decision-making (EBD means) to value generation (value output). Each step of this process has its own respective challenge. For example, when it comes to collecting available EBD, attention should be paid to ensure the 'databases' used are kept up to date. Centralizing the data means that only one location has to be searched and managed. As evidence is from multi-dimensional perspectives, and its credibility is varied due to the approaches used to generate knowledge, the assessment of evidence is not only about the strength of credibility but also, about how applicable it is to a specific context. Though research and studies have made an effort to contribute to the richness of the data, there are still questions regarding existing and new pieces of evidence integration. How do we manage the complexities of evidence from different aspects and its relationship in a co-ordinated way? This is a serious issue which could make it difficult to implement, as the value may become unpredictable when decision-making is restricted to a specific context.

For example, will the value be enhanced or compromised when taking into account the interactive and correlated effect along with other factors or, when its applicability is in another culture or region, with different healthcare or economy systems? Strategies are needed to best ensure these elements are considered at an early design stage. Furthermore, when the value generation from the EBD process is expected, the implementation reaches its very core: monitoring in an appropriate way (e.g. collect baseline performance measures) so the performance results can be measured. It allows for determining if EBD is implemented with good output (value generation). If not, it allows for taking corrective measures while implementation is in progress. It is expected that new insights will appear during this monitoring process. In this way, EBD means and value outputs are both being further validated and expanded. Another exploration of this conceptual process will be taken to evaluate whether it is right.

4 LIMITATION AND CONCLUSIONS

The evidence base in healthcare design is not yet comprehensive enough to support all decision-making contexts. This paper proposed an alternative view of EBD, exploring how the concept of EBD supports better value generation for end-users. It presents the starting point of our research in this area, an exercise in critical reflection and appraisal and a holistic view of EBD integration that supports value generation which will be a promising area for healthcare building research. From the design point of view, the research takes an integrated approach of the built environment (hospital), seeking to explain the impacts of the environment on human well-being and performance. From the end-user point of view, the research looks at design strategies with the intention to maximize the occupants' benefits and minimize buildings' maintenance and management. As this study is still at the initial stage, it is limited to a conceptual approach that still has to be explored in a qualitative/quantitative empirical setting. Also, when collecting evidence that can make a difference to end users, some factors have a negative or positive impact; some have to take into consideration trade-offs in order to maximize environmental benefits. Therefore, the review may have been over-simplified when only positive impact was included in. Despite this, it makes a contribution to EBD research and its better links to value generation as a concept, by focusing on the end-user perspective. It raises issues about the nature of how EBD helps to increase the user value and offers an understanding of the future research necessary to support healthcare building and built environment at the design stage.

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PRODUCTION PLANNING AND CONTROL TRACK

Track Chair:

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PROJECT FLEXIBILITY AND LEAN CONSTRUCTION

Glenn Ballard¹ and Hajnalka Vaagen²

Abstract: The Last Planner system was initially focused only on production control functions, trying to improve the match between SHOULD and CAN, CAN and WILL, and WILL and DID. A partial specification of SHOULD was introduced into Last Planner practice in 1998 with the pull planning of phase schedules. The next logical extension of Last Planner is to the planning of master schedules and the project execution strategies of which they are a part. One of the key elements in that extension is managing variation, both negative and positive (risks and opportunities). This paper offers a framework for managing variation. Subsequent papers will apply that framework in processes for producing project execution strategies and master schedules.

Keywords: Lean construction, Uncertainty, Flexibility.

1 INTRODUCTION AND A FRAMEWORK TO HANDLE VARIATION IN PROJECTS

Kahneman & Tversky (1982) distinguish between internal and external randomness, in order to differentiate between phenomena for which it is potentially wise to collect information to reduce the variation, and phenomena for which this makes no sense. In the context of project based production systems, that distinction appears as two types of variation: 1) Statistically describable variation, for which the mitigation strategy is a) variation reduction and b) buffering the 'at-that-time' irreducible variation; *and* 2) Low probability/high impact changes, for which creating flexibility, to adapt changes with least disturbance, is the appropriate strategy. Buffering would be prohibitively costly in time or money, and would not exploit the opportunities that are offered by such events. See e.g. Wallace (2010) for a more detailed discussion.

This paper applies two industry cases to identify and exemplify the above distinction, and offers a framework for managing variation in projects. Subsequent papers will apply that framework for producing project execution strategies and master schedules. The research foundation was established by a series of incremental steps undertaken through long term research engagement within the Aera Energy case for oil field development, and a shipbuilder for advanced marine operations.

The Aera Energy case illustrates how to manage variation that is statistically describable; including both how to reduce variation and how to buffer not-yet-reducible variation. These methods were applied to an oil field development process conceived as a multi-project processing system in which individual wells were the projects.

The shipbuilding case, with the Last Planner system (Ballard and Tommelein 2016) partially implemented, discusses design changes, where the frequency of occurrence is

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well known but the type of change is difficult to anticipate. This type of variation, along with concurrency in engineering and execution to reduce lead times, dictates a complex planning problem where the project network itself is altered (i.e. the tasks to be performed and their sequencing), not only the task durations. See Vaagen et al. (2017) for the technical aspects of the problem. The social aspects of an observed proactive behaviour, to handle low probability/high impact events, are discussed in Vaagen et al. (2016).

The proposed *framework to manage variation in projects* is illustrated by Figure 1. It consists in identification of the two major types of variation, and strategies to manage them. In Section 2 and Section 3 examples are provided for statistically describable variation and buffering strategies, then for low probability/high impact events and flexibility strategies. Conclusion and future research paths are given in Section 4.

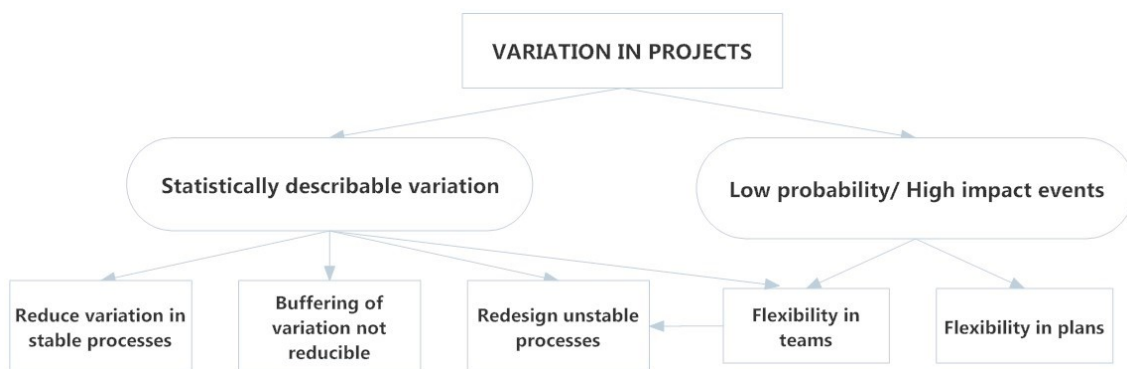


Figure 1 A framework to manage variation in projects

2 STATISTICALLY DESCRIBABLE VARIATION

Processes may be stable or unstable. This distinction is the basis for statistical process control (Leavenworth and Grant, 2000) and the basis for the lean advice to first stabilize, then improve processes (Liker, 2004). Stable processes have statistically predictable variation resulting from the nature of the process; i.e., from so-called ‘common’ causes. By definition, the variation in stable processes cannot be reduced by identifying special causes/disturbances to the process; the process itself must be redesigned.

The variation in processing durations of unstable processes can be reduced by identifying ‘special’ causes of variation and implementing countermeasures.

It is accepted that variation, though potentially reducible, is unavoidable in some degree at any point in time, and consequently that buffers are needed in all production systems. There are three types of buffers: time, inventory and capacity (Hopp and Spearman, 2011). There are also three production system design choices: type of buffer, location of the buffer and sizing of the buffer.

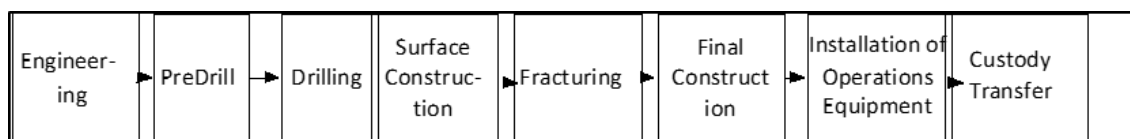


Figure 2 Oil Field Development Process

All of these elements can be seen in the Aera Energy case. When the first author began working with them in 2000, Aera Energy, already on its lean journey, asked for help applying lean to oil field development, which extends from engineering design of wells to custody turnover of the producing well to operations—as shown in Figure 2.

2.1 Reducing variation

Oil field development can be understood as a multi-project production system, in which each well is a project. In the Aera Energy case, three types of changes were made to reduce variation: 1) Reduction of batch sizes, 2) Right sizing equipment, and 3) Improving estimates of process durations.

A study of the system identified large batch sizes as a driver of wasted capacity and unnecessarily long cycle times. In an attempt to reduce the penalty imposed by setup times, the number of wells fractured from a single location had increased to as many as 50. The processes that followed Fracturing had increased their crews and equipment in an attempt to handle the 50 wells, which resulted in idle capacity during the time required for fracturing and releasing a new batch. Fracturing's batches were the first to be reduced in size, from the previous norm of 50 wells to a maximum of 12.

Another batch size problem was discovered in the packages of wells released into the process, which had grown to match the transfer batch of 50 being released by Fracturing. This batch was also reduced to a maximum of 12 and Engineering was asked to select those 12 wells for an average processing duration approximately equal to the takt time for the system, which was calculated to be 2.1 wells/day.

Since the size of transfer batches are the primary driver of cycle time (Hopp and Spearman, 2011), this reduction in batch size contributed to reducing cycle time by 36%. Having the takt target enabled better capacity allocation and provided a criterion for deciding when accelerating a well was needed. That took more variation out of the development process.

The large Fracturing batches originated in efforts to reduce the amount of time required to disassemble, move and reassemble fracturing equipment (shown in Figure 3 following) in a new location. The setup time penalty was larger than necessary because the fracturing equipment was not right-sized for the job. Aera Energy's light oil development consisted of wells approximately 2000 feet deep, but the fracturing equipment being used, shown in Figure 3, was designed for much deeper wells. The fracturing batch was reduced to a maximum of 12, and the equipment was right-sized.



Figure 3 Fracturing Equipment

Prior to the intervention described here, the duration of drilling each well was estimated by the Drilling Engineer. These estimates were used to forecast the release of wells from Drilling to Fracturing. In an attempt to improve those forecasts, a study was done comparing the Driller and Drilling Engineer's duration estimates. It was found that, after only one day (typically 25% of drilling duration), the Driller could more accurately forecast completion time of drilling.

2.2 Restructuring the system

Once the system was stabilized, it was restructured (see Figure 4 following). Changes were made to the organizational structure, a production control system was introduced, and both inventory and capacity buffers were built into the oil development process.

Value Stream Managers were appointed for each of the process boxes shown in Figure 2 previously, and the Last Planner System (Ballard and Tommelein, 2016) was introduced as a means for coordinating between processes. As found in applications of the Last Planner in other industry sectors (e.g., Vitaliy and Sacks, 2015), it not only improved reliability of work flow as a result of Value Stream Managers proactive coordination and planning, but also increased flexibility of response to the occasional plan failures, which reduced the amount of inventory and capacity needed in the respective buffers. This flexibility in plans and in teams is discussed in more detail in Section 3.

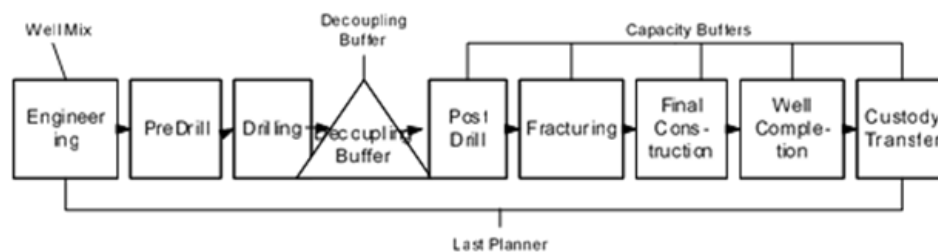


Figure 4 Production control mechanisms

A decoupling buffer was then created after drilling to release wells pulled from Fracturing. This level loaded the processes that followed Drilling, but just in case of need, overtime was reserved as a capacity buffer. The results of these initiatives to reduce variation, then buffer remaining variation were a reduction in capacity cost throughout the oil field development process of 25% and a 36% reduction in cycle time.

3 LOW PROBABILITY/HIGH IMPACT EVENTS

These events may pose risks or opportunities for project success. They typically originate from outside the project, are difficult to predict and, therefore, difficult to manage. Examples include changes in regulations, in market demand, in market conditions (competitors' actions, exchange rates, political risk). In specialized shipbuilding, design changes driven by regulations and market demand are well known, but the type of change is difficult to anticipate. It may be everything, from changes in door/ window positions (changing piping and electro systems), to large scale outfitting solutions coming late into the project execution (like the demand for helicopter deck or firefighter system), altering the project network itself by changing the scope.

The appropriate strategy for low probability/high impact events is to create *flexibility in plans* (King and Wallace, 2012, Vaagen et al., 2017), and *flexibility in teams* to quickly adapt to- and absorb variations and disturbances (also known as one capability of resilient systems; see e.g. Hollnagel et al. 2006). These are discussed below.

3.1 Flexibility

Flexibility as an operations objective refers to the firm's ability to change or adapt its operations to provide flexibility of mix (product or service), product flexibility, volume

flexibility and delivery time flexibility (Slack et al, 2007). A flexible system is one with options, where future decisions are conditioned on the arrival of new and relevant information. Strategies with options have higher initial costs than those without options (i.e. creating flexibility is usually not free), but enable adaptation to a different future scenario with least disturbance. Vaagen et al. (2017) report up to 35% lower costs of proactive (flexible) strategies as compared to deterministic reactive plans, where an initial optimal plan, developed to fit one certain design, is updated when new information arrives. A flexible strategy not only adapts to changes, but anticipates them and is prepared to react to them.

3.1.1 Flexibility in plans

Flexibility in plans can be achieved by a number of strategies, usually as a combination of hedging and postponement.

Postponement refers to decisions to be postponed to/and updated when new (and relevant) information becomes available, and when it is also feasible to update the decisions. Examples are given below.

- Structuring the work to increase knowledge about stakeholders in the project definition process to better inform decisions (see. e.g. Mok and Shen, 2016).
- Keep the solution space open and plan in greater detail as the work being planned approaches nearer in time (see e.g. Emblemståg, 2014).
- Apply the *decouple point* concept, to develop ‘two-stage planning processes’. Activities that can be executed with optimized workflow, with the information available, are assigned to the first stage. Customization activities are assigned to the second stage, after learning more about the future. The decouple point defines the degree of customization, and is the driving force behind the development of a *modular design strategy*, combining the advantages of standardization and customization in the same value delivery process (Robertson and Ulrich, 1998).

Hedging refers to developing or buying an ‘insurance’ to offset potential losses or gains. Examples are:

- *Set-based design* to develop a fallback alternative design in case it is needed to meet the Last Responsible Moment (Ward, et al., 1995).
- By consolidating *negatively correlated activities*, flexibility and free hedging can be achieved (King and Wallace, 2012). The general behaviour of correlations is that negative correlations reduce risk and are perceived as hedging in financial and product portfolio planning, while positive correlations increase risk. Planning flexibility has, therefore, low value in case of positive correlations, with planned buffers suggested as solution by Lium et al. (2009). Negatively correlated activities are observed when, e.g., design is uncertain, and one alternative potentially excludes others (may be because of weight & space restrictions). Uncertain activities competing for the same resources (e.g. equipment or space) are other sources of negative correlations; see Schuyler (2001) for more. Assessing correlations to develop prioritization rules and understand which activities to plan in parallel or sequentially, would significantly affect project risk.

The case below exemplifies postponement and hedging in specialized shipbuilding. Here, foundations for outfitting equipment are increasingly incorporated into the steel structure of the hull units. Good solution from a design perspective, but at high production costs because production of units must wait until foundations are determined, and changes of foundations also automatically lead to extra production costs. *Postponement* -by removing foundations from the steel units, and placing them in during the unit outfitting stage, when outfitting details are known- provides greater production flexibility, lower costs, and shorter time to market. A *hedging* initiative is to deck the entire prow with thicker steel sheets regardless of outfitting. Figure 5 illustrates the ‘inflexible’ situation with exact placement of thicker plates according to outfitting details, with great amount of rework time reported to adjust changes in outfitting details.



Figure 5 Illustration of outfitting equipment foundations in shipbuilding

Note that hedges need not be used in order to perform their function of preserving possible future events. For example, both the fallback alternative and the thicker steel sheets may not be needed. They are a type of insurance that enable the possibility to adopt changes. We tend to prefer not to have to use our insurance. In this respect, hedges differ from buffers, which are built into the production system, and are consumed in performing their function of absorbing variation in e.g. task duration.

3.1.2 Flexibility of Teams

Team flexibility is understood in the sense that team members recognize, adapt to- and absorb variations and disturbances, especially those that are not anticipated. The shortcomings of model-based approaches to handle low probability/ high impact changes, switched focus to the social network characteristics that facilitate a proactive behavior to cope with disturbance under pressure (Vaagen et al., 2016). Vitaliy and Sacks (2013, 2015) found that projects on which Last Planner was used strengthened their social network. Further, there have been numerous unpublished reports that project teams using Last Planner are better able to adapt to changes. A possible explanation is that teams and team members become habituated and skilled in developing plans to achieve objectives in uncertain and variable circumstances. We might call this a mindset of ‘planning to complete’, as distinct from looking back to an original plan to assess project progress.

The above suggest that Last Planner facilitates the development of responsive teams. Concretely, constraint analysis forces teams to evaluate alternative outcomes and solutions under incomplete information, while reliable commitment forces teams to actually make a decision; i.e., to make a “more-or-less intelligent” guess, postpone the decision, develop hedging or assign buffers. This, in order, leads to the understanding that team flexibility can be further improved by building the social network that can exploit options in plans and develop options not in the plan. Further research is needed here, to better understand how to apply Last Planner to explore these aspects, to help people proactively cope with disturbance under pressure.

4 CONCLUSION AND FUTURE RESEARCH

This paper provides a framework for managing variation in projects, to be applied to the development of project execution strategies and the master schedules contained in them. The framework is based on classifying variation in projects as statistically describable *and* low probability/high impact events. While the first type usually describes variation in task completion time for a given project network, the latter may significantly alter the project network itself. Methods for managing statistically describable variation include redesign of unstable processes, reduction of variation in stable processes, and buffering of variation not yet reducible. Methods for managing low probability/high impact events focus on creating flexibility in plans by postponement and hedging strategies, and by facilitating team responsiveness. These are summarized on Figure 1.

Although the suggested strategies are well established, the way they are applied and combined depends on how different frameworks distinguish between the types of randomness. For example, Husby et al. (1999) differentiates uncertainty along the project life cycle, and suggests mitigation actions based on the influence possibility throughout this timeline. Our framework is driven by acknowledging uncertainty that alters the project network itself, which also makes PERT planning methods less useful. At the same time, we acknowledge that the Last Planner system handles, to a certain extent, some of the non-anticipated changes. Which leads to the motivation to apply the suggested framework to the development of project execution strategies and master schedules within them, within the theoretical frame of Last Planner. To better understand this, consider the distinction between risks and opportunities, as the differentiation between cost- and profit-driver external uncertainties. Customer driven design change provides value with a market price for change; i.e. opportunity. This is to be treated differently from changes that are primarily cost drivers (e.g. in legal and environmental regulation). Analyzing the structural properties of the profit- and cost-driver uncertainties: the first one is a profit maximization problem, while the second is a cost minimization problem. It is obvious that, on higher planning levels, these require distinct solution approaches (and distinct project networks). However, once the options are 'paid', the problem turns to cost-focus objectives. Which suggests that the differentiation between profit- and cost-driver external uncertainties only relates to the project execution strategy and master plans, where the options that enable flexibility are to be treated. On lower levels the problem structure is similar: changes and errors are to be handled there-and-then, with least disturbance. This is where great improvements from Last Planner implementation are already reported, while the mechanisms, by which the project network itself is altered, are less understood.

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VISUALIZING DAILY ON-SITE SPACE USE

Audrey M. Bascoul¹ and Iris D. Tommelein²

Abstract: Visual Management (VM) is integral to the lean philosophy. For example, an Andon makes a light flash in the case of a deviation in the process of assembly or in the product assembled, a Kanban triggers the production of units in order to fill a customer's demand, shadow boards used in 5S help workers to locate their tools easily. What is lacking in the construction industry is simple, cost- and time-effective programs that support the understanding of the work schedule, foster transparency in daily coordination of work space among subcontractors, and facilitate production control. To address these needs, this paper presents a space scheduling program called LOSite developed for a case study project, and demonstrates that space use visualization is possible on large scale projects and can be inexpensive yet worthwhile using. The researchers prototyped LOSite in one week to help visualize the work being done during a project's interiors phase. LOSite was tested over the course of a month. Limitations to the full adoption of LOSite by the team are discussed in this paper.

Keywords: Lean construction, Visual Management, space use, space scheduling, subcontractor coordination.

1 INTRODUCTION

To remain competitive and satisfy clients, the construction industry must deliver projects faster. Decoupling activities so that they can be run simultaneously, and crashing the schedule by increasing manpower are strategies adopted to decrease project durations. Those strategies force more trades and workers to share the limited project space. However, increasing the density of workers on the project site poses a safety risk and a production control challenge if not thoughtfully managed.

This paper presents a program developed to help the project team visualize the work being done by each trade in the interiors phase. The next sections describe how this work builds upon previous research in Visual Management and space use modelling.

2 VISUAL MANAGEMENT (VM)

Visual Management (VM) is defined as a management system that increases the performance of an organization by stimulating human senses (Greif 1991, Liff and Posey 2004, Tezel 2009). VM has been in use in multiple sectors such as manufacturing, healthcare, transportation. Among them, the Toyota Production System integrates various visual tools (Liker and Meier 2005).

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In the development of standards, visual controls help to: (1) create alignment from the entire organization on the agreed standards and (2) enable workers and supervisors to recognize deviations from these standards. Once standards are consistently met, the organization can set higher standards as part of their continuous improvement cycle.

Adopting Tezel et al.'s (2015) comprehensive taxonomy of VM programs in construction, LOSite belongs to the "production control" category. Production control systems are represented by a level of: (1) initial planning, (2) lookahead planning, and (3) commitment planning (Ballard and Howell 1997). Although the project studied in this paper was delivered using traditional project management methods, the intent behind the development of the VM program was to visualize daily space use by construction trades and thereby facilitate production control. On projects using lean planning methods, trade partners could use daily space use maps to develop a shared understanding with the GC about their respective processes space needs in order to ensure continuous work flow.

3 SPACE USE

Riley and Sanvido (1995) distinguished 12 types of spaces on construction projects, including material path, staging area, and work areas. This paper will focus on work areas.

Time-space conflicts of work areas occur when two concurrent activities have overlapping space requirements. Time-space conflicts (e.g., trade stacking) are a pet peeve of project teams: they negatively impact productivity, they create safety hazards, they fuel adversarial relationships on the construction site, and they increase the likelihood of trade damage as reported in construction claims.

Time-space conflicts are more likely to occur in spaces where the so-called *work density* is high, that is: where the quantity of work (in labor-hours) per unit area and unit of time is large. Frandson et al. (2015) write that work density refers to "the situation in an area on site based on (1) the amount of work required by one trade in a particular area, (2) the trade's crew sizing and capabilities, and (3) the trade's means and methods (e.g., when prefabricating off site, the work density decreases)".

Different approaches to reduce and eliminate occurrences of time-space conflicts exist. Among them, two are relevant to this paper: (1) layout planning and (2) space scheduling. However, a fine boundary exists between the two.

Both space scheduling and layout planning are complex due to the nature of space itself: space is not a scalar variable (Tommelein and Zouein 1992) whereas other resources are (e.g., time and cost). The fine difference between space scheduling and layout planning lies in the type of relationship between space and schedule. In layout planning, that relationship is unidirectional: space requirements stem from the schedule (Tommelein and Zouein 1992). In space scheduling, that relationship is bidirectional: space requirements influence the schedule and vice versa (Tommelein and Zouein 1992). In other words, space scheduling consists in "allocating space to resources governed by a construction schedule, and conversely, changing the schedule when space availability is inadequate" (Tommelein and Zouein 1993).

Researchers have developed layout and space scheduling programs for this purpose over the last 20 years or so, while gradually augmenting dimensions (2D, 3D, 4D ...) as technology allowed it. Examples are: CORELAP (Moore 1971), ALDEP (Seehof 1971), CONSITE (Hamiani 1987), MovePlan (Tommelein and Zouein 1992), SCaRC (Thabet 1992), SEED-Layout (Flemming and Chien 1995), ArcSite (Cheng and O'Connor 1996), 4DWorkplanner (Akinci and Fischer 2000), and others. More recent and commercially

available software applications include: Synchro, Autodesk Navisworks, Bentley Navigator, to name a few.

4 PROJECT DESCRIPTION

4.1 Project Overview

The project included demolishing existing buildings and constructing a 41,000 m² (430,000 ft²) office building. The building consisted of 3 levels: a parking level, a first level, and a green roof. The project broke ground in October 2013 and lasted 16 months. The researchers joined the GC's interiors team in February 2014 and conducted "action research" on site until March 2015.

With respect to the design of the interiors, the first level resembled an immense warehouse composed of: (1) an open space called "the Big Room" in which employees can work collaboratively, and (2) about 100 clusters of rooms (called "pods") scattered across the open space. Each pod comprised between 2 and 10 rooms and is more-or-less unique, which contributed to the project's complexity.

4.2 Project Location Breakdown Structure

Although the term Location Breakdown Structure (LBS) was not used on the project, this paper employs the term for clarity. The LBS for this project changed per project phase, and the preference for each LBS varied across stakeholders. With respect to the interiors, team members juggled with two LBSs: the zone-LBS and the area-LBS. The coexistence of 2 LBSs created confusion among subcontractors, project engineers, and contributed to the project's complexity. On the one hand, the zone-LBS comprised 4 zones separated by the seismic joints of the building. The BIM implementation team used this LBS and contract documents required subcontractors to submit their 3D model per this LBS. On the other hand, the area-LBS divided the site in 5 areas of approximately the same size. The GC and the subcontractors preferred working in this LBS, because the Architect had used it to produce the 2D floor plans (Figure 1). In both LBSs, areas or zones contained a combination of a portion of collaborative open space, some pods, and some mezzanines with additional rooms and stairs.

4.3 Production Planning on the Project

The GC created the master schedule in the preconstruction phase, and used the critical path method to track project progress. The GC screened activities in a 3-week rolling lookahead schedule created in Primavera (P6) on a weekly basis, and from that schedule, assigned subcontractors tasks to perform in the coming week. The purpose of using P6 on this project was twofold: (1) meet the contract requirements and (2) manage production. The GC distributed the 3-week schedule to subcontractors in weekly meetings. The project did not use the Last Planner System.

In the lookahead schedule, the GC further grouped activities per pod. For example, the lower half of Figure 2 shows pod 1.93 that comprised 6 small conference rooms and 3 cozy rooms. Additionally, a typical activity line in the schedule included: the location (aka. a pod number), name, duration, start date, and finish date, but not the name of the subcontractor to which the activity was assigned. Examples of activities were: "Frame walls and ceilings," "Wall/ceiling rough in and backing," and "Pre-test and state inspection." This was the finest level of granularity at which activities were described.

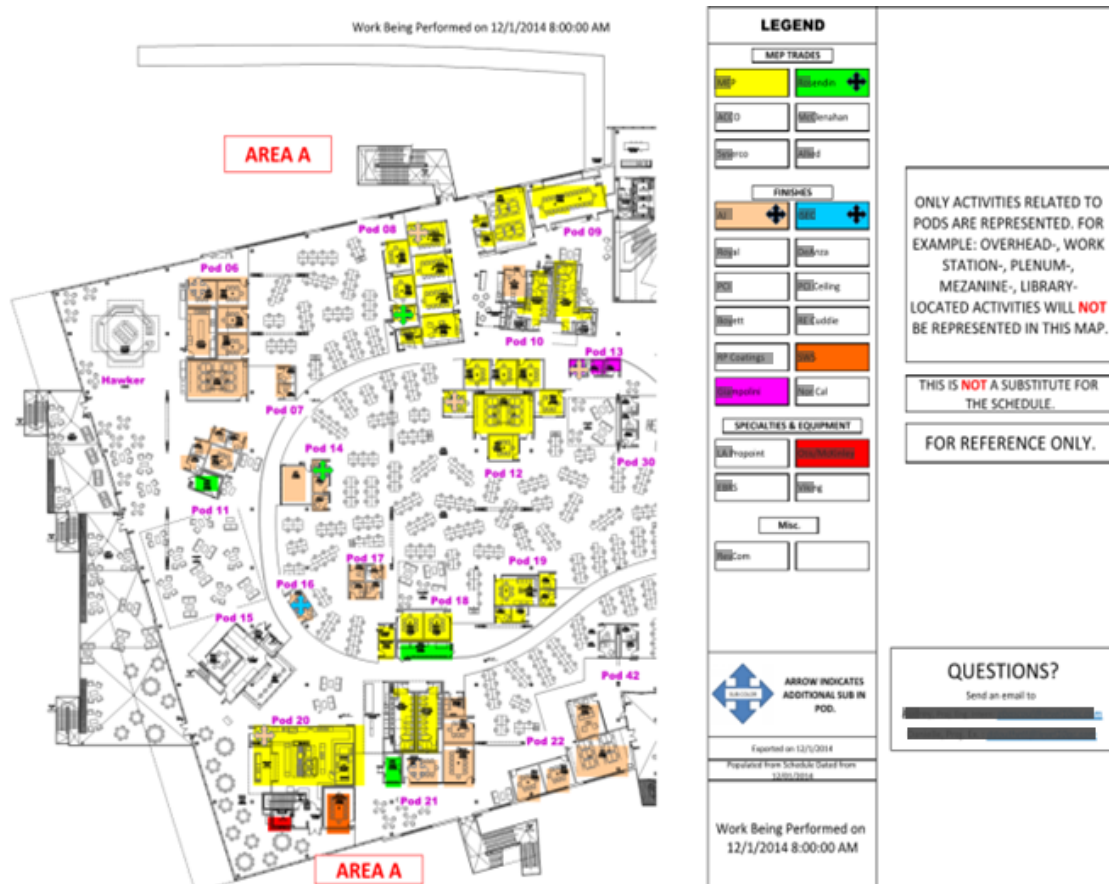


Figure 1: Output of LOSite for area A

	Activity Name	Original Duration	Start	Finish
2912	Install hoistway piping / Wiring	4	06-Nov-14 A	14-Nov-14 A
2913	Instatl cab finishes	3	12-Nov-14 A	14-Nov-14 A
2914	Pre test & state inspection	5	15-Dec-14	19-Dec-14
1.93 (6 small, 3 cozy)		96	20-Aug-14 A	06-Jan-15
2916	Frame Walls and Ceilings	4	20-Aug-14 A	21-Aug-14 A
2917	Wall / Ceiling Rough-ins & Backing	3	21-Aug-14 A	26-Aug-14 A

Figure 2: 3-week rolling lookahead schedule, line item example

4.4 Consequences of Production Planning on the Project

Since the subcontractor's name had not been populated for any activity, the P6 schedule could not be filtered by subcontractor prior to its distribution in weekly meetings. As the full 3-week schedule was handed out to the subcontractors every week, the large number of activities made it difficult for the subcontractors to (1) calculate and plan for the manpower they needed for the following week, and (2) relay instructions to their own crews on what work to do and where. If subcontractors had difficulty planning for their own crew sizes, how could they commit to weekly work plans? Poor schedule communication was experienced onsite: how could the GC rule in favor of one subcontractor or another when the two claimed work in the same location at the same time? Not surprisingly, trades had difficulty anticipating and visualizing space handoffs with the preceding and the following trades. They also were concerned with sharing work space with other trades in areas with large work density (e.g., pods), where congestion appeared to be inevitable without space scheduling. Furthermore, progress control was

also difficult on the GC's side as superintendents had no practical means of checking every day whether subcontractors had allocated enough resources to complete the work they were assigned.

As a result, subcontractors expressed the need for a better way to communicate the schedule. The researchers tried to achieve this by programming a space use visualization program, as described next.

5 LOSITE TO VISUALIZE SPACE USE

5.1 Program Design and Methodology

LOSite was initially designed to better communicate the schedule to the subcontractors than what the 3-week rolling schedule extracted from P6 did. Concerns raised by subcontractors indicated that LOSite should help them: (1) identify where they had work to complete for a given day, (2) plan for the manpower they needed for the following week, and (3) identify space-time conflicts resulting from over-allocation of space.

Although subcontractors had been identified as the main customers to LOSite, the GC also benefited from using it, as explained in the Results section.

We followed Deming's Plan Do Check Act (PDCA) cycle (action research) for the design of LOSite. The planning phase served to determine the conditions of satisfaction (COS) for LOSite. COS were then used to check results against expectations in the checking phase of the cycle. COS required LOSite to: (1) make the schedule visual to facilitate the conversation around planning work, (2) be easy to use and time-effective, (3) not require training to use, and (4) not rely on significant make-ready work. Thus, modifying the current schedule was out of the scope of this research.

Frandsen and Tommelein's (2014) work on the \$3-million dollar retrofit of an urgent care center guided LOSite design for this project. However, their project and this project differ significantly. First, their project involved takt time, which this project did not. Second, theirs was substantially smaller than ours: scope, size, number of subcontractors, etc. which entailed differences in projects complexity. The next section describes the nature of the challenges faced when developing and using LOSite, and how those challenges were overcome.

5.2 How the Daily Space-Use Visualization Program Works

LOSite was written in Visual Basic using Microsoft Excel 2014. The workbook consisted of 7 spreadsheets. Two spreadsheets contained the information exported from P6 and 5 spreadsheets contained the interiors 2D drawing of each of the 5 areas (A to E).

The level of detail the researchers chose to depict graphically on their map aimed at addressing criticism on previous research. Frandsen and Tommelein (2014) had used simple rectangles on a white background to represent work zones on site, color coded by trade for each day, but the lack of architectural detail caused trades to lose their bearing. To alleviate this problem, the researchers used the actual 2D drawings to represent space use in LOSite.

To do so, the researchers overlaid the Excel spreadsheets with the floor plans. In each of the 5 spreadsheets, they renamed the range of cells overlaying the pod with its corresponding pod number. Since activities were listed per pod number in the schedule, LOSite could identify which activity had to be performed in a given cell thanks to the cell's name.

In the same workbook, the 3-week schedule was copied-and-pasted as such on a spreadsheet. LOSite read each line of the copied schedule to check whether or not the activity was occurring on the given date (the given date was entered in LOSite by the user). If so, LOSite identified the corresponding subcontractor. The researchers created a keyword database per subcontractor so that LOSite could identify the subcontractor to assign to an activity depending on the words used in the activity's description.

Each subcontractor was represented by a color. When the subcontractor was identified for an activity, LOSite read the activity location as written in the schedule, and colored-up the corresponding range of cells that had a matching name. LOSite also colored-up the corresponding name of the subcontractor in the legend. Then, LOSite jumped to the next line in the copied schedule and iterated through the process as described.

In total, the development of LOSite took 2 weeks.

5.3 User Experience

The researchers added an interface to the workbook to facilitate the use of LOSite. This section describes the steps taken to generate the daily space schedule. The first 2 were necessary in case of a schedule update. Otherwise, the user experience started at step 3.

1. Import the schedule. The schedule was developed with P6. P6 allows users to export the schedule in.xls format. The schedule was then copied, and pasted into the Excel workbook.
2. Update the workbook (automated with Visual Basic). This step filtered out activities that did not need to be represented on the daily space schedule. Those activities included exterior activities and activities not tied to a pod number.
3. Select the area to color-up. Both the architectural drawings and the 3-week schedule were divided to show work in each of five areas A to E. The user could, for a given date, either generate the daily space schedule for a single area or generate the daily space schedule for all areas.
4. Enter the date for schedule generation and the date for the last schedule update.

The LOSite program then generated the daily space schedule for a given day for all 5 areas in 5 minutes or less.

5.4 Output

Figure 1 illustrates the output generated by LOSite. It shows the space use for area A on December 1, 2014. The legend is divided into four categories: (1) MEP trades, (2) Finishes, (3) Specialties and Equipment, (4) Miscellaneous. On the example shown, 7 subcontractors were working in the area on that day.

LOSite displayed an arrow icon on the map when two trades were working in the same location on the given day. The color of the arrow is the color of the second subcontractor sharing the space, the first subcontractor being indicated by the color of the room itself. LOSite also displayed the arrow icon in the legend next to the second subcontractor that shared the space. Note that the presence of an arrow did not necessarily imply space interference. For example, in Pod 16 the drywall subcontractor shared the space with the casework subcontractor. In this case, the drywall subcontractor could be taping the exterior of the pod, and be done inside the pod, and the casework subcontractor could be hanging plywood panels inside the room. On the project, the GC analysed and eliminated time-space conflicts on a case-by-case basis after the generation of the maps and before handing the maps to the subcontractors.

6 RESULTS AND LESSONS LEARNED

Over the course of 1 month, the researchers generated daily space use maps every Monday for the current week, and made them available to the 5 superintendents and 22 foremen (1 per trade) on their tablets. Although the COS set for LOSite were met, the GC did not take full ownership of LOSite and stopped using it after the researcher left the project for a few weeks.

Discussion with the subcontractors and the superintendents revealed some drawbacks to LOSite: (1) the open space area was not colored-up by LOSite, and (2) the name of the activity to perform in a room was not indicated on the maps.

The first drawback stressed the importance of defining an LBS that facilitates production planning, as well as the importance of precisely allocating an area to each activity in the schedule, which was not done for the open space in which multiple activities were listed as happening concurrently. Logistically, this was not a problem since the open space was large enough in each zone to allow multiple subcontractors to work concurrently and hence the work density was small. However, project progress was more difficult to assess in this area.

The second drawback was brought up by the GC even though the GC was initially not the intended audience for LOSite. Yet, the GC used LOSite for different purposes: (1) check the quality of the schedule, (2) schedule backlog activities in unassigned rooms, and (3) track resource commitments from subcontractors. Regarding (1) and (2), when a room was not colored-up on a given day, no activity had been scheduled to take place there. It either meant that the schedule was incorrect (i.e., an activity had been overlooked, a finish-to-start relationship omitted, etc.) or that a backlog activity could be assigned. Regarding (3), superintendents were using the colored maps to check that subcontractors were actually working in all of their assigned rooms on a given day.

The case study shows that space use visualization can benefit both the subcontractors and the GC. For the subcontractors, planning for manpower on large projects is facilitated when the quantity of the work is conveyed in area quantities. Manpower is also dependent on how scattered the work to be done is on the project site, which was also captured in the maps. For the GC, space use visualization helped to avoid time space interferences and catch mistakes in the schedule. Because LOSite could not capture space use in areas that were not precisely delimited (see uncolored space in Figure 1), it emphasized the importance of the LBS for production control. Ill-defined work areas were a symptom of lack of work flow coordination from the GC. It also enabled superintendents to track resource commitments from subcontractors.

7 CONCLUSION

Further research is needed to understand how one could make the project team consistently use LOSite throughout the project. Other questions are to be addressed, e.g., to which extent (if any) does visualization of site space use impact handoff reliability between trades? Finally, LOSite should be tested on other projects to gain robustness.

8 ACKNOWLEDGMENTS

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TECHNICAL TAKT PLANNING AND TAKT CONTROL IN CONSTRUCTION

Marco Binninger¹, Janosch Dlouhy² and Shervin Haghsheno³

Abstract: This paper is the counterpart to the paper Collaborative Takt Time Planning of Non-Repetitive Work of Iris Tommelein. Both papers describe Takt approaches in two different geographical and project contexts. A follow up paper is planned and will compare the described approaches and assesses their applicability and success.

This Paper describes the German Takt approach, called Technical Takt Planning and Takt Control. The authors used this method in on several projects in construction. It describes the historical development of Takt in construction in Germany and leads to the current state of the theoretical method used at the Karlsruhe Institute of Technology (KIT). The third part of the paper gives a practical example of the KIT approach.

The contribution of this paper is that it offers a characterization of the Takt approach that is used in Germany in several construction projects. The researchers try to give with the KIT Method an overview in science for the German Takt Planning and Takt Control approach. The method is for Takt integration in make to order production.

Keywords: Lean Construction, Production System, Takt Planning and Takt Control.

1 INTRODUCTION

Takt time is increasingly being used to structure construction work and thus "shape" project schedules. In the companion papers (Tommelein 2017) we refer to previous uses of Takt in production and offer a framework for characterization of Takt methods currently used in construction.

In German the word "Takt" means "beat" (Haghsheno et al. 2016) or the regularity with which something gets done. When the word is used in a Lean context, it is a concept interlinked with standardization, predictability, and many other Lean concepts. Takt refers to the heartbeat of assembly lines in the Toyota Production System (Haghsheno et al. 2016). Once a beat is set, every line can move in sync with others in a continuous flow process.

Whether at Toyota, more generally in product development and manufacturing, or in construction, Takt defines the unit of time within which a unit of production must be produced (supply rate) in order to match the rate at which that product is needed by the customer (demand rate). Takt Time is a design parameter used in a production setting, be it manufacturing, construction, or other any other setting.

The approaches used in different parts of the world and conceptualizations of Takt Time – even when applied in the same geographic region – appear to differ from one another. The aim of our ongoing study is to create conceptual clarity and highlight distinctions between approaches in the methods they use and contexts in which they apply.

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Along this line, Frandson et al. (2015) already compared and contrasted Takt Time Planning with the Location-based Management System (LBMS).

In this paper, we detail the approach for collaborative Takt Time Planning of non-repetitive work which we developed and piloted in the course of delivering a small project.

2 HISTORY OF DESCRIBED APPROACH

Using the principle of Takt is not new in the German construction industry. Takt was used in incremental launching in the 1970s (Gaillard 1974). Takt Planning was also mentioned in a context of concrete construction by Adolf Schub (1970) in his dissertation "Problems of Takt Planning in Construction Production". These approaches however, only used Takt for the purposes of planning.

The German Lean movement was started by Professor Fritz Gehbauer (2007). The main points of the method are contractual models and cooperative approaches such as the Last Planner System. Further methods and approaches, which are heavily used by consulting companies, were developed based on this. One such approach originates from a project consulted by Porsche Consulting in 2005 and is described in detail in Kaiser's dissertation (Kaiser 2013, p. 68). Kaiser's approach is based on a takt system for operational execution and includes the method Takt Planning and Takt Control. This approach is also mentioned in Friedrich et al. (2013).

The idea of takt work as part of Lean Construction and thereby seeks to create value-creating activities across the entire process chain of equal duration. This idea in combination with a short cycle control of the processes has only been implemented in Germany in the last 10 years. Since then some companies have placed a strong focus on this approach. An example of this is a medium sized enterprise described by Haghsheno et al. (2015). This approach was further developed at KIT (Dlouhy et al. 2016).

3 GEOGRAPHICAL AND PROJECT CONTEXT

The Takt approach described here was developed for building projects with clearly identifiable replicable elements such as hotel construction, and later applied to other types of construction. In the meantime, this approach is applied to all types of buildings from office to residential construction.

The example project in this paper describes the new construction of the fire department of an automobile production plant. In this case takt was used only in the fit-out stage.

The scope of the project has a gross floor area of approx. 500 m² for a German automobile producer. To minimize disruption to the fire brigade's state of readiness, the goal was to complete construction as quickly as possible to allow normal operations to resume. Therefore, the original construction sequence with a timeline of 90.5 days (or approx. 18 weeks) was takt.

4 THEORETICAL FORMULATION OF TAKT PLANNING AND TAKT CONTROL IN CONSTRUCTION

4.1 Takt Time in Manufacturing vs Takt Time in Construction

The idea of the Lean Construction methods of Takt Planning and Takt Control is to bring the processes necessary for creating value into a uniform flow. As uniformity and 100%

consistency can never be achieved in practice, the system is adjusted to the uniform Takt 'beats' given. The more fine-grained a Takt selected, the higher the level of uniformity, and therefore the higher the level of control over the system. For the level of effort needed to control the system the reverse is true. Takt in manufacturing is normally defined in seconds or minutes (Haghsheno et al. 2016)

Kaiser recommends a weekly Takt for the construction sector and justifies this by stating that a Takt under two days in length is very difficult to implement in practice (Kaiser 2013, p. 113). The selected Takt is noticeably dependent on the variability/stability of the system and product, but is not constrained by these. From a Lean perspective, the goal is to reduce the batch size and reduce throughput time.

In practice a weekly Takt is often selected due to the instability of construction processes. Individual examples (Heinonen and Seppänen 2016) of hourly and daily Takt show that the Takt time to be used cannot be seen as a fixed number for all projects. For every project there could be a different takt time.

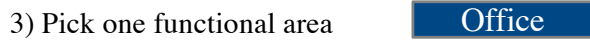
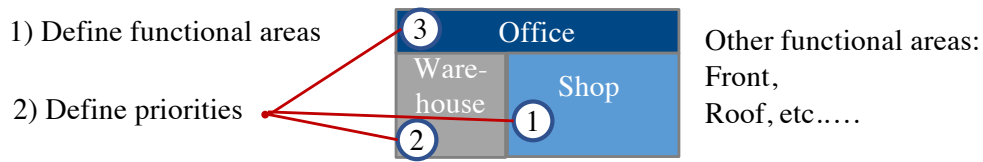
4.2 The technical Takt Planning and Takt Control method

Takt Planning

The method developed at KIT is based on Kaiser's approach with various points developed in further detail. The Takt Schedule was developed collaboratively by the project team in 12 steps. The steps are shown in figure 1.

In the first step the project was divided into functional working areas. These are sections and areas of a construction which will be carried out using various process sequences. In the second step the priority of different areas was determined from the perspective of the client, and afterwards sorted into the individual areas according to priority. For the selected area (step 3) the Standard Space Unit (SSU) was defined. The SSU is the smallest repetitive part in a project. During a workshop the project team planned works to the level of working steps in reverse order.

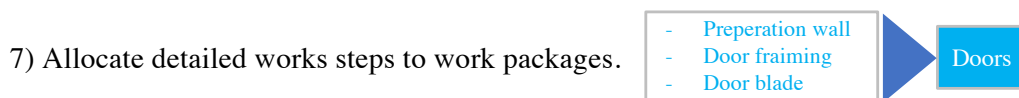
Step 6 is the most important piece of the method. Quantities were determined for the SSUs and multiplied by a performance factor. In step 7 the working steps were bundled into work packages. This bundling is strongly influenced by the traditional division of works. Step 8 organises the SSUs into practical Takt Areas and allocates the Takt Time. The Takt Time is often determined beforehand according to the needs of the client. The Takt Area is determined according to a calculation. Haghsheno et al. (2016) lists guidelines for the sizing of areas. Harmonization is completed in connection to this. This process levels the work load and is described explicitly by Binninger et al. (2016). The first result in Step 10 is a train of works. Work packages can be bundled together in one waggon if there is a no collision. Steps 4-10 are then repeated for all Takt Areas. In Step 12 the results are shown in a Takt Plan.



5) Define work packages for every SSU.

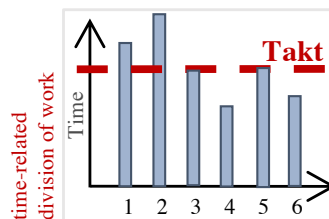


6) Do the calculation of the amount of work for every step.

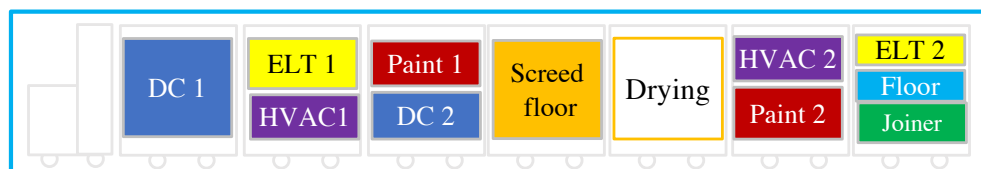


9) Takt levelling:

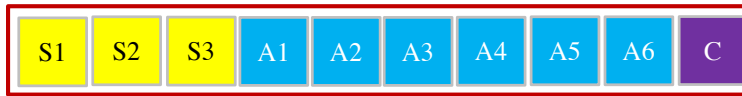
- shifting variable work steps
- Variation of manpower
- Duplication of wagons
- Buffer
- ...



10) Combine the work packages best for determined Takt time and Takt area



11) Do steps 3 to 6 for all functional areas



12) Prepare the takt schedule and determine milestones in order to customer priority

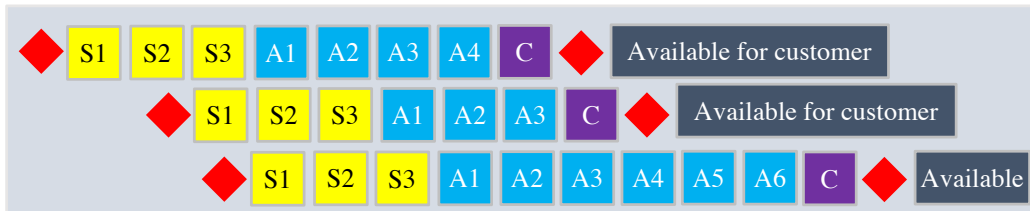


Figure 1: 12 steps of Takt Planning

Takt Control

Takt Control, also known as "managing the gemba" or "shopfloor management", has the goal of placing control at the place of value creation. Short-cycled (daily) meetings on-site are considered particularly important (Peters 2009). The meetings are moderated by the construction manager, and all persons responsible for execution take part. The site is managed through Takt Control Boards (shopfloor boards). These boards are also standardized, and serve as a medium for visualization to achieve transparency. The key to motivating employees to take part in the meetings is to integrate them in the problem-solving process. The following key points are recorded:

- Number of workers per trade
- Number of machines
- Rate of compliance with the Takt Plan
- Defects in quality
- Safety figures, number of accidents, violations of safety rules
- Number of disruptions to work
- Information on cleanness and tidiness

The key figures and effort values determined according to the Takt Control, can be utilized in the Takt Planning of future projects with little effort.

4.3 Practical example – Firestation, Dingolfing Bavaria

During functional analysis (1) the first (Corridor) and ground floors (GF) were defined as separate areas. This is shown in Figure 2. The first floor was prioritized (2).



Figure 2: Takt Areas

For the first floor (3) the corridor, bedrooms and ground floor were defined as SSUs (4) before process steps were prepared by the team (5). The works and quantities were

calculated and multiplied by an effort value (6). An extract of the calculation can be seen below.

Reference	Trade	Work Content	Quantity	Unit	Waggons
Room (15 m ²)	DC I	Place framework, single-sided duplex planking	25	m ²	W1
Room (15 m ²)	ELT I	Installation System	3	m	W2
		Run cables	30	m	
		Pipe installation	12	m	
Room (15 m ²)	Heater I	Prepare heater connection	1	Stk	
		Insulation	12	m	
Room (15 m ²)	HVAC I	Ventilation duct	7	m	

Figure 3: Calculation of the work content

The tasks were assembled into work packages (7). The following figure 4 shows the work packages for the corridor.

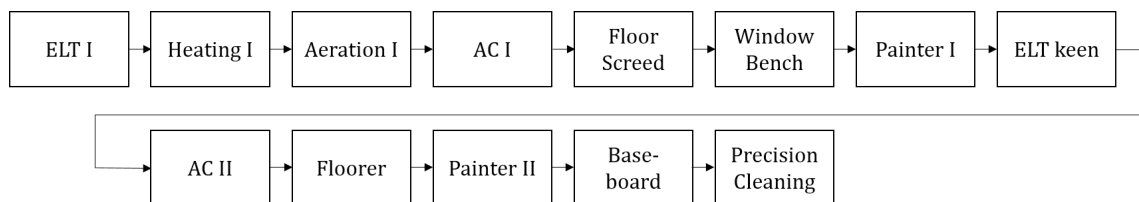


Figure 4: Work packages

After determining the Takt Time and length of the Takt (8) and harmonisation (9) the sequence of the trains was determined (10). In the next step the approach (11) was repeated for the ground floor. In this case study five Takt Areas (3x bedrooms, 1 x corridor, 1 x ground floor) were used. On the first floor a Takt Time of 2.5 days was implemented, while five days was used on the ground floor. Finally, the production timeline was prepared (12) as shown in Figure 5. The result is demonstrated in Figure 6 and 7.

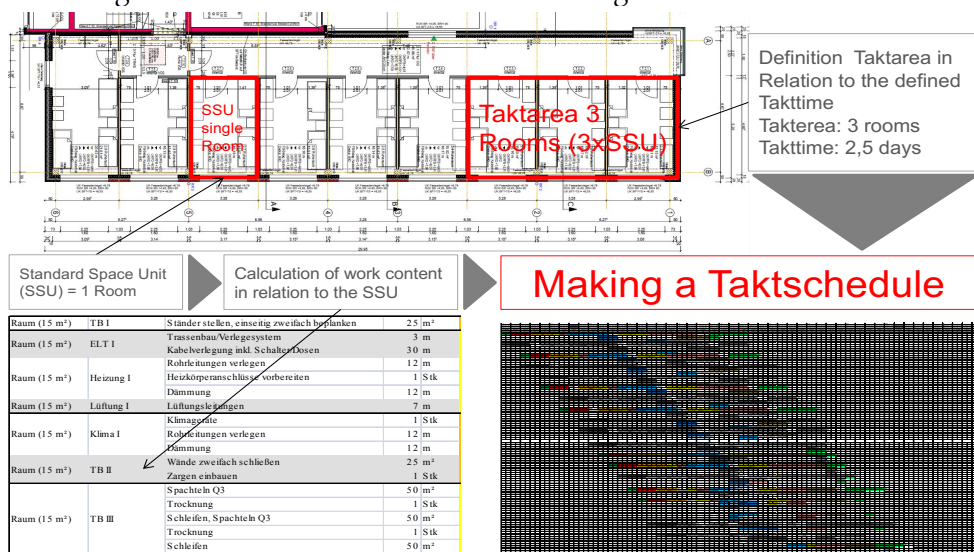


Figure 5: Making a Takt schedule

Takt Area	Date																															
	06.10.2014-08.10.2014	08.10.2014-10.10.2014	13.10.2014-15.10.2014	15.10.2014-17.10.2014	20.10.2014-22.10.2014	22.10.2014-24.10.2014	27.10.2014-29.10.2014	31.10.2014-03.11.2014	05.11.2014-07.11.2014	10.11.2014-12.11.2014	12.11.2014-14.11.2014	17.11.2014-19.11.2014	19.11.2014-21.11.2014	24.11.2014-26.11.2014	28.11.2014-30.11.2014	01.12.2014-03.12.2014	03.12.2014-05.12.2014	06.12.2014-08.12.2014														
	KW 41/1	KW 41/2	KW 42/1	KW 42/2	KW 43/1	KW 43/2	KW 44/1	KW 44/2	KW 45/1	KW 45/2	KW 46/1	KW 46/2	KW 47/1	KW 47/2	KW 48/1	KW 48/2	KW 49/1	KW 49/2	KW 50/1													
UFA TA 1 relaxation room			W1	W2	W3	W4	empty	screed	empty	W5	W6	empty	empty	W7	W8	W9	empty	empty	cleaning													
UFA TA 1 shower			W1	W2	W0	W0	W3	screed	W0	W5	W6	W0	empty	empty	W8	W8	empty	empty	cleaning													
UFA TA 2 relaxation room					W1	W2	W3	W4	empty	empty	W5	W6	empty	empty	W7	W8	W9	empty	cleaning													
UFA TA 3 relaxation room					W1	W2	W3	screed	W4	empty	empty	W5	W6	empty	empty	W7	W8	W9	cleaning													
Hall					W1	W2	W2	screed	empty	empty	W3	W4	W5	W5	W5	W6	W7	W7	cleaning													
GF	W1	W1	empty	empty	empty	empty	W2	screed/W2	W3	W3	W4	W4	W5	W5	W6	W6	W7	W7	cleaning													

Figure 6: Takt schedule DGF Fire Station (Authored by the Project Team)

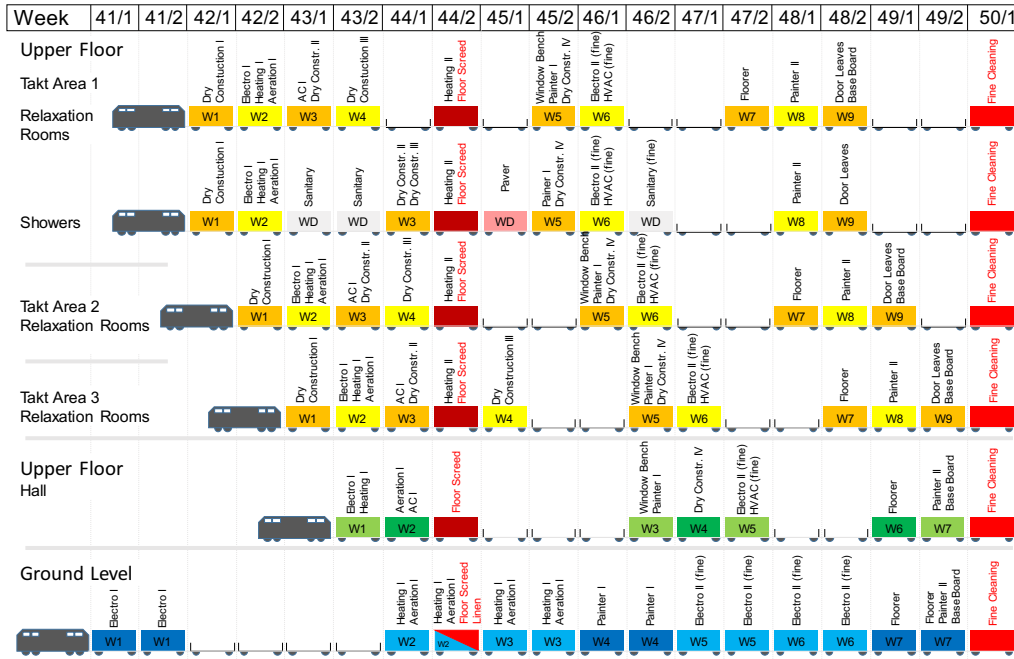


Figure 7: Takt schedule with trains

Takt Time Planning augments the Last Planner System

The three different layers of a Lean approach to construction are stated in Haghsheeno et al. (2015) as follows:

- Production Systems
- Collaborative Systems
- Contract Systems

The authors conclude that a holistic Lean approach must comprise of all three layers. Technical systems such as Takt Systems support transparency and stability by using objective data in a holistic Lean system. Furthermore, the borders of collaborative working could be expanded by using data in democratic production systems. Finally, the focus of technical Takt planning and Takt control is value for the customer while the relationship between Takt Time and Takt Areas define the speed of a project's execution.

5 ACKNOWLEDGMENTS

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integrating the authors in their Takt projects, the companies weisenburger bau GmbH and BMW AG made collecting the required data possible.

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ADJUSTMENT MECHANISMS FOR DEMAND-ORIENTED OPTIMISATION IN TAKT PLANNING AND TAKT CONTROL

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Abstract: Takt Planning and Takt Control is a crucial method utilised in Lean Construction. It has however recently undergone criticism due to its scheduling rigidity during construction and hindrance to adjustments during the course of a project. Generating a takt time plan is done at the beginning of a project and is not necessarily fixed during its whole lifetime. The Takt Plan offers a framework for a stable project execution and increased transparency throughout the construction process. In case of disruptions or changes of the framework conditions, the consequences can be visualised and managed in a targeted way. The Takt Plan can then be adjusted in accordance. The long-term goal is to reduce the required adjustments and increase the accuracy of predictions. This is done by increasing the experience of practitioners within the method by applying it and through a greater control over the construction process. During the execution of a project various adjustment mechanisms can be applied. These adjustment mechanisms can be flexibly implemented depending on the circumstances and the desired approach. The aim of this article is to introduce and categorise possible adjustment mechanisms within the scope of Takt Planning and Takt Control. In total 31 adjustment mechanisms are identified. Based on the experience of the authors, their effects and consequences are additionally presented. Using examples, a selection of the five adjustment mechanisms most used in current projects are explained in detail.

Keywords: Production Schedule, Takt Planning, Takt Time, Takt Control, Adjustment Mechanism

1 INTRODUCTION

Construction sites are dynamic systems, which require continuous adjustments to their schedule (Park et al. 2003, p. 213). Hao et al. (2008, p. 387-389) underline this fact and assume that project changes and adjustments occur during all project phases. The Takt Planning and Takt Control method provides a flexible production system for construction sites, as mentioned in "Technical Takt Planning and Control in Construction" (Binninger et al. 2017). This is also based on the practical example in the paper of Dlouhy et al. (2016). However, this method is sometimes considered rigid and inflexible. The Takt Plan set during a collaborative workshop serves as a framework for planning and controlling construction processes for everything from design to execution. The Takt time serves as a standardised timeframe, which sets the construction pace for

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individual trades. The structure provided by the standardisation enhances predictability and routine in the processes. Alternating contingencies, which are typical to the construction industry, can be dealt with using Takt time (Syben 2014, p. 82-88). A continuous improvement process (CIP) cannot be implemented without using any standards (Zimmermann et al. 2012, p. 22).

Construction schedules have limited value if construction processes are not controlled properly (Seppänen 2012). The Takt plan, as a specialised form of a schedule generated for each project, offers the flexibility that is necessary to adjust to project changes in various forms. Other options to generate a production plan are not part of this paper. The here used method of Takt planning and Takt control differs in its core principles on how the Takt time is defined compared to the methods Takt time planning by Tommelein und Frandson and the LBMS, therefore new terms and adjustment mechanisms are developed.

The mechanisms described in this article enable a dynamic execution of construction processes as required by Park und Pena-Mora (2003).

2 STRUCTURE OF THIS PAPER

The first part of this article describes the efficiency and flexibility gained by applying the method of Takt Planning and Takt Control in a case study. By defining and calculating Standard Space Units (SSU) a production plan can be developed within a short period of time (Haghsheno et al. 2015). This production plan provides a framework for planning and execution of construction processes. The method of Takt planning offers the flexibility to react to changes on site with the support of the mechanisms described in the second part of this article. The matrix in section 3.2 evaluates the mechanisms in terms of their effect on the construction process and illustrates the frequency of application in the projects. In the third section five selected mechanisms are presented and described through a case study. It is not part of the paper to explain different impacts and give a guideline how these mechanisms are treated in practise.

3 CASE STUDY OF TAKT PLANNING

The selected case study considers a care facility for elderly with three nearly identical floors. The building covers a surface of 1450 m² over three levels with 75 rooms of a similar size. Figure 1 shows a floor plan.

An initial analysis divides the building into functional clusters. In this case these are the habitable rooms, corridor, common rooms, stairwells, facade and shell. Consequently the SSU for each function cluster is determined (Haghsheno et al. 2016). Here the focus is on the fit-out of the habitable rooms, as shown in Figure 1. The common rooms (red) and corridor (blue) can in this case also be categorized as habitable rooms since their construction processes do not greatly differ. Only the colours of the floors and walls differ, which has virtually no impact on the processes. Compared to typical preparation work for construction projects, takt requires only the work sequence for one SSU and the relative work packages for that unit.



Figure 1: Floor plan using colours to show functional clusters to define the interior fit-out and the SSU of a habitable room.

Representatives from all trades participating in the process develop this sequence during a workshop. Here 16 work packages (waggons) with a total of over 130 working steps are defined. In the second step of Takt Planning the volume per SSU for each working step is determined and multiplied by a performance factor. As a result in a work distribution diagram is created for each work package within the SSU (Binninger et al. 2016). In this case the Takt time is defined as one week. The various adjustment mechanisms such as adaptation of work crew sizes or allocation of SSUs to a particular Takt area is harmonised using the work distribution diagram. The process to generate an initial Takt plan takes only a few hours. Here approximately six habitable rooms are combined into one Takt area along with corridors and living rooms. This particular combination results in 17 Takt areas. The selected size of the Takt areas is between 170 and 200 m². The guidelines for Takt size proposed by Haghsheno et al. (2016) are applied in this instance.

Subsequently the production plan along with associated costs, crew sizes and material flows is approved and agreed upon by all participants. At this early planning stage, adjustment mechanisms such as reducing crew sizes, incorporating required buffers, adapting interfaces, parallelising trades or accelerating the Takt plan can be used. Likewise, there are additional adjustment mechanisms for later control. The established adjustment mechanisms from practice are listed and categorised in the section 3.3.

3.1 Description and categorisation of the identified adjustment mechanisms

The identified adjustment mechanisms identified are named in this section and it is determined whether these are primarily used in Takt Planning, Takt Control or both. In many cases this is not a trivial categorisation. The evaluation is based on the authors' practical experience. Furthermore, every adjustment mechanism is briefly described as well as the associated effect on the construction process. Based on the frequency of usage, the adjustment mechanisms are allocated into three categories and described in greater detail for further evaluation. Category A represents mechanisms, which according to the authors' evaluation has been used in over 30 cases. Category B mechanisms were used in five to 30 cases, and category C represents mechanisms used in less than five cases. The categorisation can be seen in the following table.

Table 1: Categorisation of adjustment mechanism

#	Name	Planning	Control	Category	Description	Effect
1	Decoupling of Takt areas	X	X	A	Reorganising the sequence for completing Takt areas	Change in the order areas are completed
2	Empty waggon	X	X	A	Planning of buffer times (slack); for example drying-out periods	Visualisation of required buffer; lengthening of the construction time
3	Phase interlinking	X		A	Different process phases require different sizes for Takt areas. Adjustment for these differences results in efficiencies.	Optimisation of the construction process
4	Soft start	X		A	Delaying following trains, if more than one train is used. This allows learning from the starting train.	Lengthening of the construction time, stabilisation of site processes
5	Train stoppage		X	A	Stopping the construction process due to a problem	Longer duration of construction
6	Combining handover times	X	X	B	Arranging the handover by combining Takt areas to larger areas.	Bundling of Takt areas for handover
7	Coupling into and onto	X	X	B	Adding or Removing waggons to change the process sequence.	Lengthening of the construction time
8	Jumpers	X	X	B	Using flexible labor to deal with peaks in required work	Harmonisation of the work process
9	Split of train order	X	X	B	Splitting the construction sequence, because conditions demand for extended process durations.	Lengthening of the construction time
10	Takt time reduction	X	X	B	Reducing the Takt time	Harmonisation of the process sequence; shortening of the throughput time
11	Takt time increase	X	X	B	Extending the Takt time	Harmonisation of the process sequence; lengthening of the throughput time
12	Train split	X	X	B	Paralleling multiple trains with similar sequences to pass the construction site.	Shortening of the construction time
13	Waggon acceleration	X	X	B	Ensuring a stable Takt time by optimising a waggon in detail	Harmonisation of the process sequence (Levelling); shortening of construction time
14	Waggon overlapping	X	X	B	Following waggons start before the preceding waggon is completed	Optimisation of the process sequence
15	Waggon parallelisation	X	X	B	Completing waggons in parallel	Optimisation of the process sequence
16	Hard start	X		B	Starting multiple waggons at the same time	Shortening of the construction time
17	Inserting fixed buffers	X		B	Planning slack at the end of a sequence/train	Slack is built in to stabilise the construction process
18	KIT Move	X		B	Combining multiple work packages to use the full Takt time in a waggon.	Harmonising of the process sequence; shortening of the construction time
19	Shunting yard	X		B	Utilizing available process sequences	Changing construction site

20	Splitting Takt areas	X	(X)	B	Reducing the size of Takt areas	processes Harmonisation of the process sequence
21	Takt area enlargement	X	(X)	B	Increasing the size of Takt areas	Harmonisation of the process sequence; lengthening of the throughput time
22	Waggon subcontracting	X	(X)	B	Completing individual waggons with subcontractors	Stabilisation of construction site processes
23	Multiple train levelling		X	B	Using multiple trains to increase efficiency within workers and trades	Stabilisation and optimisation of the construction process
24	Train station		X	B	Re-planning the process sequence	Changing construction site processes
25	Use of fixed buffers		X	B	Making use of buffers (slack) at the end of a sequence/train	Slack is used up, the construction process is stabilised
26	Work package acceleration		X	B	Targeting optimisation of work packages within a waggon	Optimisation of the process sequence at the micro level
27	Work package shift		X	B	Reallocation of a work package to another waggon	Optimisation of the process sequence
28	Waggon switch	X	X	C	Swapping the position of at least two waggons in the process sequence	Optimisation of the process sequence
29	Division of materials/logistics	X	(X)	C	Decoupling of value creating and logistical tasks	Focus on the value chain
30	Waggon shift		X	C	Moving a waggon to a different position in the process sequence	Optimisation of the process sequence
31	Work package switch		X	C	Swapping work packages between waggons	Optimisation of the process sequence

4 SELECTED ADJUSTMENT MECHANISMS

4.1 Overview

The following section will describe the Category A adjustment mechanisms more in detail. These are according to the authors' experience the most frequently used ones. This covers the adjustment mechanisms for the decoupling of Takt areas, empty waggons, phase interlinking, soft start and train stoppage. These mechanisms are illustrated in charts, where the X-axis shows weekly Takts beginning with W1 and the Y-axis shows Takt areas beginning with TA 1.

4.2 Decoupling of a Takt area

If individual Takt areas cannot be completed to follow the order of the train, they can be decoupled and reallocated. For example, when planning is not fully completed or approved for a certain area, when the client changing its requirements, when materials are not ready or when approvals are still awaited. This mechanism is implemented the same way as in production industries, for instance when a car is reallocated back into the production line at a later stage. In the following example the client's decision has not been made in Takt area TA 2 and the Takt area is reallocated after TA 5. According to the one-week-Takt this means that the necessity of the decision-making can be delayed by three weeks.

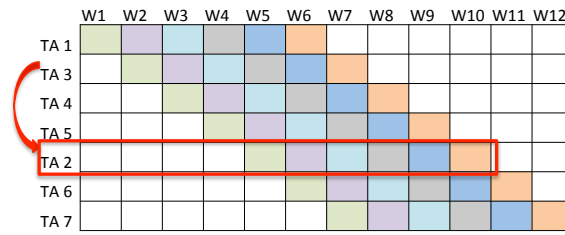


Figure 2: TA 2 is reallocated next to TA 5.

4.3 Buffer waggons

A buffer waggon is a planned buffer, which can ensure stability in certain situations. It can be implemented to account for drying times. A classic example would be after the screed waggon or if a problem is spotted during Takt Control. The completion and throughput time are increased by the time period of one Takt by adding an empty waggon.

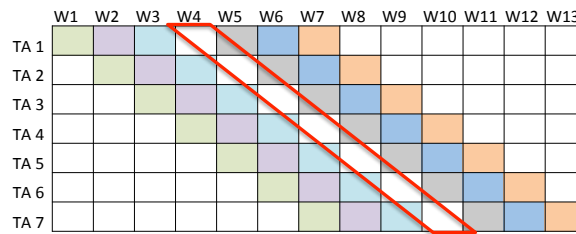


Figure 3: Inclusion of an empty waggon in the middle of the train

4.4 Phase interlinking

A typical construction project is divided into phases such as the division between designing and execution phase or shell and fit-out works. The goal of this mechanism is to reach a very close interlinking and the proper selection of the same batch size and Takt time. This means the gradient of each parallelogram in Figure 4 is equal. In many cases this might not be possible. Therefore, the goal is to reduce the amount of slack (empty spaces in the production plan) to increase the efficiency of the project. In the following example a batch size of two TAs and a Takt time of two weeks is anticipated for the shell construction (phase 1). In the second phase of construction the size is one week for each waggon and Takt area. The speed of construction can be interlinked, even with slack.

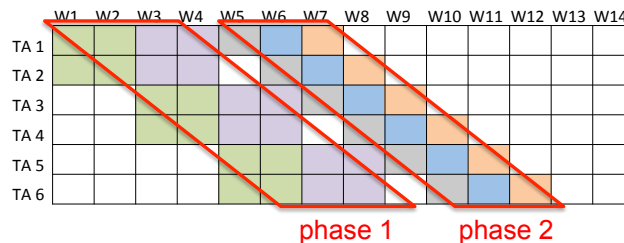


Figure 4: Interlinking of Phase 1 and Phase 2

4.5 Soft start

If multiple trains are used, the choice between a soft and a hard start is possible. A soft start means that not all trains start at the same time. This allows one to collect experience from the first train and use it for the start of the second train. A disadvantage is the fluctuation of manpower in the starting phase as well as slow start of the construction site.

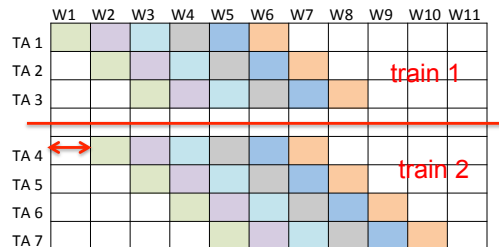


Figure 5: Example of the soft start of train 2

4.6 Train stoppage

Train stoppage leads to a disruption of the construction process. The reason for this is the occurrence of a problem that is not immediately solvable (i.e. within the Takt).

This type of disruption means that the entire train must be stopped until a sustainable solution has been found. Hence the disruption and its resolution are given the necessary attention. This mechanism is comparable to stopping the conveyor belt in production industries. In this Takt the catch-up works of disruptions are planned so that the train can continue with the next Takt. The construction process is only restarted once a sustainable solution has been found.

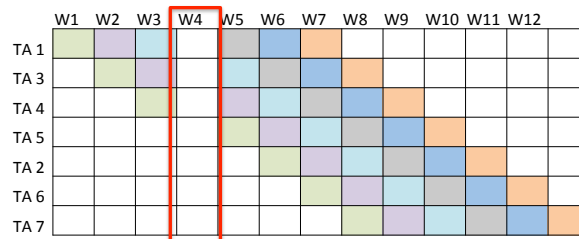


Figure 6: Train stoppage in Week 4.

5 CONCLUSION AND OUTLOOK

This article challenges previous theories by enabling an unprecedented level of flexibility while implementing the Takt Planning and Takt Control methods during the designing and execution phases of construction projects. The 31 adjustment mechanisms identified show the variety and flexibility of the methodology. By describing the five mechanisms of decoupling the Takt area, buffer waggons, phase interlinking, soft start and train stoppage the flexibility of the method is shown. In addition by presenting a formula for the calculation of the throughput and completion time a quantitative performance measurement is introduced.

It has to be noted that this article covers an initial compilation of adjustment mechanisms gathered from the authors' own projects. The list must therefore not be viewed as exhaustive. Future additions and further investigation are necessary.

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A BALANCED DASHBOARD FOR PRODUCTION PLANNING AND CONTROL

Trond Bølviken¹, Sigmund Aslesen², Bo Terje Kalsaas³ and Lauri Koskela⁴

Abstract: The paper proposes a concept for a dashboard to be used as part of Last Planner based production planning and control. The dashboard is constructed to be used, not primarily by management, but by the last planners. For this reason the dashboard has to be simple (it should focus on some few but important metrics), and it has to be balanced (it should give a holistic view of the status of the process and where it is heading). It is proposed that the dashboard should consist of three sections: planning, production flow and outcome. Each of these three sections should comprise one or a few metrics, put together so as to and provide a consolidated overview of both status and direction. We present a specific dashboard consisting of six metrics in all. This dashboard will be tested in a forthcoming case study.

Keywords: Dashboard, Scorecard, Metrics, Measurement, Last Planner.

1 INTRODUCTION

A dashboard is a visual management tool. The idea behind visual management is to facilitate control and continuous improvement by making the process status available to the participants in real time and in an intuitive and understandable way (Tezel et al. 2016). It is hard to imagine one single metric⁵ capable of providing a holistic view of the entire process. This can be achieved only through a set of metrics, a dashboard. In this paper, we present a concept for a dashboard to be used as part of Last Planner⁶ (LPS) based planning and production control (Ballard 2000). The dashboard is constructed to be used by the last planners to monitor and improve the process in the project, not by management to supervise the project or to benchmark between projects. For this reason, the dashboard has to be simple and intuitive, it should be continually updated and provide an at-a-glance overview⁷.

Several lines of thinking have inspired the proposed dashboard concept: visual management; discussions within IGLC on LPS related metrics, production flow and waste;

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⁵ By metric, we in this paper mean a standard measurement.

⁶ The Last Planner is a registered trademark of the Lean Construction Institute.

⁷ Although the topics are related, our means and ends are therefore very different from those of Sacks et al. (2016). For them the goal is to inform management, to compare alternative production management and control strategies and to compare projects with one another (pp. 46 and 48). In order to do this, they propose one single composite indicator.

the balanced scorecard approach developed by Kaplan and Norton (1996) and the use of metrics as an integral part of Virtual Design and Construction (VDC)⁸.

2 HOW SHOULD THE DASHBOARD BE STRUCTURED?

As presented by Kaplan and Norton (1996), a balanced scorecard is a set of metrics / key performance indicators (KPIs) put together in such a way as to provide a holistic overview of the current state of affairs and an indication of the direction in which a company is heading. Our topic is to measure a process, not a company. The way Kaplan and Norton compose their scorecard is therefore of less relevance for us. What is relevant, on the other hand, is their focus on the scorecard being balanced, that is, that it covers the different relevant aspects in a holistic manner and that it addresses both the current state and the direction in which things are heading⁹.

Construction is project-based production. In this type of production, planning is a major productivity strategy (Ballard 2000, Bølviken 2012). Therefore, monitoring the quality of the planning process should be part of our balanced dashboard.

Koskela (2000) sees production as a flow of transformations creating value in the form of a product. While the mainstream approaches to production have mainly focused on the transformation perspective, lean approaches are mainly focused on the flow and value perspective. Consequently, we seek a dashboard that reflects the production flow and the extent to which the intended outcome (the goal) is being reached. In the lean tradition, the goal is usually referred to as value and the ultimate goal is value for the customer. However, there must also be value for all others involved in the process (without value, they would not be interested in contributing to the process). The dashboard we seek is to be used by the last planners, that is, the people actually doing the production. The value we seek is therefore value for the producers.

The aim of the dashboard is to facilitate control and continuous improvement. Improvement processes in projects or companies will always be contextual. For this reason, the dashboard will also have to be contextual. This means that it should have a generic structure that can be given a specific contents relevant to the specific case. The principle of continuous improvement can be applied both internally in the planning and production process (e.g. through improved flow and reduced waste), and externally to the outcome (e.g. through increased value or reduced cost for the customer). Therefore, we have not included continuous improvement as a separate, independent section in the dashboard, but will instead integrate it into the other sections.

Summing up, we find that the dashboard should consist of the following sections:

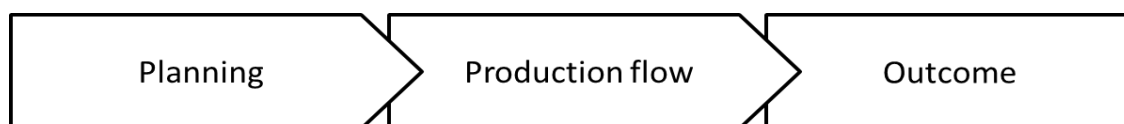


Figure 1: The three sections of the balanced dashboard

⁸ VDC is a design method for effective leverage of information technology in support of product-organization-process (POP) modeling in construction (Fischer and Kunz 2004).

⁹ While Kaplan and Norton use the term 'scorecard', we prefer to use 'dashboard'. The reason for this is that we perceive 'scorecard' as connoting benchmarking and measuring from the outside (management), whereas 'dashboard' denotes a set of instruments giving the driver needed information along the way (in our case giving the last planners important information needed when planning and doing the job).

3 WHICH METRICS COULD WE USE?

Within this conceptual framework, different metrics and quantities of metrics can be used. The simplest possible balanced dashboard could consist of only three metrics, one within each of these three perspectives, but this has to be considered against the need for more information than what can be given through such a limited number.

A phenomenon can be measured directly or indirectly (Bølviken & Kalsaas 2011). An indirect measure is called an indicator. When using an indicator, we measure a different phenomenon than the one about which we are seeking information. When measuring indirectly, we assume that there is a causal relationship between the phenomenon we want to measure and the indicator; we assume the indicator is covariant with the phenomenon we actually want to measure. An example of direct measurement is measuring work done by counting the number of products produced. An example of indirect measurement is using the rate of sickness-related absence as an indicator for workplace satisfaction. Indicators are normally used when direct measurements are impossible or hard to establish. A main disadvantage with indicators is that people tend to confuse the phenomena one wants to address and the indicator. The result can be that they do things that influence the indicator, even though it has negative or no effect on the fundamental phenomena one wants to address. When constructing our balanced dashboard, we will therefore seek direct measurements and avoid indicators as far as possible.

Continuous improvement can be achieved both by separating improvement activities and by integrating improvement into other activities. Improvement can be measured through improvement-related activities and as outcomes. If there are specific improvement activities in the project, the measuring of these can be included in the dashboard. On the outcome side, improvement can be measured by establishing timelines of metrics.

In the following, we will present and discuss some of the metrics we find most relevant. We will thereafter present the specific dashboard we will test out in the case company.¹⁰

3.1 Planning

Ballard and Tommelein (2016) include the following four metrics in their current benchmark for the Last Planner System (LPS): Percent Plan Complete (PPC), Tasks Made Ready (TMR), Tasks Anticipated (TA) and Frequency of Plan Failures (Ibid. pp. 13 and 20-21, Hamzeh et al. 2012). They argue that key factors to successful LPS implementations are having stable lookahead schedules, requesting and obtaining reliable commitments to remove constraints, and developing and implementing countermeasures to prevent repeated plan failures. They therefore recommend metrics addressing these topics to be developed, and present the following possible metrics: Percent Promises Made¹¹, Percent Promises Kept¹², the number of countermeasures implemented relative to the number of plan failures over some past time window and the extent to which trade crews will be able to work without interruptions (pp. 25-26).

PPC measures workflow reliability and by this the effectiveness of the planning system (Ballard & Tommelein 2016). PPC does not measure the production flow as such or the outcome of production. It is however correlated to both, and is therefore often used as an indicator of production flow and productivity. When using PPC, one has to decide whether

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¹¹ The number of reliable commitments to remove unresolved constraints/total number of unresolved constraints.

¹² The number of constraints resolved in the week as promised/total number of constraints promised to be resolved in the week.

the PPC objective should be 100% or lower. A traditional view has been that one should go for a PPC of around 85– 90%. The argument for this has been that the goal is continuous improvement, and that if we go for 100% PPC, there is a risk that the weekly targets will be set too low. There are nevertheless some important arguments for setting the goal for PPC at 100%. The first is that this is a consequence of understanding planning as giving and keeping reliable promises (Ballard et al. 2009). When you give somebody a promise, you can have no other goal than to keep the promise, that is, a PPC of 100%. In recent years, we have seen an increased interest in combinations of takt planning and LPS. One important feature of takt planning is perfect handovers between trades. This is a PPC = 100% approach. The last argument is that a target lower than 100% makes PPC hard to communicate and interpret. For example, if we have a PPC of 85%, is this too low, too high or just fine? In line with Ballard and Tommelein (2016, pp. 29-30), we conclude that 100% should be the goal for PPC. This means that continuous improvement should be pursued in two steps, first to get PPC close to 100%, and then to consider decreasing the manning or increasing the amount of work to be included in the forthcoming weekly plans.

The use of PPC is often combined with cause analyses to identify the main constraints causing delays or interruptions. For dashboard purposes, we find it expedient to include only the constraint directly causing an interruption in the production progress (e.g. by using the seven preconditions for a sound activity (Koskela 1999)), whereas a root cause analysis typically will include several dimensions and factors. Some projects have used a moderated PPC indicating whether or not a delayed task prevents subsequent tasks. Moderated this way, PPC can also be seen as an indicator of production flow. For a further discussion of the more sophisticated Last Planner related metrics, we refer to Emdanat and Azambuja (2016) and Sacks et al. (2017).

Aslesen et al. (2013) propose a model to integrate safety analyses as part of LPS. The model indicates how safety risk should be identified and thereafter eliminated or mitigated at each plan level in LPS. The model is now under implementation in our case company. A metric indicating how well this process is going would be very relevant to include in the dashboard. As far as we know, such a metric has not yet been developed.

3.2 Production flow

From the perspective of transformation, the conceptualization is to transform resources (inputs) into products (outputs). This perspective entails a tendency to see increased input as a main strategy to increased output (“to get more out of more”). In contrast to this, the flow perspective is predominant in lean approaches. From the flow perspective, the main strategy for productivity is to improve the flow and reduce the waste (“to get more out of less”). In the production part of our balanced dashboard, we therefore seek metrics focusing on flow and the waste in the flow.

Bølviken and Koskela (2016) find that while waste in manufacturing tends to be present and visible over time, waste in construction tends to come as a parade of singular (unique), evanescent events. This makes waste in construction harder to see, understand and combat. How can we capture an evanescent phenomenon? We think the answer is to track it over time. We therefore seek metrics that track the overall level of waste in the workflow. Kalsaas (2013 and 2016) reports on measuring the amount of direct work, indirect work and lost time. The measuring is done through both shadowing¹³ and self-assessment¹⁴. In the self-assessment case, the workers were also asked for the reasons for the time losses.

¹³ Researchers following and observing workers.

¹⁴ Workers estimating the daily amount of direct work, indirect work and lost time.

From a practical and economic perspective, shadowing can only be done in a limited number of research projects. It is therefore interesting that Kalsaas (2013) finds that the figures obtained through shadowing correspond quite well with the self-assessment of the workers. In addition, we see it as an advantage that self-assessment compels the workers to reflect over what they have been doing during the day. There are however two preconditions that have to be met, in order to make self-assessment viable approach. The first is that it presupposes trust, motivation and an improvement culture among the workers and between the workers and the management. The second is that even though the self-assessments are done on an individual level, the result should be aggregated to the team level and discussed collectively within the team.

How should we then include safety in the dashboard? To count the number of injuries might seem an obvious choice, but would not work simply because there at the project level are so few injuries that the figure would very often be zero and not say much about the safety situation in the project. To count near misses is another possibility, but could just as well reflect the level of reporting as the level of safety. A tidy work area is related to safety (Aslesen et al. 2013, Srinivasan et al. 2016), and obviously also to productivity and production flow. A relevant metric could therefore be the level of tidiness.

Good flow is a combination of high production volume (throughput) and uniform production volume per time unit (smoothness) (Bølviken & Kalsaas 2011, Schmenner 2012). Metrics related to both throughput and smoothness are therefore relevant. In manufacturing, the product flows through production, and the main focus is therefore on this particular flow, called 'process' by Shingo (1988), and 'product flow' by Bølviken et al. (2014). In construction, the production (work) flows through the product, and the main focus should therefore be on this specific flow, called 'operations' by Shingo (1988) and 'workflow' by Bølviken et al. (2014). In construction, the product flow can be understood as the overall progress of the construction process. The throughput dimension in the product flow can be reformulated as the length of the construction period or the project's ability to comply with the due dates, and can therefore be included not only as part of the production flow section of the dashboard, but also of the outcome section.

The amount of direct work, indirect work and lost time is a measure of the waste at an individual level inside each trade. It can, to a certain degree, also be considered a flow metric. Complementarily to this, we therefore propose to use a flow metric that is focused on the flow between the trades. The number of deviations in the handovers between trades is a metric that can be captured relatively easy. This metric is basically measuring the smoothness in the product flow, but will also reflect the making-do waste (Koskela 2004) and quality.

3.3 Outcome

The main outcome dimensions are traditionally seen as quality, cost and time. In the production flow perspective, we discussed the number of deviations in the handovers between trades. As mentioned, this can also be seen as a quality metric. What about cost and time? Both PPC (from the planning perspective) and the waste metrics (from the production flow perspective) are also related to cost and time. Nevertheless, they focus only on cost and time so far in the process and provide limited information on the likelihood that the project will meet its total time and cost budgets. We therefore propose to include forecasts on total duration and cost on the dashboard. The forecast on duration

should relate to the milestones in the master or lookahead schedule as a baseline.¹⁵ From the last planners' perspective, cost boils down to working hours. In most cases, the construction company will have worked out a cost estimate/budget for the work. Explicitly or implicitly, this is based on estimates of total working hours. A forecast of the total working hours could therefore be included on the dashboard, with an agreed estimate as the baseline.

4 WHICH METRICS WILL WE USE IN THE PILOT STUDY?

Our plan is to test the dashboard concept presented in this paper in a pilot study. Based on the arguments presented here, we plan to include the following six metrics in the test version (Figure 2): In the planning section, we intend to use PPC as the only metric. PPC is both a well-established and intuitive metric. Although it basically measures the planning process, it can also be seen as an indicator of production flow. In the production flow section, we plan to include three metrics. The first is a self-assessment of direct work, indirect work and lost time. The second is the number of deviations in the handovers between trades, and the third is the level of tidiness. The first is mainly a metric related to waste, the second to quality and the third to safety. All three can however also be seen as indicators of production flow. Because we have one metric related to quality in the production flow section, we have chosen to limit the outcome section to two forecasts, one on time and one on cost.

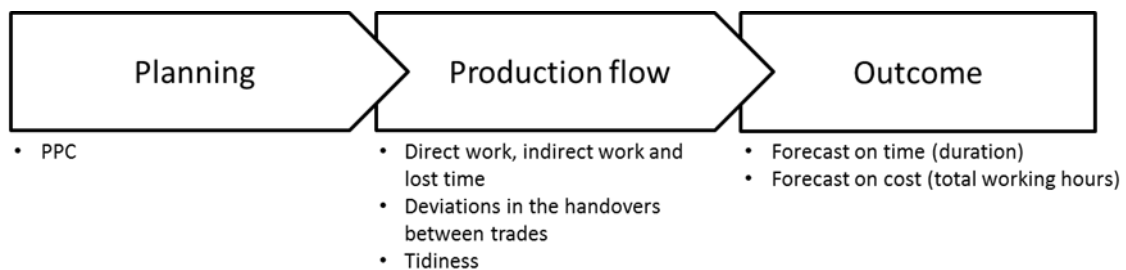


Figure 2: Test version of the balanced dashboard

5 CONCLUSION

In this paper, we have conceptually presented a dashboard, designed to be used by the last planners in their day-to-day planning and control. We have argued that the dashboard should be simple, intuitive and balanced, meaning that it should address the most important aspects of the process in a holistic way and provide an overview of both the status of the project and the direction in which it is heading.

The presented concept comprises the three sections Planning, Production flow and Outcome (for the producers). Within each of these sections, there should be a limited number of metrics, and the metrics should be combined so as to complement one another and provide an overview of both status and direction.

Our next step is to test a version of the dashboard with six metrics (Figure 2) in a case study. The aim of the case study will be to test the overall structure of the dashboard, how

¹⁵ Here we make a firm distinction between a baseline and a goal. Budgets and cost estimates include the normal/established level of waste (Koskenvesa et al. (2010), Glenn Ballard (private communication)). Due to this, they should be seen as baselines or forecasts based on the current state of affairs, but not as goals.

useful the different metrics are, how well they complement one another, how the dashboard should be presented, how it should be used to support planning, control and improvement and to what degree it all in all turns out to be useful for the last planners. As part of the case study, we also hope to develop a metric indicating how well the safety analyses integrated into the LPS process are running.

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LEAN METRIC SYSTEM: PROPOSAL FOR A PERFORMANCE MEASUREMENT SYSTEM FOR CONSTRUCTION PROJECTS

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Abstract: The application of Information Technology (IT) for the constructions management is mentioned as an important success factor. Improved IT management tools can help reduce important issues such as information gathering, misrepresentation, and lack of process standardization. These issues are related to the information flow and transparency, one of the principles of Lean Construction (LC), which will be explored in this research.

This paper aims to present the development of a Performance Measurement System (PMS) with IT application, named Lean Metric (LM). Developed for the application of construction projects, LM uses concepts of hierarchical planning to monitor the constructions term and cost, based on information collected at the construction site.

The LM was developed and tested in the last three years by a consulting company of planning and control of constructions in Fortaleza city. Its creation was crucial to increase the company's competitiveness, reducing operational costs and increasing confidence in the collected data. In addition, indicators are automatically calculated in real time, resulting in transparency in project results.

Keywords: Project Control, Lean Construction, Project Management.

1 INTRODUCTION

In face of the new challenges imposed by the globalized market, the inappropriateness of the Performance Measurement Systems (PMS) used by companies was noticed. This is due these PMSs were based solely on financial accounting (Franco-Santos et al. 2012).

In the construction management area, this was no different. There are several initiatives, at organizational and operational levels, that are well represented by benchmarking clubs around the world (Costa et al. 2004; Horta, Camanho, & Moreida da Costa 2010; Sector 2013) such as: Construction Industry Institute Benchmarking and Metrics (EUA), Key Performance Indicators (UK) and Performance Measurement System for Brazilian Construction Industry (SISIND, Brazil).

Despite these initiatives, Cândido et al. (2016) highlight as the main difficulty the activities operationalization of measurement and control. Other authors point to problems to the operation level, such as overestimation for the supply of materials, undue payments of completed activities, reports preparation, among others (Luu et al. 2008).

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In addition, the information flow is fragmented and erratic, making difficult the management actions that lead to project success. These problems are related to the principles of lean construction: transparency in construction (Koskela 1992), reduction of waste (Ohno 1997) and standardization of control processes (Nakagawa, 2006).

Facing these problem, a consulting company in construction management developed a system to improve its performance measurement process. This system was called Lean Metric (LM) because it was based on the Lean Construction principles.

Thus, a research question arises: how can LM improve the process of performance measuring in lean construction projects? As a premise, the focus control should be in the complete process (Koskela, 1992) instead of the micro control.

Thus, this paper aims to analyze the contributions of the LM to performance measurement process. To accomplish this, it is presents the development, the implementation and test of Lean Metric System as well as its benefits, difficulties of development and implementation and its contributions.

2 PERFORMANCE MEASUREMENT AND LEAN CONSTRUCTION

Between the period from 1945 to 1990, a paradigm shift in production management occurred with the spread of new management concepts such as Total Quality Management (TQM), Just-in-time, and Lean Thinking (Womack et al. 1990; Spear & Bowen 1999). These concepts came to the construction sector through the 11 principles of Koskela (1992), which later were called Lean Construction by the International Group for Lean Construction (IGLC) in 1993 (Koskela 2004).

Around the same time, in the late 1990s, a variety of quality certifications increased the companies' attention about the creation and implementation of a Performance Measurement System (PMS) (Costa et al. 2004). In general, the performance measurement of construction projects is focused on traditional tripod measures: delivered on time, below or within budget and according to specifications (Toor & Ogunlana 2010). However, performance in LC projects cannot be achieved only with traditional measures (Horman & Kenley 1996).

Projects under lean construction principles aim to maximize value, minimize waste, reduce cycle times (Ballard et al. 2001) and provide production stability improving the construction flow (Sacks et al. 2017). Notwithstanding, as proposed by Cândido et al. (2014), the measurement of performance in lean construction projects should be grounded on physical and qualitative aspects of production progress and not only in financial outcomes. Besides that, improve the information flow it's a critical issue in lean construction (Koskela, 2000). Thus, it is clear the complexity of the performance measurement of lean construction projects (España et al. 2012).

3 METHOD

This study was carried out under Design Science (DS) methodological approach. The DS approach is eminently focused on solving a practical problem (Collins et al. 2004) and is cited as an opportunity to create and develop a good idea without using the rigor of science (Holmström et al. 2009).

In the IGLC community some articles such as Rocha et al. (2012), Brady et al. (2012) and Brady et al. (2013) support the use of this methodological approach and justify its

application to this research. Thus, seven steps were set for the development of this research (Figure 1).

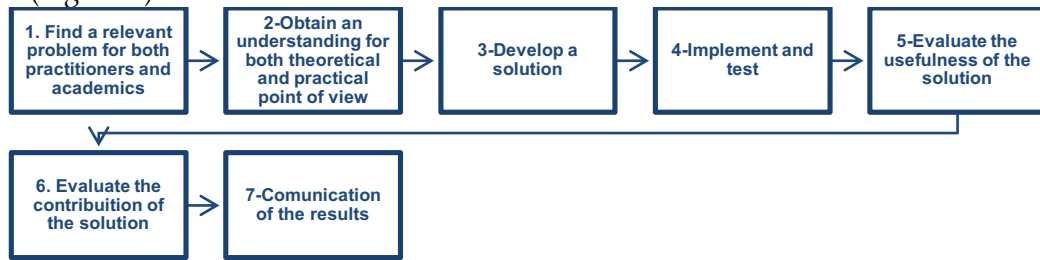


Figure 1: Research process

In following, the results are presented in three parts: 1) development of Lean Metric, corresponding to the steps one to three; 2) implement and test, corresponding to the steps four and five and, 3) evaluate the theoretical contribution of the solution, that cover the steps six and seven.

For the sake of completeness, in the second part (implementation and test), the artefact was evaluated through a case study, as recommended by Hevner et al. (2004). Thus, a secondary methodological approach was applied, the case study (Yin 2010). To collect data for this, semi structured interviews were carried out with managers of consulting companies, who developed and/or used the artefact (Lean Metric).

4 RESULTS

4.1 Development of Lean Metric (LM)

This research was developed within the framework of a construction management consulting firm from Fortaleza, Northeast of Brazil. The company claims the application of lean construction concepts as the main foundations of its consulting practices. To lean principles are added concepts from Theory of Restrictions and good practices of project management, according to the PMI.

The idea of developing the measurement tool was based on the need to standardize the projects measurement and control process. With the expansion of the company, it was found that the field data collection and the consolidation of the results report were very time consuming, making the process more expensive and less competitive.

When it was verified that this problem of improving the performance measurement process was also relevant to the academy, it was decided to develop the Lean Metric while maintaining the theoretical rigor necessary for the application of control tools, according to lean principles.

The first step to develop the Lean Metric was the review of the overall process of Production Planning and Control of the Consulting Company. This process review was based on lean construction, theory of restrictions, project management and performance measurement. As the focus of this paper is the process of control, we present only the results of this step (Figure 2).

The control process is based in the Last Plan System (LPS) (Ballard 2000). The framework of the LPS ensures the integration of the initial (master) planning, the lookahead and the commitment. Complementarily, a Earned Management Analysis (Fleming & Koppelman 2010) was carried out.

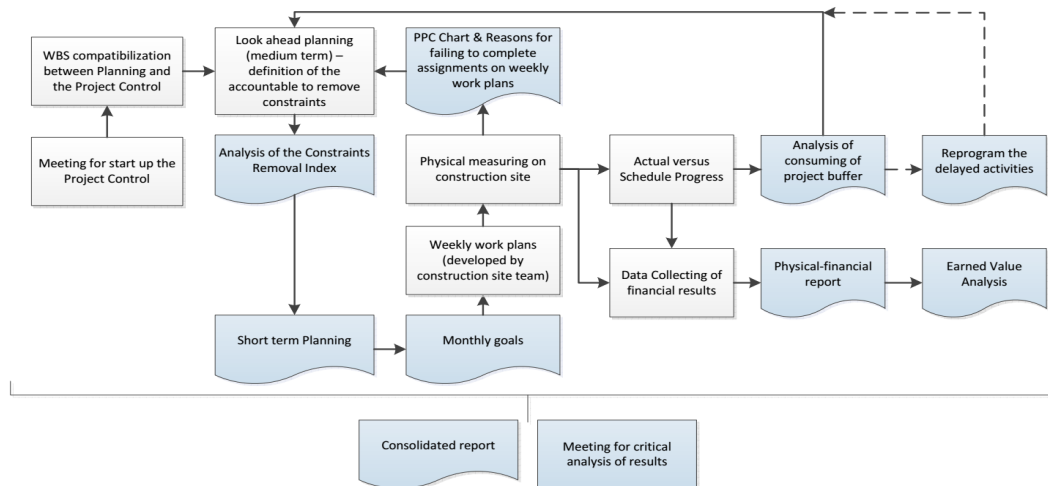


Figure 2: Standardization process of control

First, in the standardization of process of control, the compatibilization between the work break down (WBS) structure (commonly used in PERT planning) with project control is also carried out. The WBS used to budgeting is also compatibilized.

A lookahead planning is carried out to identify the constraints and an accountable is chosen to solve them, shielding the production (Ballard & Howell 1998). A Constraints Removal Index is analyzed as a performance indicator to lookahead planning.

A short-term planning is elaborated considering the status of the production system to generate the monthly goals. So, a weekly work plan is developed in construction site by site staff. The PPC chart and the reasons for the failure to complete the work are analyzed and it becomes an input (feedback) to lookahead planning in the next period of measurement.

At the same period, the physical progress is measured. To make this feasible, all physical measurement criteria were standardized. The criteria adopted were 100% of the work completed, which naturally led to the improvement of service termination.

With the work done and the information from the accounting sector it is possible to calculate the actual cost, which is compared with budgeted cost of the work performed in an earned value analysis. The current progress is compared with planned and the project lung is evaluated to verify the delay tendency, triggering or not the process of replanning.

Finally, plans are drawn up to reverse any distortion with planning. It is at this stage that information is managed and delivered to stakeholders. Through of results presentation, workshops and dashboard at construction site.

4.2 Implement and Test Lean Metric (LM)

For LM implementation, a programming company was contracted to develop a tablet application, used in field data collection. The initial planning and budget of the construction work are inserted in the system so that the activities, durations, dates, costs, labor and measurement criteria are controlled through the LM.

The data collection in the field is done by the clients (staff of construction site) via tablet, and sent to the consulting company from any place with internet access. This ensures the weekly monitoring of the projects, at a reduced operational cost and covering the national territory.

In the tablet application, there is a function with the measurement criteria, in order to standardize data collection, increasing reliability, and resulting in the transparency

improvement. There was an expenditure of time, about 3 hours, after the field measurement for data compilation, but that time was extinguished after using the system.

Through the constraints module, some minutes of meeting with the medium term plans is generated, identifying the constraints that occur in the next three months of the construction work. Moreover, the responsible for its removal and with the deadlines are also registered (Figure 3). In this way, the long term is more integrated and reducing the deviations.

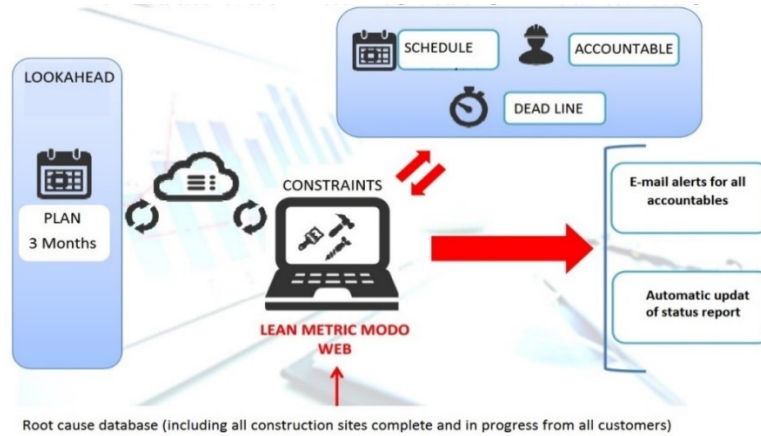


Figure 3: lookahead level of control

LM also has a database with standard constraints. At each new constraint meeting held with clients, if a different constraint occurs, the database is updated. For the measurement of the indicators of constraints removal, automatic emails are sent so that the responsible ones remove them, when they are solved. With this, the Constraints Removal Index (IRR) is generated automatically, which previously required about 45 minutes.

The weekly control - called the short term - is monitored according to the measurements made by clients, in real time, in order to evaluate the Evolution of Weekly Production, Targets, PPC and reasons for the failure to complete the work. Without LM this weekly monitoring could not be done by the consulting firm (Figure 4).

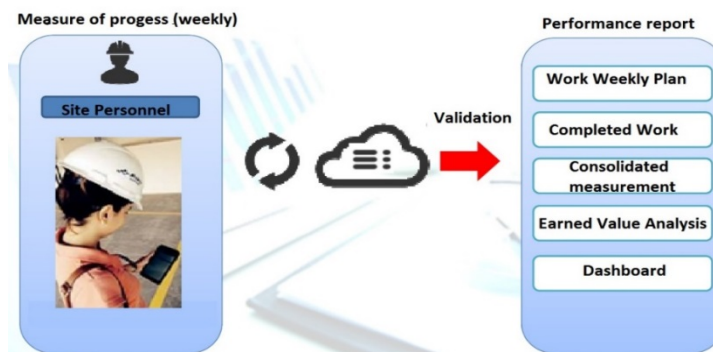


Figure 4: worksite data collection and key issues of performance report

Finally, a ranking of indicators was developed with all the construction works accompanied by the consulting firm, thus generating a benchmarking among the construction works.

During the last three years, the model has been tested and improved in more than 60 construction projects throughout the country, in addition to being used in various types

of construction: Commercial, Residential, Hotels, Malls, Lots, Condos. The improvements achieved with the LM implementation are presented below.

4.3 Improvements with Lean Metric

With the implementation of LM, the following gains occurred:

- Data and indicators are generated in the same planning and budgeting WBS - same packages linked to the short, medium and long term;
- The IRR is generated automatically, which previously demanded about 45 minutes;
- The time for data collection and compilation of all indicators before LM was 44 working hours, being reduced to 24 hours;
- The schedule of purchase of the materials and contracting of services is linked to the physical goals of the construction work;
- For the value-added analysis, after feeding the financial data, as reported by the client, the indicators related to this methodology are generated (Cost Performance Index (IDC), real cost, cost projection, estimate at completion);
- Human errors in the generation of indicators fell in 90%;
- The number of steps that do not add value to the process has been reduced, such as conferences and data manipulation for reporting, in a way that has reduced the operational cost of data collection.

4.4 Lean Metric Contributions

The LM tool showed that it uses the LPS concepts to manage the term and monitor the costs of the construction work, based on the information collected at the site, with more detailed control and reduction of the operational cost in data collection. The contributions of the implementation of the tool are presented in table 1, relating them to the principles of Lean.

Table 1: Lean Construction Concepts x Lean Metric

Principles	For Consultant company	For Customers
Transparency	The automatization of sharing information with customers reduced the doubts in the process of control	Generation of reliable information to improve the decision- making
Reduce the cycle time	Reduction of lead time from data collection to report	Real time performance indicators
Continous improvement	Simple performance and database of information provide continuous improvement of developed tool	The cycle of measurement enables the continous improvement of management actions for construction site along the project time
Standardization	Standardization of process f control Standardization of performance indicators	Standardization of projects performance indicators
Benchmarking	Database of Root cause for failure to complete work	A ranking with all indicators is carried out between different projects for different construction companies

5 CONCLUSIONS

This paper aims to analyze the contributions of the Lean Metric System, an IT tool developed to improving performance measurement process in Lean construction projects. The quality of the system was attested by the number of applications of the tool in different construction works and contexts (61 projects in total).

The first contribution of the system was in the development phase, when it was necessary to standardize the control process, the performance indicators used, the measurement criteria, which made possible to improve the transparency and the continuous improvement of performance measurement process.

It was verified that the simplicity of the LM allows a quick evaluation of the project performance, reducing the time between the information gathering and the decision-making. This provides a twofold benefit: for consulting company and for project manager. By receiving LM reports in a timely manner, managers can change practices to achieve reasonable performance levels.

For the consulting company, there was a reduction of time spent for data collection, reducing delays to producing result report and reducing the client's doubts about the process.

The combination of participatory management, process transparency and the short cycle of control (reduction of control lot and information batch for decision-making) created conditions for continuous improvement for both ways, to performance measurement processes and the project performance.

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LAST PLANNER SYSTEM – THE NEED FOR NEW METRICS

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Abstract: Several metrics have been used to evaluate the planning performance within the Last Planner System (LPS). Percent Planned Complete (PPC), which measures the reliability of weekly work planning, is the most commonly used metric. However, studies have shown the need to complement PPC with other metrics to measure performance. Researchers have developed many metrics to assess the make-ready process, workflow reliability, and weekly work planning. Many of those metrics were either inconsistently used, showed no correlation with the overall project performance, or required data that was too difficult and time-consuming to collect. This paper offers an overview of the various metrics proposed in the literature. It also proposes new metrics and details their calculation method to measure aspects not yet supported by a measurement metric. This paper is useful for last planners who can employ the newly suggested metrics to assess weekly work planning performance taking into account activity characteristics.

Keywords: Last Planner[®] System, Workflow, Planning Reliability, Metrics

1 INTRODUCTION

The Last Planner System (LPS) is widely used in construction projects to improve workflow and increase the reliability of construction planning. LPS acknowledges the shortcomings of forecasts and thus recommends planning in greater depth as the team gets closer to completing the work. It is best described as a mechanism for transforming the work that should be done into what can be done, forming an inventory of work made-ready from which the Last Planners commit to what they will do (Ballard 2000).

LPS consists of four planning stages: (1) Master Scheduling: Summarizes all the work that should be done in abstract terms. (2) Phase Scheduling: Defines project phases and is used to coordinate actions that extend beyond the lookahead window. Phase schedules provide more details regarding what should be done and when. (3) Lookahead Planning: Presents a time frame of roughly two to six weeks and is the stage where tasks are broken down and made ready. (4) Commitment Planning: Indicates the most detailed planning stage that results in commitments to deliver the work that was placed on the Weekly Work Plan (WWP) (Ballard 2000; Tommelein and Ballard 1997).

Many researchers and practitioners have developed metrics to measure the planning performance when applying the LPS in addition to PPC. Some metrics measure the success of the lookahead stage at anticipating tasks and removing constraints to make activities ready for implementation. Others measure productivity and progress both at the project level and the weekly work plan level. More metrics were proposed to align long-term

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planning with short-term planning (Ballard 2000; Chitla and Abdelhamid 2003; Emdanat and Azambuja 2016; Gonzalez et al. 2008; Hamzeh et al. 2008; Hamzeh et al. 2015a; Hamzeh et al. 2015b; Jang and Kim 2007; Mitropoulos 2005).

This paper presents a review of all current LPS related metrics. To address aspects of production planning that are not addressed by current metrics, this paper proposes new metrics to assess weekly work planning performance and overall workflow. The suggested metrics complement PPC which naturally assumes that all activities are of equal value and importance. The proposed WWP metrics take into consideration activities status (Required, Not Required, Backlog, and New). Required activities are critical activities in the traditional Critical Path Method (CPM) understanding. Backlog activities are excess tasks that are ready but not necessary and which are to be executed in case of available capacity. New activities are tasks added to the WWP that were not foreseen in the lookahead process (Rouhana and Hamzeh 2016). The proposed workflow metrics considers the volume of the activity and the number and duration of its successor tasks.

2 LPS METRICS

Researchers and practitioners have developed several metrics for use within the LPS environment. This section presents an overview of most metrics discussed in the literature.

As previously mentioned, PPC is the most commonly used metric. The common understanding is that successful weekly work planning and a good implementation of LPS is linked to a high PPC. The metric is a “post production” measure of the reliability of weekly work planning. PPC is defined as the percentage of tasks completed at the end of a short future time period in comparison to the tasks that were promised to be completed at the beginning of that period (Ballard 2000). It is wrongly believed that having a high PPC value must result in shorter project durations. Other metrics are necessary to complement the PPC and measure the overall reliability of the lookahead process and the fulfilment of target milestones.

$$PPC = Did/Will \quad (1)$$

To align the weekly work plan assignments with the lookahead plan, Tasks Anticipated (TA) and Tasks Made Ready (TMR) can be used. Ballard first proposed the two metrics, initially called “Assignments Anticipated” and “Assignments Made Ready”, in 1997, to evaluate the lookahead planning process. TA measures the performance of the lookahead planning process in anticipating tasks that will be committed to, for instance, two or three weeks in the future. On the other hand, TMR measures the ability of lookahead planning to make tasks ready for execution. It is the ratio of tasks with all their constraints removed in a certain time interval (usually two to three weeks) preceding execution to the tasks that were anticipated along the lookahead plan (Ballard 1997; Hamzeh and Aridi 2013). High values for TA and TMR can indicate shorter project durations (Hamzeh et al. 2015a; Hamzeh et al. 2015b).

$$TMR = Did/Can \quad (2)$$

$$TA = Will/Can \quad (3)$$

Planned Work Ready (PWR) is a metric that assesses the quality of the lookahead process. PWR was proposed by Mitropoulos to indicate the percentage of work in the lookahead plan that is expected to be ready as planned in the lookahead horizon. The PWR metric acts as a forecast, and, it can provide a better evaluation of schedule performance when it is complemented with PPC (Mitropoulos 2005).

$$PWR = \frac{\text{Work Expected to be Performed in Lookahead}}{\text{Work that Should be Performed in Lookahead}} \quad (4)$$

Mitropoulos (2005) also tried to measure the make ready process by suggesting three deltas: Delta_1 measures the constraints that prevent planned tasks from being ready. Delta_2 is the ratio of constraints removed compared to those that were expected to be removed. Finally, Delta_3 is the ratio of new constraints that were undetected during planning compared to the constraints identified. However, it is not easy to use the three deltas in assessing the make ready process since constraint analysis depends on the type of project and tends to differ from company to company.

$$\Delta_1 = (\text{Constraints Promised to be Removed}) / (\text{Constraints Identified}) \quad (5)$$

$$\Delta_2 = (\text{Constraints Removed}) / (\text{Constraints Promised to be Removed}) \quad (6)$$

$$\Delta_3 = (\text{New Constraints}) / (\text{Constraints Identified}) \quad (7)$$

Jang and Kim (2007) proposed an additional metric, Percent of Constraint Removal (PCR), to measure the performance of the make ready process. PCR compares the number of constraint-free tasks when scheduling the WWP to the number of all planned tasks found on the lookahead plan. This metric is considered a leading indicator of workflow predictability and thus is calculated before the weekly work plan starts. Authors who have proposed this metric have successfully indicated that PCR and PPC are correlated (Jang and Kim 2008).

$$PCR = \frac{\text{Number of Constraint Free Tasks When Scheduling WWP}}{\text{Number of Planned Tasks at Lookahead Plan}} = \frac{\text{Ready}}{\text{Can}} \quad (8)$$

Furthermore, Alarcón et al. (2014) analyzed PPC, Schedule Performance Index (SPI), PCR, and schedule progress curves for ‘successful’ and ‘unsuccessful’ projects. The success of the projects used was determined based on their schedule performance. The results showed that an increase in planning reliability (PPC and PCR) could improve project progress. It was also observed that for successful projects, it is not enough to have high values for the metrics, for it is important as well to control their variability.

In contrast, some researchers tried to correlate workflow reliability to productivity. Ballard and Howell (1998) used the Performance Factor (PF) as an indirect measure to show the impact of LPS on productivity. PF is the ratio of actual to earned productivity and is usually represented in labor hours. However, no statistical relationship was found between PF and PPC (Gonzalez et al. 2008).

$$PF = \frac{\text{Actual Labor Hours}}{\text{Earned Labor Hours}} \quad (9)$$

Chitla and Abdelhamid (2003) investigated the difference between improvements based on PPC vs those that are based primarily on the Labor Utilization Factor (LUF). They expressed LUF in terms of productive and non-productive time and found that an increase in PPC causes an increase in LUF. However, an increase in LUF does not result in an increase in PPC. They recommend project managers to focus on PPC instead of wasting resources on improving LUF as LUF is only a measure of local production activation.

$$LUF = \frac{\text{Effective Work} + \frac{1}{4} \text{Essential Contributory Work}}{\text{Effective} + \text{Essential Contributory} + \text{not useful}} \quad (10)$$

Gonzalez et al. (2008) reformulated LPS metrics in order to be able to compare them with activity level performance indicators. For this, they proposed two metrics: Project

Productivity Index (PPI) and Process Reliability index (PRI). PPI is considered an aggregate productivity index that overcomes PF limitations. It is calculated as the average of the Activity Productivity Indexes (API) where API is the ratio of average labor productivity to maximum labor productivity. PPI can reflect real productivity improvements because it is computed from maximum productivity on-site and not from expected productivity as is the case with PF. PPI has a good correlation with PPC. The other proposed metric, PRI, is a planning reliability index at activity level and is measured as the ratio of actual to planned weekly progress of a certain activity. Consequently, PRI was found to overcome PPC limitations for analyzing LPS effects at the activity level.

$$PPI = (\sum API/N) \times 100 \quad (11)$$

$$PRI = (AP/PP) \times 100 \quad (12)$$

Emdanat and Azambuja (2016) proposed three additional metrics to complement PPC, TA, and TMR in aligning short and long term planning. The first metric, Commitment Level (CL) is the percentage of the total committed required/critical activities with respect to the total required activities for any given work plan cycle. Fluctuations in CL were found to be correlated with an increase in late paths and decrease in float.

$$CL = \text{Required Will/Should} \quad (13)$$

Other metrics proposed were Percent Required Completed or Ongoing (PRCO) and Milestone Variance (MV). PRCO is the percentage of required/critical activities that are completed or expected to be completed on or before their promised completion dates with respect to the total required activities on the work plan. On the other hand, MV is the difference in days between the forecasted date to complete all remaining activities and the required date of the milestone. Emdanat and Azambuja (2016) demonstrated that teams who re-plan to maintain CL, PRCO, and PPC had a lower overall MV and hence were more reliable.

$$PRCO = \frac{\text{Required completed} + \text{Required Ongoing on Track}}{\text{Required Will}} \quad (14)$$

Finally, Priven et al. (2014) developed a Lean Workflow Index (LWI) to describe workflow. LWI is a polynomial function that uses multiple location-based scheduling parameters including: (A) the product of the root mean squares of all flowlines, (C) the percentage of time with no breaks after finishing a floor, (D) the percentage of time crews are working, (E) work in progress, and (F) work out of sequence. The weight of each parameter was calibrated by using goal-seeking algorithms based on subjective survey results of Location Based Management Schedules. No correlation was found between LWI and PPC. Yet, LWI can be used to achieve a smooth workflow alongside PPC.

$$LWI(t) = 7\% \times A^2 + 33\% \times C^2 + 4\% \times D^2 + 31\% \times E^2 + 25\% \times F^2 \quad (15)$$

3 SUGGESTED METRICS

Many metrics outlined above ignore activity characteristics and assume all activities are equally important. Further, there exists a very high dependency on PPC in the industry as its limitations are generally overlooked. PPC not only disregards activity characteristics but also neglects the consideration of successor activities. Consequently, this paper proposes additional metrics to improve weekly work planning and overall workflow. The metrics are designed to complement PPC and other metrics and not to replace them.

3.1 Weekly Work Plan Metrics

Required Level (RL):

RL measures the number of required/critical activities with respect to the number of activities on the weekly work plan. This metric is a natural complement to the CL and PRCO metrics discussed before.

$$RL = \text{Required Will/Will} \tag{16}$$

The purpose of RL is to help planners determine the criticality level of their activities and is thus calculated before the WWP starts. A high RL value means that many activities on the WWP are considered critical. Therefore, the team should attempt to complete all activities and obtain a high PPC as well.

Completed Uncommitted (CU):

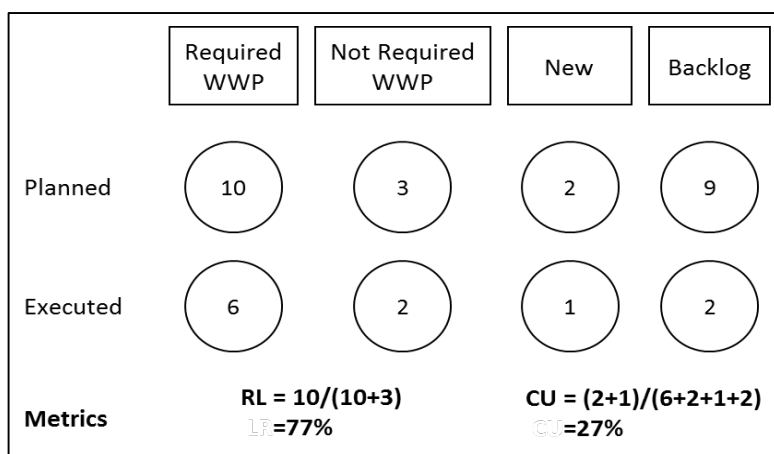
CU is a metric that measures work performed that was not on the WWP with respect to the total activities completed. It is important to note that total activities completed here is different from the “Did” in PPC, as backlog and new are not included in PPC calculations.

$$CU = \frac{\text{Executed} - \text{Executed from Will}}{\text{Did} + \text{Backlog} + \text{New}} \tag{17}$$

$$CU = \frac{\text{Executed from Backlog} + \text{Executed from New}}{\text{Did} + \text{Backlog} + \text{New}} \tag{18}$$

CU is proposed to address some PPC limitations. PPC does not distinguish between WWP, backlog, and new activities. As a result, an increase in CU can indicate problems in anticipating tasks and in the make ready process.

Figure 1 demonstrates how to calculate RL and CU. The figure shows the number of activities planned and the number of activities executed with respect to their status: Required on WWP, Not Required but on WWP, New, and Backlog. Dividing the number of planned required activities (10) by the total number of planned activities on the WWP (13) gives an RL value of 77%. On the other hand, dividing the executed New activities (1) + executed Backlog activities (2) by the total number of activities executed (11) results in a CU value of 27%.



3.2 Workflow Reliability Metrics

Labor Reliability (LHRI):

Figure 1. Sample Calculations for RL and CU

Hours Index

LHRI compares the percent of work completed in terms of labor hours with respect to the total amount of expected labor hours. For clarification, two cases are shown below. Both cases show the same ten activities but with different percentages of completion. It is observed that the PPC is easily impacted.

$$LHRI = \frac{\% \text{ of Work Completed} \times \text{Expected Labor hrs}}{\text{Total Expected Labor hrs}} \quad (19)$$

Activities (Case 1)	A	B	C	D	E	F	G	H	I	J
Labor-hrs of Activity	100	200	250	150	300	600	400	100	50	50
% Comp.	100%	50%	30%	10%	80%	100%	100%	50%	0%	0%

$$PPC = \frac{3}{10} = 30\%$$

$$LHRI = \frac{(100 \times 1) + (200 \times 0.5) + (250 \times 0.3) \dots \dots}{100 + 200 + 250 \dots \dots} = \frac{1580}{2200} = 71.8\%$$

Activities (Case 2)	A	B	C	D	E	F	G	H	I	J
Labor-hrs of Activity	100	200	250	150	300	600	400	100	50	50
% Comp.	100%	100%	100%	100%	100%	0%	100%	100%	100%	100%

$$PPC = \frac{9}{10} = 90\%$$

$$LHRI = \frac{(100 \times 1) + (200 \times 1) + (250 \times 1) \dots \dots}{100 + 200 + 250 \dots \dots} = \frac{1600}{2200} = 72.7\%$$

As can be inferred from cases 1 and 2, PPC ignores the amount of labor hours an activity needs. This is misleading since not all tasks are of equal value. Case 1 shows that a low PPC and an average LHRI show an average performance. Alternatively, case 2 shows that a high value of PPC can be accompanied with an average value of LHRI indicating an average performance. Accordingly, these metrics can be used together to show a more refined assessment.

Progress Priority (PP):

Progress Priority is based on the time plus sum of sons priority rule. In general, the priority rule ranks any given schedule’s activities based on the time required by the activity plus the time required for all activities that succeed it (Khattab and Choobineh 1990). Therefore, PP compares the time of the activities completed in addition to that of their successors with respect to the time of all activities on the WWP that should have been completed in addition to the time of their successors.

$$PP = \frac{\sum \text{Time Plus Sum of Successors Completed}}{\sum \text{Time Plus Sum of Successors of WWP Should}} \quad (20)$$

Two cases are shown below to explain the calculation of the PP metric. Calculations are based on the CPM Network shown in Figure 2. Activities shown in red represent activities that were placed on the WWP.

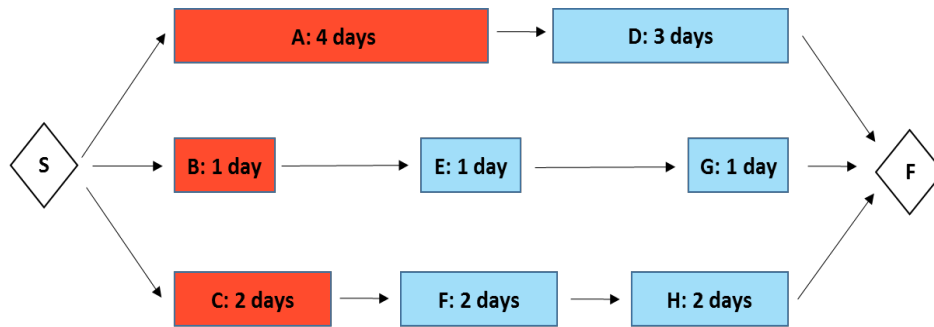


Figure 2: CPM Network

Case 1:

Activities A and C were 100% completed. However, activity B was not fully completed by the end of the week.

$$PPC = \frac{2}{3} = 66.7\%, \quad PP = \frac{7 + 6}{7 + 3 + 6} = \frac{13}{16} = 81.25\%$$

Case 2:

Activities B and C were 100% completed. However, activity A was not fully completed by the end of the week.

$$PPC = \frac{2}{3} = 66.7\%, \quad PP = \frac{3 + 6}{7 + 3 + 6} = \frac{9}{16} = 56.25\%$$

It can be inferred that PP can be different for the same value of PPC. PP can be used to maintain a smooth workflow as it measures the amount of work done and the amount of work opened by the completed activities for downstream tasks compared to the amount of work that was expected to be opened. To ensure a good workflow, the authors recommend looking at the plan as a whole and not on individual activities.

4 CONCLUSION

This paper presents an overview of most LPS metrics that have been developed so far. Currently, PPC is the most used metric in the industry. Nevertheless, many metrics have been proposed in the literature to complement PPC. Additional metrics are proposed in this study to address weekly work planning and workflow. RL and CU should be used to complement PPC at the work plan level. RL is a leading indicator to show the percentage of critical tasks on the WWP. CU distinguishes between WWP, backlog, and new activities and measures the amount of work done that was not on the WWP. Moreover, LHRI and PP are suggested as workflow metrics to address the PPC limitations in measuring the volume and amount of work opened, respectively.

This paper highlights the fact that many metrics are currently available and new metrics are being developed. However, there is little research that systematically applies those metrics to identify their predictive power in isolation or in combination. Research is difficult to conduct because of how teams document LPS. The advent of database-driven LPS tools provides an opportunity for the systematic analysis of the LPS metrics. Research can help advance how LPS tools are implemented and the resulting organized datasets can advance research by providing well-organized and structured datasets for further analysis. In this context, the authors are in the process of applying these metrics on actual projects to assess their utility and highlight major issues in production planning.

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A CONSTRUCTION DELAY ANALYSIS APPROACH BASED ON LEAN PRINCIPLES

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Abstract: Delay is a quite common problem for construction projects. The existing practice of construction management is usually based on assessment of delays, liabilities and claims. However, this approach does not serve to remove the underlying causes of delay problems. In addition to estimation of delays, there is a need for a systematic method that will prevent delays in projects. Lean construction has tools and techniques that can serve for this purpose. However, a formal delay analysis procedure does not exist in lean practices since CPM adaptation is not well accepted. This paper advocates that integrated utilization of CPM and lean principles can help assessment of existing delays and minimization of delays in forthcoming stages.

The methodology proposed in this study has not been applied on a real project, however, in this paper, its implementation steps are demonstrated using real project data. The proposed methodology is expected to help construction practitioners in delay analysis and when lean principles are applied appropriately, it can prevent delays, enhance schedule accuracy, and improve communication between the parties.

Keywords: Lean construction, delay analysis, last planner system, critical path method, pull scheduling.

1 INTRODUCTION

Delay is one of the most typical consequences of performance problems in the construction industry. There are numerous reasons for construction delays, including problems related to design, labor, materials and equipment, subcontractors, weather, planning, and work execution (Gonzales et al. 2014).

Existing construction management practices are often oriented towards how delays can be calculated more precisely. There are many delay analysis techniques, which can be grouped as as-planned vs. as-built analysis, impact as-planned analysis, collapsed as-built analysis and time-impact analysis (Arditi and Pattanakitchamroon 2006). Each of these methods have different approaches for estimation of delays and assessment of liabilities. However, they lack of a systematic mechanism and protective approach that shields projects from further delays while analyzing the existing ones (Birgonul et al. 2014).

Delay analysis based on the Last Planner System (LPS) principles can make a significant contribution to overcoming this problem. Pull based approach of the LPS

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enhances both the flow of work packages and the level of communication on the construction site (Priven and Sacks 2013). With these features, LPS and lean principles can enable the minimization of delays. Nonetheless, there is not a formal delay analysis procedure in lean construction since lean philosophy does not advocate the utilization of CPM schedules in today's complex, uncertain, and quick construction projects (Koskela et al. 2002). This paper, on the other hand, proposes a methodology based on integrating CPM with LPS and lean principles. Forthcoming sections describe the proposed delay analysis methodology and its implementation.

2 INTEGRATING CPM INTO LEAN CONSTRUCTION

In current construction management practices, detailed CPM schedules are being prepared at the beginning of projects by considering the whole project duration although there are various uncertainties associated with the as-planned schedule. It is not a realistic approach to prepare a work schedule representing project conditions of the forthcoming years and considering it as the baseline throughout the project. Construction activities are prone to several risk factors, and it is very hard to predict future project conditions accurately at initial stages of the project. Validity of the baseline schedule may be restricted due to many reasons, including change of project scope, design documents, and even project teams. For these reasons, it is very common phenomenon in construction projects that a few months after the preparation of the baseline schedule, it becomes unpractical. Then, project team tries to adopt a new baseline schedule, which requires extra time and money. However, delay and other performance problems of the construction projects cannot be associated with CPM methodology only. They are rather related to the way CPM is implemented and utilized for decision-making. Moreover, the role of CPM in construction projects cannot be ignored due its widespread utilization and contractual requirements of owners (Olivieri et al. 2016).

In order to eliminate waste due to long and complex baseline schedules, a pull schedule approach similar to LPS should be adapted. Huber and Reiser (2003) indicate that CPM scheduling and the LPS can be complimentary to each other and utilization of them together can improve work and crew flow. An integrated planning system, which has been developed by a Norwegian building contractor, reveals that benefit of the LPS can be still maintained with the integration of CPM (Kalsaas et al. 2014). CPM, LPS, and their production control metrics are not conflicting with each other, but on the contrary, they can improve project management efficiency when they are used together (Ponz-Tienda et al. 2015). This paper also suggests an integrated approach for construction delay analysis by combining CPM with the principles of lean construction. Although LPS is adapted as core principle, other lean construction principles are also integrated to proposed methodology. Principles such as, including project participants to decision making process and organizing regular meetings are integral parts of the methodology. These lean principles increase the communication between the project stakeholders, so that the work schedules can be created more realistically and repeating delay events can be minimized. The methodology is believed to represent project conditions better with its communication-based continuous learning mechanism and provide a better benchmark for delay analysis.

3 PROPOSED METHODOLOGY

This section describes implementation steps of the proposed methodology. As explained in previous sections, the methodology is based on the idea of integrating CPM with core principles of the LPS and lean construction. Figure 1 illustrates the overview of the proposed delay analysis methodology.

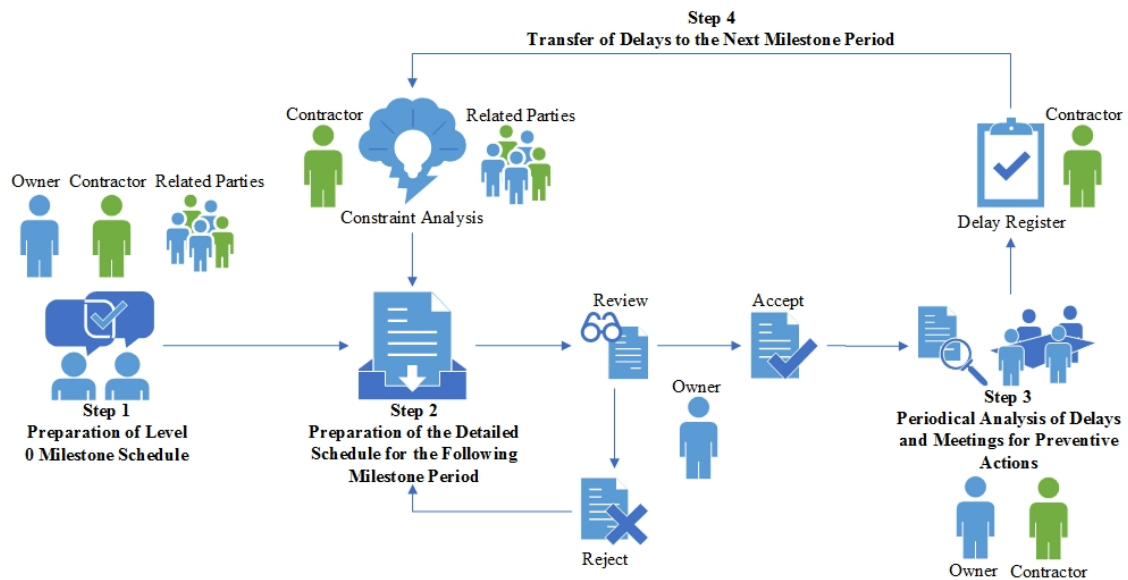


Figure 1: Implementation Steps of the Delay Analysis Methodology

The methodology has four steps. First step is similar to the master planning phase of the LPS. A milestone schedule should be prepared based on contractual documents and requirements of the Owner. This work schedule should contain the dates of milestone activities that physically exist in the project. It would be more appropriate for delay analysis if time interval between two milestone activities is not too long. Although it depends on the type of the project and frequency of the updating periods, 6 weeks time intervals can be utilized as suggested by the LPS (Ballard et al. 2002). Milestone activities should be selected so that milestone periods should not be intertwined. If nature of the works or limited experience of the contract parties prevent determination of milestone activities explicitly, a more detailed schedule with CPM logic can be used to estimate them. Milestone schedule should be prepared by participation of all project stakeholders. From the perspective of lean construction, the approach of consensus based milestone scheduling will help to establish better communication between the contract parties at the very early stage of the project.

Second step is preparation of a detailed schedule for the period between first two milestone activities. This steps includes procedures of lookahead planning in LPS. Before preparing the schedule, a constraint analysis should be carried out by the project team and alternative plans should be developed for the expected problems. A formal risk analysis procedure will serve for these purposes. Constraint analysis will not only protect work flow from uncertainties, but also improve participation and project integration of the stakeholders. As an output of this analysis, work packages to be completed in milestone period should be pulled and execution plan of the activities should be estimated with CPM logic. Even though this delay analysis approach is based on integration of CPM with lean principles, complicated network relationships should be

avoided. For example, utilization of Start-to-Finish relationship should be prevented, and Start-to-Start and Finish-to-Finish relationships should be restricted. Furthermore, relationship lags and constraints should not be preferred. The pull based scheduling approach will support lean construction principles by constituting a continuous work flow. The work schedule finalized by the Contractor should be submitted to approval of the Owner for a sufficient period of time. The schedule will be the basis for delay analysis throughout the period.

Third step has two main processes: periodical analysis of delays and meetings for preventive actions. Similar to commitment planning phase of LPS, success of the lookahead schedule is measured by estimating delays periodically. Before delays are examined, duration difference between the original milestone period and as-planned schedule should be estimated as initial delay. It should be calculated at the beginning of the period and be granted to the Contractor as a positive or negative delay. Then, a window based delay analysis approach can be utilized to estimate delays throughout the regular update intervals. Results of the delay analysis are directly influenced by the size of window span. Using large intervals causes the dynamic changes in the critical path to be missed. Therefore, accuracy of the analysis will be better when window size is as small as possible (Hegazy and Zhang 2005). Following the quantification of delays at each window, delay meetings should be organized between the project team and the Owner representatives. Delay meetings correspond to the learning phase of LPS. A delay register should be the output of these meetings. Subjects of the delay register may include; delay reasons, responsible parties, preventive actions for similar delays, supportive strategies to prevent further delays, impacts of third party delays, and reduction strategies. Main contribution of the delay meetings to lean principles is improved communication between the contract parties throughout the project. In addition, lessons learned from the current delays will be transferred to following period while preparing its schedule. By this way, information will be updated at all phases of the project.

Last step of the proposed methodology is transfer of delays. Inexcusable delays, excusable-compensable delays, and excusable-non compensable delays estimated at the end of third step are transmitted to the following period. This operation is repeated for each period until the end of project.

Using this methodology, delay amounts and liabilities will be established at each phase of the project without the need for a forensic schedule analysis. More importantly, as fundamental principle of this delay analysis approach, delays and their impacts will be minimized in the forthcoming phases of the project. Following section demonstrates the implementation procedure of the methodology with a numerical example.

4 IMPLEMENTATION PROCEDURE

This section explains how the proposed delay analysis methodology can be used in a construction project. Although the methodology has not been implemented directly in the project, its implementation is demonstrated using real project data and actual delays happened in this project. The example project involves the construction of towers for an energy transmission line. There are 34 towers in the project. Basic activity groups are foundation works, erection works, and wiring of the transmission line. The project has estimated duration of 8 weeks and includes 171 activities in total. There is not any non-working day or holiday in the calendar. The work schedule of the project is updated weekly. Therefore, the delay analysis is performed on a weekly basis.

In order to implement the proposed methodology in the project, a milestone schedule is created as shown in Figure 2. The milestone schedule is composed of four milestone activities and three milestone periods whose durations are also indicated in Figure 2.

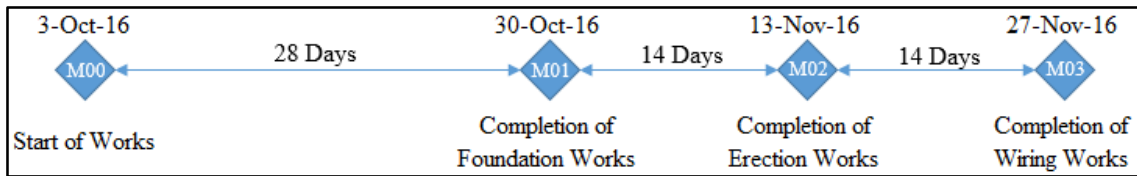


Figure 2: Milestone Schedule

Before the initiation of first milestone period, a detailed schedule is prepared for this period. It should be noted that work packages should be pulled as a result of a detailed constraint analysis for real cases. Figure 3 depicts approved schedule for this period. According to as-planned schedule; the start date of construction is 3rd of October, which is same as the first milestone date. However, finish date shows that the Contractor expects to complete foundation works 5 days earlier than the second milestone date. This duration difference will be granted to the Contractor as an initial negative delay.

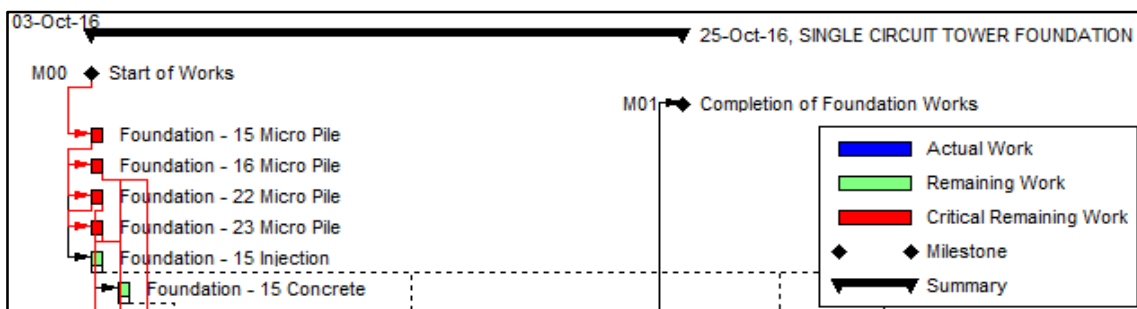


Figure 3: As-Planned Schedule of Period 1

Delay analyses are performed for the first period throughout the weekly updates. As-built schedule obtained at the end of this period can be seen in Figure 4. Completion date of the first period indicates that there is a considerable amount of delay in the project. Works are expected to be completed on 25th of October in the as-planned schedule, whereas actual date is 22nd of November.

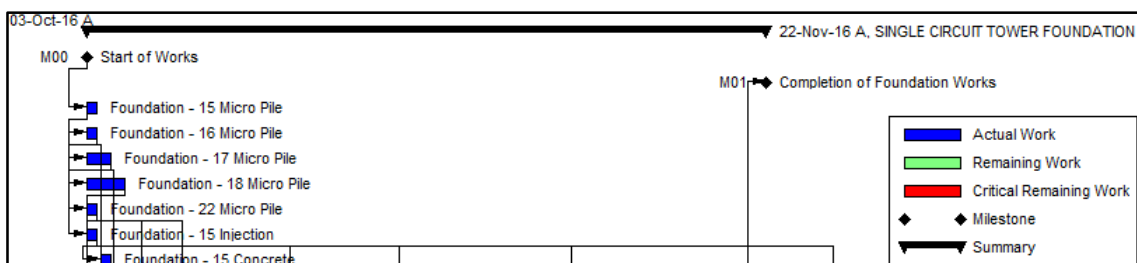


Figure 4: As-Built Schedule of Period 1

When this methodology is used in real projects, assessment meetings should be conducted following each delay analysis window. As a result of these meetings, a detailed register of delays should be created in order to illuminate the other phases of the

project. An example of delay register for the major delay items is shown on Table 1 in which responsible parties are determined according to the contract conditions. Table 2, on the other hand, presents the delay analysis calculations and results for the first period according to delay register data in Table 1. Delays estimated in this period will be transferred to second milestone period.

Table 1: Delay Register Example

#	Delay Item	Delay Cause	Delay Amount	Responsible Party	Strategies for Similar Delays
1	Slow work progress	Inadequate resources	3 days	Contractor	Resource increase
2	Suspension of piling works	Default of piling subcontractor	12 days	Contractor	Changing the prequalification criteria for subcontractors
3	Prevention of site usage	Expropriation problems for the 31st and 32nd tower	5 days	Owner	Completion of expropriation prior to start of works
4	Administrative disturbance	Delay in getting permission from the local electricity authority	8 days	Third Party	Establishing better relationships with local authorities

Table 2: Delay Analysis of Period 1

Delay Parameter	Quantity
Original Duration of Period 1 [1]	28 Working Days
As-Planned Duration of Period 1 [2]	23 Working Days
Initial Contractor Delay in Period 1 [3]=[2]-[1]	23-28 = -5 Days
As-Built Duration of Period 1 [4]	51 Working Days
Total Delay for Period 1 [5]=[4]-[2]	51-23 = 28 Days
- Inexcusable Delay [5.1]	15 Days
- Excusable-Compensable Delay [5.2]	5 Days
- Excusable-Non Compensable Delay [5.3]	8 Days
Total Contractor Delay in Period 1 [C1]=[3]+[5.1]	-5+15 = 10 Days
Total Owner Delay in Period 1 [O1]=[5.2]+[5.3]	5+8 = 13 Days

In order to carry out delay analysis for the second period, detailed schedule for this period should be ready. It should be prepared before the completion of first period. However, very early preparation of the work schedule will restrict the utilization of lessons learnt in the first period. Late preparation, on the other hand, will shorten the approval process. There should be an appropriate time interval between the completion

of the first milestone period and schedule submission of the second milestone period. Figure 5 demonstrates the approved as-planned schedule for the second period. As shown in the schedule, the Contractor plans to accelerate works. As-planned duration of this period is 9 days, whereas original milestone period equal to 14 days. It means that, there will be 5 days initial negative delay for the Contractor.

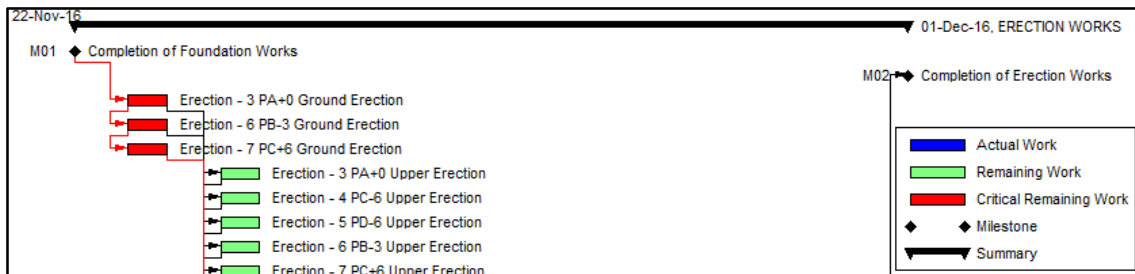


Figure 5: As-Planned Schedule of Period 2

Similar to the first period, delay analyses are performed in each updating period. As-built schedule of the second milestone period is given in Figure 6. It indicates that the Contractor performed better than planned. The erection works have been completed in 6 days. There is a negative delay for the Contractor realized by the increase of resources.

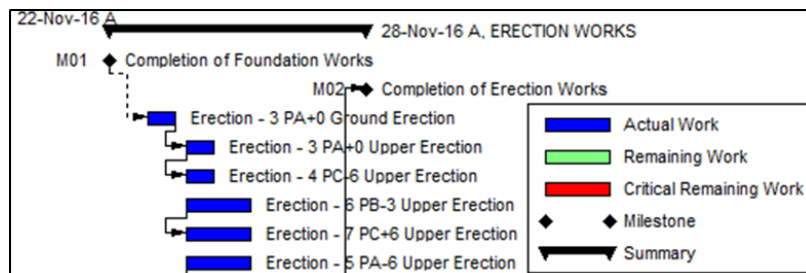


Figure 6: As-Built Schedule of Period 2

Delay analysis calculations and results for the second period are represented in Table 3. The Contractor has succeeded to reduce the delay amount, but the project is still behind the schedule due to delay in the first period. According to the schedule, foundation works and erection works have been completed on the 28th of November. Related completion date was 13th of November in original milestone schedule. As of the end of the second period, there is 15 days delay in total. 2 days delay belongs to the Contractor, while 13 days delay is under the liability of the Owner. These delays should be passed to following period by repeating the same steps.

Table 3: Delay Analysis of Period 2

Delay Parameter	Quantity
Total Contractor Delay in Period 1 [C1]	10 Days
Total Owner Delay in Period 1 [O1]	13 Days
Original Duration of Period 2 [1]	14 Working Days
As-Planned Duration of Period 2 [2]	9 Working Days
Initial Contractor Delay in Period 2 [3]=[2]-[1]	9-14 = -5 Days
As-Built Duration of Period 2 [4]	6 Working Days
Total Delay for Period 2 [5]=[4]-[2]	6-9 = -3 Days
- Inexcusable Delay [5.1]	-3 Days
- Excusable-Compensable Delay [5.2]	0 Day
- Excusable-Non Compensable Delay [5.3]	0 Day
Total Contractor Delay in Period 2 [C2]=[C1]+[3]+[5.1]	10-5-3 = 2 Days
Total Owner Delay in Period 2 [O2]= [O1]+[5.2]+[5.3]	13+0+0 = 13 Days

As a result, this example demonstrates how the proposed methodology can be implemented under real project conditions. Results reveal that it can be used at different stages of the project to estimate delays. In traditional practice, delays are analyzed through unrealistic baseline schedules, and claims arise during and after the project. This methodology, on the other hand, can analyze delays based on more realistic schedules and minimize the non-value adding processes, such as disputes and claims. Moreover, the methodology focuses on establishing a continuous learning mechanism in the project. Delay register example aims to demonstrate that lessons learned at a certain stage of the project can be used in the future. Although how the project parties can communicate could not be demonstrated in the example, proposed methodology is believed to advocate a consensus-based decision making at each step of delay analysis. This approach can serve to reduce communication barriers and disputes between the project stakeholders.

5 CONCLUSIONS

This article recommends an integrated methodology for delay analysis based on lean construction principles. It has a potential to improve the performance of construction projects by providing a delay-preventive mechanism, accurate and contemporaneous schedule information, and improved communication.

The proposed methodology depicted in this paper is the initial step of an on-going research project. In the future, the applicability this methodology is planned to be tested on real cases by using action research methodology and its advantages/disadvantages will be tried to be evaluated by conducting interviews with construction professionals. It is also believed that development of a tool that facilitates the implementation of the methodology can increase its applicability. Utilization of such a tool can help recording the constraint analysis and delay registers of projects, and it may be used for assessment and minimization of delays in forthcoming projects.

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PROBABILITY DENSITY FUNCTION FOR PREDICTING PRODUCTIVITY IN MASONRY CONSTRUCTION BASED ON THE COMPATIBILITY OF A CREW

Laura Florez¹, Jean C. Cortissoz²

Abstract: During the different phases of a masonry project, contractors collect detailed information about the labor productivity of its workers and the factors that influence productivity. Information includes quantitative data such as hours, activities, and tasks, and qualitative data such as ratings and personality factors. Personality factors have been found to be a key aspect that influences the compatibility of a crew and the productivity in masonry construction. This paper proposes a mathematical framework to determine how the compatibility between the workers in a crew can be used to predict productivity. A standard method for quantifying personality is used to determine the compatibility of a crew and empirically define a probability density to predict productivity. The probability density determines, for a given compatibility, the average productivity for a crew. The most interesting part of this probability density is that it accounts for variations in the productivity, resulting from the interaction and the relationships between the workers in a crew. The proposed probability distribution can be used to make more realistic predictions, by calculating confidence intervals, of the productivity of masonry crews and to better estimate times of construction, avoid crew conflicts, and find practical ways to increase production.

Keywords: masonry construction, productivity, process improvement, crew formation, probability density

1 INTRODUCTION

Personality factors have been demonstrated to be useful for explaining and predicting attitudes, behaviors, job performance, and outcomes in many organizational settings (Ones et al, 2007; Shuck and Reio, 2013; Hogan and Holland, 2003; Campion et al, 2005; Cohen and Bailey, 1997). The big five personality dimensions (Goldberg, 1993) are: openness to experience (O), conscientiousness (C), extraversion (E), agreeableness (A), and neuroticism (N), commonly known as OCEAN, and are used to indicate human personality (Ones et al, 2007). The OCEAN dimensions have been investigated in meta-analytic studies (Hogan and Holland, 2003; Cohen and Bailey, 1997), and have been used in applied psychology and human resource management to determine the relationship between personality and job performance. Results of these studies have shown that organizations use personality factors not only for recruitment and personnel selection, but also to support

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decision making when forming effective groups of workers (Kristof-Brown and Stevens, 2001).

In construction, groups of workers are known as crews. Crews specialize in a given skill to complete a task (Ng and Tang, 2010), and the foreman in the jobsite is responsible of forming crews to maximize productivity. Crew formation is the process of determining the size and the composition of each crew to complete a project (Hassanein and Melin, 1997). Decisions on how to form crews and what is the proper grouping of workers to increase productivity in construction have been addressed by a number of studies (Nerwal and Abdelhamid, 2012; Mitropoulos and Memarian, 2012; Hassanein and Melin, 1997; Rojas 2008). These studies provide clear guidelines and specific characteristics that need to be considered to form lean and effective crews.

However, the current crew formation literature in construction lacks of a framework that considers personality factors and how the interpersonal compatibility between workers in a crew can be used to form effective crews and predict productivity. This paper proposes a mathematical framework to determine how the compatibility between workers in a crew can be used to predict productivity. A probability density is empirically defined to predict productivity. The probability density determines, for a given compatibility, the average productivity for a crew and can be used to better estimate times of construction.

2 CREW FORMATION

2.1 Essential concepts

Crew formation is one of the key tasks in construction project management (Hassanein and Melin, 1997). The process of selecting the workers in a crew is crucial for ensuring the success of a construction project and improved labor productivity. Crew formation is the process of determining the size and the composition of each crew to complete a project (Mitropoulos and Memarian, 2012). The composition of a crew impacts directly the estimating and scheduling process in construction because it has a direct relation with task durations and labor costs and consequently with the productivity of a construction project (Nerwal and Abdelhamid, 2012).

2.2 Forming masonry crews

Crews in masonry are formed considering not only time and cost constraints but also considering the characteristics of the masons. Masons have different skills, abilities and personalities and typically the foreman in the jobsite considers these characteristics when forming its crews. By considering these characteristics, the foreman tries to maximize productivity by assigning the proper mason to the proper wall (Florez, 2015). The skills of a mason are considered to either assign a mason to a wall that has many details and cuts or to a wall that has little details. The abilities are considered to either assign a mason to a brick wall or a block wall. The personality is considered to assign a mason to a crew with masons that have similar characteristics rather than to a crew with masons that have dissimilar characteristics.

Personality has been found to be a key aspect that influences the composition of masonry crews. Personality not only influences the interpersonal compatibility between the masons in a crew, but also has a major impact on the performance of a crew which directly affects its productivity (Florez, 2015). A number of studies have been developed to determine the personality factors and preferences that need to be considered to form effective groups in construction such as good communication and confidence (Hiyasatt et

al, 2016), consensus and heterogeneity (Mach and Barush, 2015), teamwork coordination (Mitropoulos and Memarian, 2012), team motivation and satisfaction (Nerwal and Abdelhamid, 2012; Borcharding and Alarcon, 1991), and good relation with workmates (Kazaz and Ulubeyli, 2007) among others. An interesting approach to personality for electrical works can be found compiled in a book edited by Rojas (2008). However, there is no study that has attempted to evaluate and quantify the impact that personal compatibility has on the configuration of crews and whether compatibility can be used to predict productivity.

3 PERSONALITY FACTORS

3.1 The Big Five personality dimensions

It is well known that group work is organized by determining what will be done and who will do it and in this process, group members make a big effort to get along (Mach and Baruch, 2015). In order to get along with a group, people cooperate and seem compliant, friendly, and positive, and people that get along usually have similar personality factors. The big five personality dimensions OCEAN are used to describe human personality (Ones et al, 2007) and have been used in meta-analytic reviews in applied psychology since personality factors are useful predictors of job performance (Hogan and Holland, 2003).

3.2 Test to measure personality

There are a number of tests that can be used to indicate personality factors using the Big Five model. These tests are used in meta-analysis to determine workers' personality factors to evaluate their compatibility with a group (Kristof-Brown et al, 2005; Burch and Anderson, 2004) and are widely used to select personnel and form effective groups (Chiocchio and Essiembre, 2009; Dineen et al, 2002). One of such tests is the Belbin test, which is used to form successful groups based on personality traits and roles that each person may contribute to the group (Belbin, 2017). Another is the Myers-Briggs test, which is used to classify personality preference types and identify how people make decisions (Rojas, 2008). These tests have been extensively used in applied psychology and allow managers to form compatible groups of workers (Hobman et al, 2003).

3.3 Compatibility

A number of studies have demonstrated that personality factors influence the compatibility of a group (Kristof-Brown and Stevens, 2001; Witt, 1998). Compatibility reflects the tendency of a group to have similar ways to work, get along well, get things done, and facilitate group performance (Kristof-Brown and Stevens, 2001). In compatible groups, workers are more willing to communicate, share information, and resolve conflicts effectively, which translates in increased job performance and productivity (Dineen et al, 2002). In other words, a compatible group is a team in which the characteristics of its workers have been well matched (Kristof-Brown and Stevens, 2001). In this case, a compatible group is a crew in which the masons get along well and can work well together and have better productivity rates. The next section illustrates how to use the compatibility to predict productivity.

4 PREDICTING PRODUCTIVITY: CASE STUDY

4.1 Mathematical framework

Figure 1 shows the mathematical framework that supports masonry contractors in the process of predicting productivity. To obtain productivity estimates, a series of steps need to be followed (see Figure 1). Firstly, a literature review was performed for definitions of the OCEAN factors. Based on these factors, masons complete a test to indicate and quantify their personality. Based on their personality, the foreman determines a compatibility score for all the possible crew formations. After defining the compatibility score, measurements on-site are conducted to measure the productivity for multiple crews that have the same compatibility score. From the field measurements, the productivity density function is developed, that is, an average productivity can be estimated for crews that share similar compatibility. The distribution, alongside the confidence intervals, can be used to better predict productivity, estimate times of construction, and determine productive crew formations.

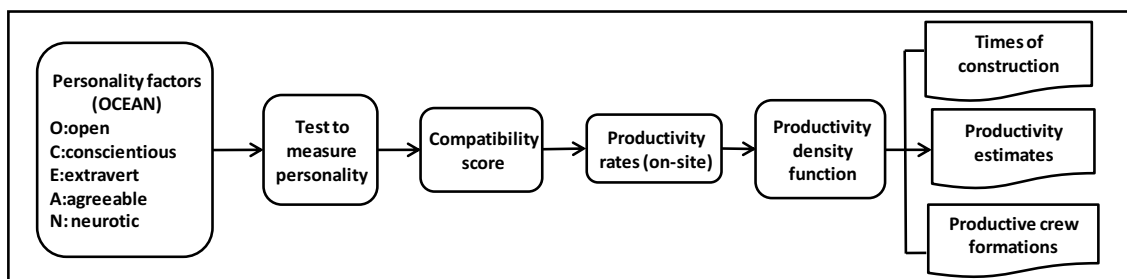


Figure 1: Mathematical framework

4.2 Personality factors and compatibility scores

To illustrate how the personality of the masons determines the compatibility of a crew and how the compatibility can be used to predict productivity, let's consider a masonry project. Assume the project has two walls (wall 1 and wall 2) and wall 2 can only be started if wall 1 is finished. There are seven masons available (m1, m2, m3, m4, m5, m6, m7) to build the walls. The mason's personality factors are known in advance. That is, each mason completed one of the personality tests (stated above) as part of the interview process and its personality is now available to the foreman. Table 1 shows the score for the OCEAN dimensions to indicate quantitatively the personality of each mason. Note that a high score in an OCEAN dimension indicates that a mason has that personality factor.

Table 1. Personality factors for the masons

Mason	Openness (O)	Conscientiousness (C)	Extraversion (E)	Agreeableness (A)	Neuroticism (N)
m 1	0.10	0.70	0.10	0.90	0.90
m 2	0.80	1.00	0.40	0.20	0.30
m 3	0.10	0.50	0.20	0.80	0.80
m 4	0.40	1.00	0.80	0.90	0.20
m 5	0.90	0.90	0.90	0.20	0.30
m 6	0.30	1.00	0.90	0.80	0.10
m 7	0.30	1.00	0.90	0.80	0.10

For instance mason 4 is conscientious, extrovert and agreeable but not open and neurotic. Let's assume that masons with similar characteristics work better than masons with dissimilar characteristics, as stated in some meta-analytic studies (Mach and Baruch, 2015; Witt, 1998). That is, mason 4 will work well with mason 7. Table 2 shows the compatibility score for different crews and its corresponding masons. These scores were determined by using the personality factors shown in Table 1.

Table 2: Compatibility score for crews

Crew	Masons	Compatibility
c 1	m1, m3, m5	0.50
c 2	m2, m4, m6, m7	1.00
c 9	m1, m3, m4, m7	0.80
c 12	m2, m6, m7	0.40

Note that the higher the compatibility score, the better the masons in the crew get along. That is, masons that work well together will have a higher compatibility score, whereas masons that do not work well together will have a lower compatibility score. For instance, crew 2 has a compatibility score of 1.0, since mason 4, mason 6 and mason 7 have similar personality factors and will get along well.

4.3 Probability density function

Let's also assume that crew 1 will build wall 1. Crew 1 has three masons and its compatibility score is 0.5. On the other hand, wall 2 is build by crew 2 and crew 2 has four masons and a compatibility score of 1.0. The productivity data has been collected empirically for crew 1 and crew 2 (see Table 3 and Table 4). Crew 1 (compatibility of 0.5) lays blocks at the following rates per period of time (see Table 3). Crew 2, (compatibility of 1.0) lays blocks at the following rates (see Table 4):

Table 3: Productivity rates for crew 1

Number of units	Probability
220	0.20
250	0.30
270	0.30
290	0.10
300	0.10

Table 4: Productivity rates for crew 2

Number of units	Probability
450	0.30
470	0.30
490	0.30
500	0.10

These observations should be made in the field by recording the productivity of crews with the same compatibility scores. To simplify our computations, let's assume an exact number of blocks associated to each probability, and not intervals as it should be done. Again, to simplify our computations we will assume that once a crew settles on a productivity rate, it keeps the same rate until the wall is finished. Wall 1 has 500 blocks, and wall 2 has 1000 blocks thus the previous data can be converted into data of how long it will take each crew to finish wall 1 (Table 5) and wall 2 (Table 6), respectively.

We then can compute the mean and variance for the units of time it takes each crew to finish its respective wall, so for crew 1 we have that the random variable that gives the amount of time that it will take to complete wall 1, we shall call X, has a mean of $X = 1.948$ units of time, whereas the random variable that gives the amount of time that crew 2 takes to complete wall 2, we shall call Y, has a mean of $Y = 2.117$ units of time.

Table 5: Prediction of time for crew 1

Wall 1	
Time periods	Probability
2.27	0.20
2.00	0.30
1.85	0.30
1.72	0.10
1.67	0.10

Table 6: Prediction of time for crew 2

Wall 2	
Time periods	Probability
2.22	0.30
2.13	0.30
2.04	0.30
2.00	0.10

Second we compute the variance of both distributions and we obtain 0.037 and 0.006 for X and Y, respectively. We want to use a continuous probability density to approximate our probability densities as this allows more general estimates to be made. Now, as we only use the mean and variance as reliable observables and given these two, and the probability density with the highest entropy is the normal with these mean and variance, for the first crew we have the following probability density for the time it takes to complete wall 1:

$$P_x(x) = \frac{1}{\sqrt{2\pi * 0.037}} \exp\left(-\frac{(x - 1.948)^2}{2 * 0.037}\right)$$

,and for crew 2, the probability distribution for the time it takes to complete wall 2 is:

$$P_y(y) = \frac{1}{\sqrt{2\pi * 0.006}} \exp\left(-\frac{(y - 2.117)^2}{2 * 0.006}\right)$$

As we have assumed that wall 1 should be completed before starting wall 2, then the two walls are expected to be completed in $x + y = 1.948 + 2.117 = 3.065$ units of time. Now, as the two walls are different and the composition of the crew only matters for the compatibility score it produces, we may assume that the random variables x and y are independent, so its probability density is given by:

$$P_{x+y}(z) = \frac{1}{\sqrt{2\pi * 0.043}} \exp\left(-\frac{(z - 3.065)^2}{2 * 0.043}\right)$$

We can make now more accurate predictions. For instance, the probability that it will take more than 3.5 units of time to complete both walls is given by:

$$\frac{1}{\sqrt{2\pi * 0.043}} \int_{3.5}^{\infty} \exp\left(-\frac{(z - 3.065)^2}{2 * 0.043}\right) dz \sim 0.018$$

In other words, the work will be completed in less than 3.5 units of time with a probability of 0.98 (that is, with almost certainty). For more complicated projects, the computations will be more elaborate, but will follow the same spirit. Recall that we define the value of the productivity function at a given compatibility score as the mean of the productivity distribution function for that compatibility score. Then we use this productivity function in the allocation model (Florez, 2015) to compute the average time in which the project should be completed. A similar reasoning to the one presented in this example will help predict time intervals for completion with an assigned probability, but this will be the subject of a forthcoming paper.

5 CONCLUSIONS

Crew formation is the process of determining the size and the composition of crews. In masonry construction, superintendents in the jobsite use a number of factors to determine the masons that will be part of a crew. Personality has been found to be a key parameter to form crews and has been identified that the interpersonal compatibility of a crew influences productivity.

To illustrate how the compatibility of a crew can be used to predict productivity, a mathematical framework has been proposed. The framework describes the methodology to measure the personality of the masons, determine the interpersonal compatibility score of a crew, and use the score to predict productivity.

The proposed productivity density function aims to help contractors estimate times of construction, avoid crew conflicts, and find practical ways to increase productivity. The function is based on the compatibility of a crew and uses personality factors and interpersonal characteristics to quantify productivity. These new considerations should prove useful to masonry contractors and enable them to better estimate times of construction, predict of productivity, and identify effective crew formations. Following this study, the idea is to quantify the compatibility of multiple masonry crews and measure their productivity. By doing so, a productivity function in terms of compatibility can be theoretically determined and be used by contractors to more precisely estimate times of construction and total project costs.

One of the limitations about this methodology is that for simplicity, we are assuming that productivity can be predicted by considering the personal compatibility between the workers in a crew. Other factors that influence productivity, internal and external to the operations, may also need to be considered for better estimating times of construction. Following this study, the idea is to formulate a probability distribution function that considers a more holistic set of factors, including those beyond personality.

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DIGITAL KANBAN BOARDS USED IN DESIGN AND 3D COORDINATION

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Abstract: The hypothesis of this research is that the Last Planner System® (LPS) in combination with the Kanban Method is better suited than conventional project production planning and controls to manage the design phase. In the Toyota Production System (TPS) the Kanban (sign board) is attached to the material or product and is pulled through the manufacturing process. In design and product development the Kanban is attached to the information or knowledge and is pulled through the design process. In the presented case studies, the authors developed several prototypes of a Kanban board. One is used in architectural design and in pre-construction processes to manage the 3D design and 3D coordination process and another is used to manage the design issues in an integrated and concurrent design process. The physical Kanban board displays each stakeholders' tasks across multiple swim lanes, so the team can readily assess the task assignment and work in process (WIP), of team members in one glance. The physical boards are kept up to date with digital Kanban Boards. These Kanban applications facilitated "real time" synchronization among stakeholders for monitoring of both current and future activities (look ahead) and delivering promised design decisions for information required by upstream customers. In two of the case studies the LPS was used as the initial planning tool to develop a phase pull plan to define milestones, develop a design cycle plan and establish a design phase constraint log. The combination of LPS metrics with Kanban board metrics resulted in eliminating schedule uncertainty and improved information flow including less latency of the delivery of design-builder's work. The Kanban method was also found to be more agile than purely the LPS for managing the circular iterations of design decisions. These benefits also resulted in acceptance by design professionals to use a Lean design management approach.

Keywords: Kanban, work in process (WIP), agile, burn-down-chart, communication systems, design management, design/build, integrated project delivery, IPD, concurrent design

1 INTRODUCTION

The LPS offers many valuable production planning and control principles and as applied to both design and construction, in practice LPS has become the de-facto management approach for highly technical and collaborative projects. However, stakeholders in the design phase have found it to have limitations.

The primary limitations of LPS is the iterative nature of design. This results in work stacking due to concurrent design activities. It creates a shift in priorities and a redirection of production resources.

Traditional design phases of schematic design SD, design development DD and construction documents CD evolved and became a standard of practice for measuring the completion of design deliverables. The sign-off process to meet design hand-offs is outdated and too narrowly defined sequence that is no longer applicable in a concurrent design approach. A hand-off occurs whenever we separate knowledge, responsibility, action and feedback (Ward A. 2007). The traditional handoff points are now defined as

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Level of Development (LOD). LOD defines model geometry with three of the most common uses of design deliverables in mind – quantity take-off, 3D coordination and 3D control and planning. We will use this nomenclature to describe the information flow in the case studies. [see <http://bimforum.org/lod/>]

Although, the Lean Product Development System the equivalent in product design uses “pull” to sort through a vast amount of data to get the right information to the right engineer at the right time (Morgan & Liker, 2006). Knowledge is the fundamental element (material) in product development and design. Current scheduling software, which do not effectively account for circular logic that naturally occurs during the design phase. Designers are not motivated to meet scheduled tasks until design solutions are optimized considering integrating overall system needs.

The LPS provides stakeholders visibility of the overall design phase plan that defines milestones, develops a design cycle plan and establishes a design phase constraint log. It creates a picture of the desired flow of information, knowledge and design decisions required to complete upstream activities (permits, materials orders and other items).

The Kanban method pulls the work through as the Kanban signal is generated. Like the LPS it also makes the work visual both workable backlog and WIP. Kanban is a flexible tool and allows adjustment of work on the fly. Progress can be measured as unplanned tasks can be added to the board. Reasons for variation are not as important as the visual effect of seeing new unplanned work or unresolved constraints on a design solution’s completeness.

The visibility of constrained items focuses the team on resolving issues sooner and encourages discussions about pivoting and/or finding the best solution – not the perfect solution.

2 BACKGROUND

Generally, in a manufacturing environment, units are transported to the next production stage, as soon as they are ready. Kanban, meaning signboard or label, is used as a communication tool in this system (Imai M., 1986) Ohno, reversed this, so that each stage was required to go back to the previous stage to pick up the exact number of units needed.

In the Toyota Production System (TPS), Taiichi Ohno (1978) defines six rules for a Kanban system:

1. Customer (Downstream) processes withdraw items in the precise amounts specified on the Kanban. Kanban serves as a withdrawal order, an order for conveyance or delivery.
2. Supplier (Upstream) produces items in the precise amounts and sequences specified by the Kanban. It serves as a work order.
3. No items are made or moved without a Kanban. It prohibits picking up or producing goods without a Kanban.
4. A Kanban must accompany each item, every time. It is required to be attached to the goods.
5. Defects and incorrect amounts are never sent to the next downstream process. 100 percent defect free products.
6. The number of Kanban is reduced carefully to lower inventories and to reveal problems. This way a Kanban prevents overproduction.

Kanban cards usually signal (control) production in a pull system. In product development and design, knowledge and information are the materials that are required by the downstream activity (Morgan & Liker, 2006). Tactile properties have been less

researched, though important industrial applications have been developed. The Kanban system uses physical placement of documents (cards or tags) to facilitate improved production flow (Rooke, Koskela & Tzortzopoulos, 2010).

A digital Kanban Board offers managers a variety of measures that assist in interpreting and managing the flow of a project team's activities. The metrics of Kanban are expressed in velocity, flow efficiency, and throughput, WIP flow through the board. A cumulative flow diagram (CFD) offers managers an understanding of activities that are flowing through the board. CFD is a visual representation of when an activity starts moving from backlog to WIP to review, to done or returned to the backlog of work for later activity, or advanced to an accelerated completion or finally to done. The project team agrees to limit WIP based on their capacity to complete the work. WIP is adjusted daily and or weekly to represent the estimated and actual man-hours required to complete activities. The measured "Cycle Time" to complete activities assists the project team understand both current demands and predict future completion or throughput trajectories. Because the board is visual the cumulative effects of flow of activities are visible to the project team and allows for rapid improvement and adjustment in the PDCA cycle. Adjustments are made to limit WIP as the project proceeds.

3 CASE STUDIES

The first case study is the design & engineering of support infrastructure of a semiconductor manufacturing production line for a manufacturing facility for a confidential client. The Lean Design management consulting company Sword [1] established and implemented a Kanban System to improve the information flow of the integrated project team both during the planning and design phase (LOD 100-200) and the production of spooling documents (LOD 300-400). The second case study is the architectural design phase of the San Francisco International airport Terminal 1 rebuild. It is a \$630M project with Woods Bagot [2] in a design joint venture (JV) with HKS Architects. The design JV uses a digital Kanban board to manage information flow and knowledge distribution on the project. The WB-HKS JV has been using Trello Kanban software since the end of the Design Development. Woods Bagot uses Kanban boards on all their projects of the San Francisco and New York office. The third case study is the same project as the design joint venture, it is the Terminal 1 Boarding Area B of the SFO airport. Webcor Builders [3] is in a joint venture with Austin Industries (AWJV) representing the General Contractor on the project. The project is a public project therefore using an IPD type contract is not possible yet but the contract is a design-built contract with a collaborative spirit. The airport has the intent to run the project as much collaborative as possible in the public environment with the full spirit of IPD. Subsequent an airplane hangar was built out to create a collaborative work space for the project teams of Terminal 1 Central and Boarding Area B. This space houses the two design teams, the two general contractor teams and all the core trades. The space is called "The BIG ROOM" and is located on the SFO airport property.

3.1 Methodology

This research can be classified as constructive research. This approach aims to generate scientific knowledge, developing an artefact to solve a real problem (Holmstrom et al.2009). Despite their different underlying philosophies and controlling mechanism, the authors put forward the proposition that there are benefits of integrating LPS and a Kanban method.

In all three case studies the initial framework for all the work was established based on BIM with a Model Progression Specification (MPS) Matrix. The MPS Matrix is the equivalent of a “Story-Board” as used in Agile Software development, a framework for the project. The matrix which overlays a project’s building systems in one axis over the time frame of the project on the other. The BIMForum LOD specifications definitions are used by the project team to establish the agreed level of completion of the different system modelling for “fixing” the elements and handing off to upstream customers. Optimally, the project team would engage pull planning sessions to define different information flow pathways. The outcome gives an understanding when the different BIM for building systems must be completed by the design team and at what LOD level it is necessary to dovetail with the production team’s responsibilities to support buy-out, permitting, pre-manufacturing, supply chain and construction flow.

3.2 Kanban Use in Design

The key to get the right process steps is to value stream map current practice. The individual steps defined by the process map are the activities represented by the Kanban cards that will be placed on the Kanban board. In early design activities, depending on the project type, these value streams are incomplete or very chaotic. Initial efforts undertaken by a project team often serve to define knowledge gaps and other missing information and decisions that will be needed later as the team moves from the problem definition stage of programming to the problem-solving stage of design.

The problem statement, then, is the interface between programming and design (Peña, Parshal, 2001). In the beginning, they are manually represented on a Kanban Board physically located near the project team’s workspace. Initially, they serve to define both known information as well as information gaps. Often when the project team maps the value stream, the team will attempt to recast the value stream to reflect the initial or contracted sequence presented in the Master Schedule. This tendency to recast the project to fit contractual arrangements must not be allowed the VSM must reflect a true picture of the actual process being used. (Anderson, 2010).

To map the value streams the teams use the pull planning methodology of the LPS. In ad hoc meetings where cross-functional team members value stream map the steps to solve a problem, post-it notes are used to agree and write down the process steps and the right flow of the information to solve a specific problem. The tactile part of discussing and writing, and posting it to the wall has psychological benefits. Putting the process steps into a digital system is not a wasted overproduction, it has various benefits. First, it instantly becomes visible to the entire project team, second it is in the system so the process is recorded and if a similar problem arises, the process steps can be re-used without the necessary re-mapping of the value stream. Third applying the standardization thinking opens the opportunity to improve on the process, e.g. necessary re-sequencing and better understanding what level of effort it takes to execute the steps.

As mentioned above the initial framework is set by agreeing on the deliverables and defining a MPS-Matrix in the BIM execution plan (BIMex). Teams – Architects, Engineers, specialty trades, General Contractor and Owners or their representatives are responsible for establishing target budgets and controlling costs and fulfilling design intent objectives and schedule. The clusters independently define design program and then present design solutions that through experience and performance results are most suited for the stated goals and objectives of the project.

The short term iterative processes of solving various problems in design are mapped and undertaken by the project team clusters in short cycles or “sprints”. The products of

a sprint are evaluated in relation to overall goals, objectives and target budgets. The tasks required by the team in these short-term intervals are listed on the Kanban. The Kanban board provides an actionable schedule of tasks required to make decisions and highlights critical interdependencies of decisions. The learning generated in a cycle is documented on an A-3 placemat. This is analogous to sprint-planning in Scrum in an agile software development.

A sprint allows the project team to rapidly assess the viability of partially developed alternative solutions, discover and visualize constraints and test assumptions. The sprint methodology gives the collaborative project team just enough information that can be used to indicate if they should proceed to develop a design solution further or pursue a different line of thinking. Should the team decide they would need to change course, the team then may send the issue back to be reworked. This is known as a “pivot”.

The velocity of decision making is displayed so that all can see the flow of decisions, information gaps and critical co-dependent relationships of information required for a design team to progress the project to meet schedule and budget milestones. The Kanban cards are very visible and their tactile nature offers the project team – including the Owner -- visual clues regarding deliverables and key decisions changes as the board physically appears different (Hiranabe, 2008). In the environmental, architectural, and product design fields, for example, there is a focus on specific user related knowledge such as graphical information, architectural clues and other forms of visual and tactile cues (Arthur & Passini 1992).

4 FINDINGS

4.1 Kanban System in Design

4.1.1 Kanban in Design & Engineering

The first case study is the design & engineering of support infrastructure of a chip manufacturing production line for manufacturing facility for a confidential client. A basic use case for the Kanban Method is in the early stages of Design. The owner required the project team to utilize a collaborative integrated approach for the design phase (LOD 100-200) of the project. The design engineer was also responsible for creating spooling drawings (LOD 300-400) for the infrastructure rack below the manufacturing level. See Figure 3 & 4 following.

As more of the engineers designers and technical personnel became involved in the project it became increasingly difficult for everyone to schedule and balance the design team work loads, status owner and trade signoffs and generally maintain the flow of both the design engineering and spooling throughput. The design engineer team at the direction of Sword established a digital Kanban Board. It was decided that the Kanban method would make transparent the tasks required to complete designs and visualizing of the activities would allow the project team to more effectively status both the information and the activities needed by a design team to complete team or design problems.

The project was first divided into multiple smaller batches based on the construction team’s plan; LPS established the needs of upstream players, Figure 2. This step confirmed master schedule milestones. The project’s intermediate milestones were adjusted and the major milestone durations were refined and optimized.

Handoffs to trades for fabrication had the highest priority and all critical dates included the Kanban cards. This made visible both, the information and work products needed to get “fixity” and deliver the designers work products to purchasing and delivery by the

trades. The Kanban was also used by the designers to level the work load among in-house producers, inform them of the work backlog and the WIP, allowing the design team to prioritize and manage the deliverables on a daily and weekly basis.

1. The Designer found that they could rapidly rebalance production engineering and drafting/modelling manpower as the client’s scope changed, enabling them to pivot between design and spooling tasks more efficiently.
2. Both the project’s designers and trade partners reported that “problems” with spooling documents didn’t make it to the field.

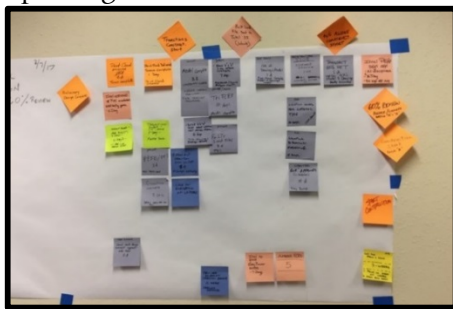


Figure 1: Pull Plan - (LOD 300-400)

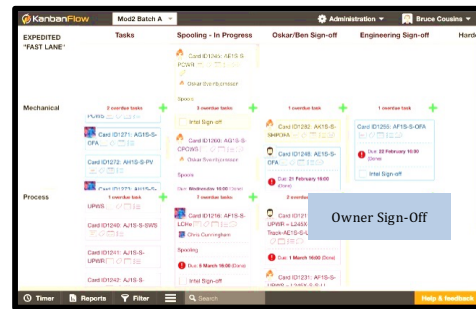


Figure 2: Kanban board – (LOD 300-400)

4.1.2 Kanban in Architectural Design

Case study two shows the use of a Kanban system in the architectural design phase. The architects are using a digital Kanban board to manage information flow and knowledge distribution on the project. Initially there was a slow adoption of the Kanban method because of the reluctance to introduce a management system, but quickly the team realized that they could easier visualize and communicate their design tasks between the two firms and their consultants. The team found it beneficial using the introduced LPS customs of writing the task requester, performer and clearly defined actionable description on the cards. Daily stand-up meetings in the design clusters and weekly meetings with all team members reviewing the board items ensured the alignment of short and long term goals of the project.

The digital board created a project wide transparency and better overall communication between owner, construction manager and the designers. Woods Bagot has standardized their Kanban board to address three types of Kanban, these are information, knowledge and decisions. The milestones in the board visualize the progress toward them and have been built according to the project Model-Progression-Specification (MPS) Matrix. The MPS is showing their design deliverables developed around the framework of LOD. In this case study the team is using Trello to manage their Kanban see Figure 3.

4.2 Kanban System in 3D Coordination

The third case study is also taken from the SFO airport Terminal 1 project. This case study focuses on another use case for the Kanban Method in design and preconstruction phases of the project. In 3D Coordination LPS thinking is used to develop the basic location based schedule. The location break down structure (LBS) of the construction is followed in 3D coordination. Pull Planning Sessions develop the coordination plan working from construction back to the point when, which system and area must be modelled to a LOD 350 so 3D coordination with clash detection and clash avoidance on composite 3D models of all systems is ready.

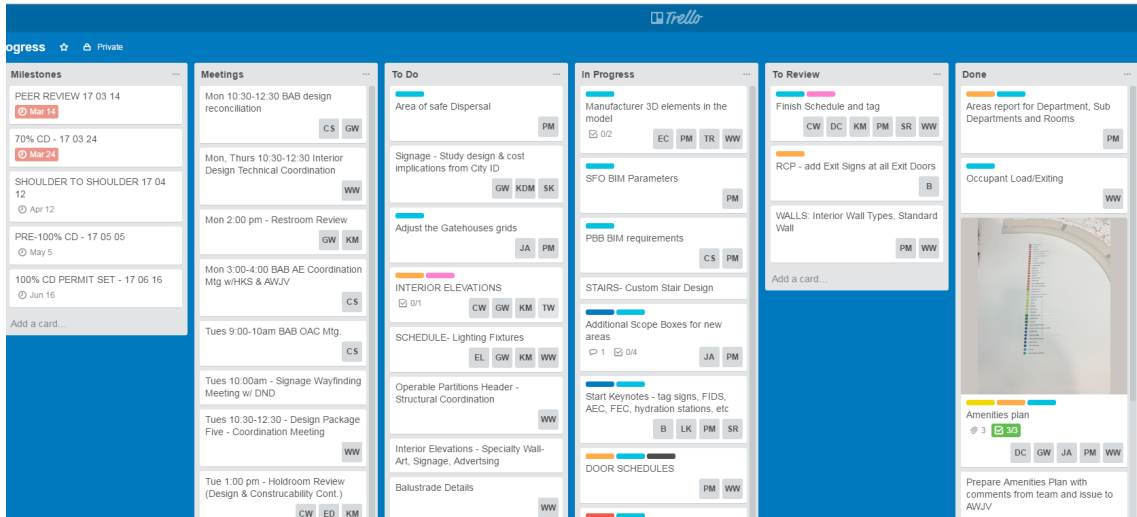


Figure 3: Design Kanban board

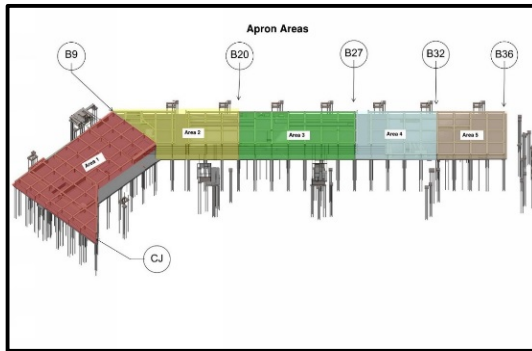


Figure 4: Location Break Down BIM

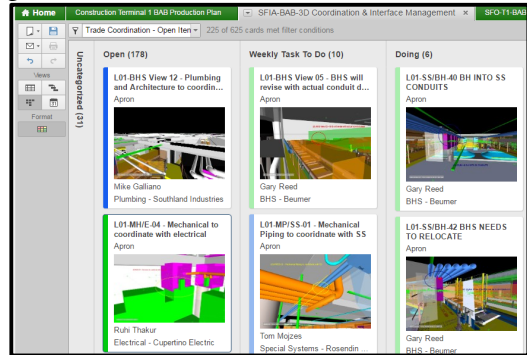


Figure 5: 3D Coordination Kanban Board

The Kanban has an assigned trade with a designated building system colour, a performer and the actionable task description, see Figure 5. That column becomes the committed plan like the weekly work plan in LPS. The actual point in time before somebody executes the committed Kanban he/she moves the card into the doing column and after he/she is done into the "Done" column. The Kanban Board helps the team understand how they are doing as well as what to do next. (Hiranabe, 2007). This in combination with the cloud based access of Autodesk BIM 360 Glue to the combined 3D models of all project participants, underlines the collaborative and self-directing aspects of the two technologies and creates synergies which results in faster problem solving cycles.

5 CONCLUSIONS

By using a Kanban in design or 3D coordination the Kanban is attached to the information, knowledge or decision and is moved up or downstream through the design process. The tool displays each designer's tasks across multiple horizontal columns or rows (swim lanes). Therefore, users can assess the task assignment and workloads, WIP, of team members in one glance. The board also links up with digital Kanban Boards -- Trello, Lean Kit, KanbanFlow, SmartSheet and JIRA. These offer the feature of real time synchronization among clients for distributed development. The digital Kanban boards have the benefit to attach data to the Kanban and after the project the knowledge is not lost like in a conventional design process. The data can be archived and later easily accessed on the cloud. The use cases showed that the proposed approach was effective. Furthermore, in

both case studies the LPS was used as an initial planning tool to develop a master design plan as well as a look ahead plan. The combination of LPS metrics with the typical Kanban board metrics resulted in synergies and information flow improvements and less latency of the design/builders work products in the validation and design development phase of the projects. The hypothesis, that a Kanban Method when combined with a LPS is well suited to management of the Design Process, has been proven true.

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REAL-TIME TRACKING OF PRODUCTION CONTROL: REQUIREMENTS AND SOLUTIONS

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Abstract: Production control in construction has been mainly discussed within the scope of Lean Construction, through tools and methods such as Last Planner System (LPS), Location-Based Management System (LBMS), and Takt Time Planning (TTP). However, despite the increasing use of these systems, information about the use of equipment, labour, and materials is still gathered through manual data collection, if at all. Real-time process information about these production factors is missing.

This paper proposes an intelligent system for real-time production control (iCONS), which has been developed based on the requirements set by construction professionals from four countries, the existing technical solutions that have been used in real-time tracking, and on the proposed new solutions that can fulfill the requirements. Four types of requirements were identified based on interviews: 1) safety management, 2) monitoring process information, productivity and waste, 3) material logistics, and 4) location-based information on pull basis. The proposed system fills the key requirements by sharing and integrating real-time information between materials tracked with RFID tags, labour and equipment tracked by Bluetooth beacons, communicating with location-based gateways and iCONS app through a cloud-based solution. Project teams can use this system to improve production efficiency, management of suppliers, and safety conditions.

Keywords: Lean construction, production control, tracking, resources, communication systems.

1 INTRODUCTION

Production control in construction has been mainly discussed within the scope of Lean Construction. Among others, its tools and methods include: 1) the Last Planner System (LPS, Ballard 2000) which focuses on the social process of planning and reliable commitments; 2) the Location-Based Management System (LBMS, Kenley and Seppänen 2010), which includes a technical system and a process for better planning and control using locations and; 3) Takt Time Planning (TTP, e.g., Frandson et al. 2013) which is a related planning and controlling approach using fixed durations for each location. Various combined approaches have also been proposed. For example, the combination of LPS and LBMS was proposed by Seppänen et al. (2010). Although good results of LBMS have been reported in literature (e.g., Seppänen et al. 2014), contractors are complaining about the difficulty of manual data collection (e.g., Cruz Rios et al. 2015). Furthermore, all of the production control approaches rely heavily on social processes and manual data collection (Pradhananga and Teizer 2013). For example, the LPS is typically implemented with

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manual techniques, such as using post-it notes to plan collaboratively in a phase scheduling meeting (e.g., Tsao and Hammons 2014). Recent approaches include mobile applications, which distribute the plan to the workers and allow them to use mobile devices to report progress (Dave et al. 2014). LBMS has been implemented in software (currently Vico Schedule Planner) but progress tracking remains manual using control charts (Kenley and Seppänen 2010). TTP is a different scheduling methodology but in software terms has been typically implemented with Vico Schedule Planner as well (Frandsen et al. 2013). Each approach relies on manual collection of information through discussions or spreadsheets, requiring substantial amounts of human labour to collect and analyse data, which eventually was prone to human error (Costin et al. 2012), besides it is an expensive, inaccurate and inefficient process (Jiang et al. 2012).

Construction sites are usually characterized by a complex set of interactions between space, equipment, labour, materials, and final product (Golovina et al. 2016). Moving resources efficiently on site, and between projects, requires good coordination of activities and specialized information systems (Vasenev et al. 2014), resulting in an accurate process information. With the current manual approaches, it can be said that the full potential of production control have not been achieved.

Technology has been developed to the point where it is possible to configure a system for a truly intelligent construction site, where all resources can be tagged and located in real-time (e.g., Cheng and Teizer 2013; Jiang et al. 2015). Mobile technology enables real-time communication with workers (e.g., Dave et al. 2014) and building information modelling (BIM) provides context for decision-making. However, although improving construction productivity through integration and automation, it is essential to identify the processes where technologies may be implemented in a cost effective manner (Grau et al. 2009). Despite the increasing use of BIM and production planning technologies, real-time information about the production factors, equipment, labour, and materials, is still gathered through manual practices, if at all.

The aim of this paper is to propose an intelligent construction site system for real-time production control, named iCONS. The system will be part of an international research project managed by Aalto University and supported by construction companies, software companies, operators, and international universities from four countries: Finland, USA, Brazil and China. iCONS will be developed based on the main requirements of the companies, the existing technical solutions that have been used in real-time tracking, and new developed solutions that can address any gaps. In this paper, a literature review was carried out to identify existing tracking solutions and the use of real-time data in construction management. After that, an interview study among building practitioners was conducted to evaluate the main requirements of real-time production control. Finally, a lean real-time production control system is proposed.

2 BACKGROUND

A lean production control system must consider resource flows, continuity of work for resources, reducing cycle time, forecasting based on actual progress and eliminating waste. In relation to resources, Koskela (1999) defined seven types of flows (or preconditions) for a construction task: 1) design information, 2) components and materials, 3) labour, 4) equipment, 5) space, 6) connecting works, and 7) external conditions. If there is a problem with any of these flows, making-do waste will result (Koskela 2004). iCONS and real-time production control could help particularly with materials, labour, equipment and space

flows. Real-time information about the status of these flows could enable better production management and less waste in the process.

Tracking material resources and their respective locations, implies two sets of requirements: 1) determining the location when materials are delivered to a construction site and; 2) once delivered, tracking the location of materials with enough accuracy (Song et al. 2006). Different manufacturing environments may define product delivery strategies, such as Make-to-stock (MTS), Assemble-to-order (ATO), Make-to-order (MTO) and Engineer-to-order (ETO) (Olhager 2003). Each one of these requires a different real-time tracking mechanism. For example, ETO products have elaborate supply chains and a long process from design to installation. It is a challenging task to efficiently identify, track and locate these components through a construction supply chain as the process is usually monitored manually by using paper-based methods. Manual material tracking methods result in problems such as late deliveries, missing components and inefficient assembly, reflecting in additional labour and material costs (Demiralp et al. 2012). In this paper, we are focusing on materials and components including both off-site and on-site logistics. Although the main use case will be tracking ETO products, the system should be able to handle also other types of important materials.

Tracking of labour is an important issue to keep production flowing. In addition, the quantity of labour hours spent completing tasks represent a large portion of costs in a project (Costin et al. 2012). Thus, maximizing labour productivity is an important factor affecting both costs and production. However, labour consumption tracking has been a challenging problem, involving multiple human behavioural and qualitative factors (Jiang et al. 2015). Trying to solve this problem, real-time tracking may be used on identifying critical personnel and activities instantly, increasing the flow of project information and control actions (Cordova and Brilakis 2008). This information could be used to drive LBMS technical calculations (Kenley and Seppänen 2010), highlighting problems in real-time rather than based on weekly manual input. In addition, real-time tracking could help on identifying typical construction wastes, such as unnecessary movements, poor logistics conditions, and making-do (Koskela 2004).

It is widely known that construction jobsites are hazardous environments due to the continuous and dynamic interactions between various entities, such as heavy equipment and workers on foot (Wang and Razavi 2015; Golovina et al. 2016). On a worksite, it is important that construction workers and equipment operators can recognize each other in real-time (Golovina et al. 2016). Considering the high number of contact accidents and the severity of the consequences, potential collisions should be prevented in a timely manner (Wang and Razavi 2015). Despite the development of recent solutions, such as sending alarms based on the proximity of workers and equipment (Wang and Razavi 2015; Park et al. 2016), or the integrated use of BIM to pro-actively improve construction safety, there is a lack of studies on remote monitoring for improving safety and health of the construction workforce (Cheng et al. 2013).

Despite improvements in remote data sensing and intelligent data processing systems, few data on visualization tools are used in a virtual reality environment in real-time (Cheng and Teizer 2013). For example, Dave et al. (2014) proposed a solution integrating video-cameras and magnetic boards on monitoring tasks progress. However, this solution requires manual insertion of data on the boards. Thus, there is a clear disconnection among real-time information, resource flows and locations, representing an opportunity for developing a lean real-time production control system.

3 METHOD

First, a literature review was conducted, aiming to investigate the existing solutions of real-time production control. After that, face-to-face interviews with building professionals were done, aiming to investigate: 1) the main challenges of real-time production control; 2) the expected benefits on implementing an intelligent system, using real-data; 3) the most demanding and interesting use cases and; 4) the possible integration of Building Information Modelling (BIM) and an intelligent production control system. A standard list of ten questions was prepared and seven interviews (one with each end-user partner) were done in three countries (Brazil, China and USA). Additionally, a focus group interview with all Finnish partners was conducted in Finland. Based on the findings of the interviews and focus group, four most relevant requirement themes were found. Then, an intelligent system was proposed, considering requirements, existing solutions, and solutions to be developed and tested in future research.

4 FINDINGS

4.1 Interviews

The interviewed companies highlighted the following themes as the most relevant requirements of real-time production control:

- **Safety management:** highlighting work in hazardous areas and risks related to interactions between equipment and labour; safety aspect is also critical to provide value for workers so that they can accept to be tracked.
- **Process information, productivity and waste:** tracking movements of the workers on construction site, and controlling how much time workers spend in one location, analysing productivity rates and waste of time, analysing what has been completed in each location, linking images automatically to locations.
- **Material logistics:** controlling the logistics of off-site and on-site materials.
- **Location-based information on pull basis:** giving information to superintendents and foremen in real-time based on the location they are in.

4.2 Proposed real-time production control system

To address the requirements, an intelligent construction site (iCONS) scheme is proposed, as shown in Figure 1. The central idea of this system is real-time tracking of production factors, where an app will integrate several technological tracking solutions and provides real-time information for decision-makers. The app, installed on smartphones devices of the project team, will receive real-time information of materials, through reading RFID tags or via wireless (Link 1). The position of mobile resources, such as workers and equipment, will be determined through the interaction between beacons and gateways, which are installed in distinct locations (Link 2). The app determines the location of the foreman / superintendent by accessing the same gateways (Link 3). A data storage cloud system will receive online information from the gateways (Link 4), automatically updating data on the app (Link 5). The app is used to update production status based on location-based suggestions and to link pictures and notes to the location (Links 3 and 5). When the plan is known and workers who have spent time in the location are known, it is possible to ask targeted questions about what scope was completed and to document the completed

work in a picture linked to the location. Table 1 shows a sample of existing solutions found and proposed links and solutions, aiming to cover the requirements.

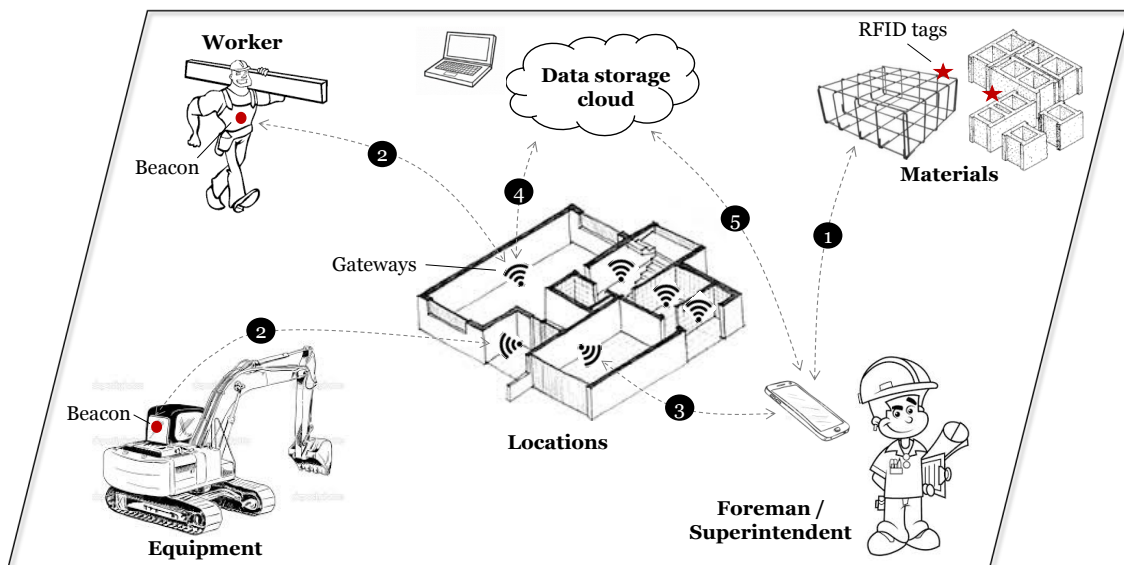


Figure 1: iCONS system

Key: Link 1) Interaction between RFID tag materials and iCONS app; Link 2) Interaction between beacons sensors and gateways; Link 3) Interaction between iCONS app and gateways; Link 4) Interaction between gateways and data storage cloud; Link 5) Interaction between iCONS app and data storage cloud.

5 DISCUSSION

The great novelty of the iCONS system is not related to the proposed individual links because each has been previously explored individually, but the interactions among them in a common platform, connected through a data storage cloud and an app, providing real-time information to the project team (summarized in Table 1).

Existing solutions in safety control have been providing enough information of behaviour of workers (Cheng et al. 2013), hazardous areas, and the interaction between workers and equipment (Golovina et al. 2016). However, locations, equipment and workers have not been integrated. The integrated use of beacons and gateways, which are installed in strategic locations, combined with previous BIM simulations and analysis, may facilitate the identification of hazardous areas, sending alarms where and when necessary. Furthermore, risks can be mitigated through the combination of BIM simulations and real-time resources tracking.

Currently, the actuals work in place (scope), production rates and quantities are not automatically gathered. However, technologies such as photogrammetry and laser scanning can be considered to fulfil this gap, generating real-time information for Last Planners to make comparisons with the plan.

Traditionally, labour on construction sites has been tracked with good accuracy (Montaser and Moselhi 2014). However, it has been very difficult to know what the workers have been working on and in which locations they have spent time (Jiang et al. 2015). Process information has not been commonly connected with real-time status; in addition, productivity is still measured through manual practices (Pradhananga and Teizer

2013). With the implementation of iCONS, real-time control may be provided through the integration of location, workers and the app, via data storage cloud, where the project team would receive online information about labour productivity and to compare the status of each location to the project schedule or weekly commitments. iCONS will also provide opportunities for analysing wasted time in real-time, alarming the management of problems and making waste visible to the team. The goal is to make information cycle more agile, improving the efficiency of the crews and fixing errors faster than when using manual controls. Furthermore, this process will help to automate production control, once it is possible to get real-time status information with a high level of accuracy.

Table 1: Requirements, existing and proposed solutions

Requirements	Samples of existing solutions	Proposed links and solutions
Safety management	Monitoring safe and unsafe behaviour (Cheng et al. 2013); Proximity detection and alert system using beacons (Park et al. 2016); GPS on identifying and analysing hazardous areas (Golovina et al. 2016);	Link 2. Beacons positioned in equipment and workers will interact with gateways, detecting and alarming potential risks in hazardous areas, which will be previously identified through BIM model;
Process information, productivity and waste	Tracking labour through video cameras (Cordova and Brilakis 2008) or websites, computers, tablets and smartphones (Jiang et al. 2015); Triangulation and proximity to identify the location of the workers (Montaser and Moselhi 2014);	Links 3, 4 and 5. Real-time information will be provided through the interaction between data storage cloud and app. The project team will be able to analyse productivity of subcontractors, comparing the status with the schedule and identifying the wasting time;
Material logistics	RFID systems (Demiralp et al. 2012); RFID integrated with mobile devices and web portals (Wang 2008);	Link 1. RFID tags will provide accurate information of materials manufacturing status, quantities needed and delivered, and location;
Location-based information on pull basis	Real-time positioning sensors (Cheng and Teizer 2013); UWB system (Cheng et al. 2011);	Links 2, 3 and 4. Locations identified through gateways. Location information such as time spent, the planned schedule, required quantities, quality checks etc., will be provided in real-time

RFIDs tags have been applied for tracking materials (Demiralp et al. 2012). Through the integration of materials status with locations, internal and external logistics process may be facilitated, and delivery locations can be prioritized in accordance with the project schedule. The supply chain process can be automatically updated. Thus, manufacturing, delivery and internal storage will be integrated with the needs of every location.

Real-time position sensors (Cheng and Teizer 2013) and recent systems (Cheng et al. 2011) have been applied for indicating the location of resources relatively accurately. However, this real-time information is not integrated with labour productivity in locations. Thus, real-time and accurate information could improve production control, helping on rescheduling process, defining control actions and prioritising activities.

Real-time information would support production control, and help reducing waste, particularly that related to flows of material, labor, equipment and space. For example, the real-time tracking of locations and production rates will improve the analysis of overproduction. The tracking of labor and movement will improve the analysis of waiting time.

6 CONCLUSIONS

The iCONS system proposes the integration of several technological solutions to form a lean production control system supporting LPS, LBMS or takt-time planning, providing real-time information to the project teams and potentially improving the production control process. The proposed system fills the key requirements gathered in interviews of building professionals in four countries. Project teams can use this system to improve production efficiency, management of suppliers, and safety conditions. The iCONS system is under development and its benefits will be validated in future research.

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INTRODUCING NEW CAPACITY PLANNING METRICS IN PRODUCTION PLANNING

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Abstract: The need for proper and reliable planning is essential for project success. Capacity planning has received good attention in the construction community but few metrics exist to assess its performance. Since it is impossible to improve what cannot be measured, the goal of this paper is to introduce new capacity planning metrics that will help visualize and understand the current state of capacity planning on construction projects. Is there an overloading or under loading of resources? The new metrics developed in this research, will attempt to help in assessing the state of equilibrium in choosing the weekly load of tasks to match the existing capacity, or at least, to minimize the gap between the two as much as possible. These new metrics, in theory, will achieve the goal of informing planners and last planners about the status of load vs. capacity, the matching between the two, and the reliability of capacity planning on a project.

Keywords: Last Planner SystemTM, lean construction, planning and scheduling, capacity planning, capacity planning metrics, matching load to capacity.

1 INTRODUCTION

Planning is an essential step in managing production flow on a project. If the proper time and resources are adequately allocated to planning efforts, the probability of success of the project will increase. Furthermore, much of the risk, that may not have been perceived prior to planning, can be greatly reduced (Aziz and Hafez, 2013). The investment in defining and developing the scope of the project, the requirements, and technical specifications have a positive impact on the success of a project (Dvir, Raz and Shenhar, 2003). But although planning is very crucial at early project stages, ongoing planning during production which includes capacity planning is instrumental in shaping production; and thus worth studying.

A lot of research has gone into understanding the planning and the scheduling of tasks from a chronological point of view, but there is also the planning of how to assign the activities and tasks (the load) to the available labour, equipment, and resources (the available capacity). This is known as capacity planning. With this new face of planning comes another dimension to the problem of planning and scheduling, which is the issue of matching load to capacity. How many of the activities should we allocate to the labour? How much work can the labour force accommodate at a time? Is there an optimum ratio between load and capacity? It is important to study the balance problem between load and capacity. Allocating adequate time and resources to planning is only one solution to the problem, but it cannot contribute to the success of the project if there is a mismatching

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problem between capacity and load. Therefore, it is important to understand the relationship between capacity and load and to have the adequate metrics to assess the status of resource allocation in an attempt to figure out how to strike a proper balance between the two.

2 LITERATURE REVIEW

2.1 Project Planning

The level of planning and effort exerted on a construction project highly affects the extent of the success of the project (Abbas, Ud Din and Farooqui, 2016). The upper third of projects, when it comes to completeness of planning, had an 82% chance of meeting their budget goals (Hamilton and Gibson, 1996). This leads to the question of how much planning is enough planning?

Research suggests that not enough time is allocated to properly plan for the average project. Furthermore, the effort put into the planning phase was found to have the strongest relationship with the overall project success. When the level of effort during the planning phase is reduced, final value to customers, stakeholders, and the company is also reduced. On the other hand, projects with planning phases that are too long had low success ratings, similar to the projects with short planning durations low and planning efforts (Serrador and Turner, 2015).

2.2 Task Planning

Different stages of the project require different levels of planning effort and control. Planning is performed from a long-term perspective first, and from a short-term perspective later on. The long-term planning phase is where the major project milestones are set, after which the milestones are broken down into phases. Later, short-term planning starts, where 6-week look-ahead plans are set, that are then broken down to weekly work plans. Therefore, planning is performed in greater detail the closer we get to start the activity (Hamzeh and Langerud, 2011). Similarly, a task that is planned in this way will have fulfilled the objectives and requirements it sought out to fulfil when it is executed and completed.

Planning involves several aspects including cost, scheduling, quality, and making sure that the prerequisites of the task are well-defined and available (Hamzeh, Zankoul and Rouhana, 2015). Additionally, an important step in task planning is the analysis of the potential problems that might arise (a what-if analysis) (Junnonen and Seppanen, 2004). After all, the emergence of problems is largely due to the existence of unforeseen circumstances and the presence of variability.

Furthermore, due to the dynamic and uncertain nature of construction projects, there are always "new" tasks that emerge during the week which they are to be executed. These are the tasks that are "not included in the weekly schedule or are included in it but are allocated within the wrong time frame." (Rouhana and Hamzeh, 2016). Thus, these "new tasks", are activities that were not part of the initial plan and task breakdown but have now appeared as activities that need to be executed for the completion of the project.

2.3 Variability

Variability is a fact of life that. It is ubiquitous, and the field of construction is no exception. Ben-Haim and Laufer distinguish between two types of uncertainty. It can either be structured, which is the usual year to year variation of the weather, or unstructured which

is “a substantial information-gap between what we do know and what we need to know to perform optimally” (Ben-Haim and Laufer, 1998). Furthermore, variability negatively affects the many aspects of project performance and “leads to ineffective production, increased cycle times, increased cost, and derailed plans” (Gupta, Gonzalez and Miller, 2012).

When it comes to construction projects, variability can be detected in factors such as the production rate, the productivity of labour, and the schedules of construction (Gonzalez, Alacron and Molenaar, 2009). Uncertainty and/or variability have been acknowledged as reasons for poor construction project performance (Ballard and Howell, 1998). Moreover, the Parade Game was created to illustrate how variability impacts performance and production. It can be concluded that variability and unreliable work flow cause a decrease in throughput, a delayed completion date for the project, and an increase in waste (where some production phases do not use their full output capacity because “they starve for resources”) (Tommelein, Riley and Howell, 1998).

2.4 Matching Load to Capacity

So far, the dynamics of variability, in the field of construction, have not been completely understood. Therefore, planners often fall into the problem of matching load to capacity which is not an easy task to achieve. Ballard defines load as the quantity of work needed to be done in a specific time allotted by planners, and capacity is the quantity of work a crew can complete given their tools, methods of work, and conditions on-site (Ballard 2000). When load and capacity estimates are different from the actual measurements, the planning crew must either alter load to match capacity by postponing or fast-tracking work flow, alter capacity to meet load by changing the quantity of resources, or an amalgamation of both (Gonzalez et al., 2010).

Production planning endeavours to match load to capacity with top accuracy based on given circumstances (Ballard et al., 2007). Thus, production planners require information regarding workloads and resource capacity (Kim and Kim, 2012). Kim et al. (2008) came up with a workforce information (level of skill, history of accidents, etc.) database to help solve the problem of matching load to capacity. “The workforce database system allows the user to consider workforce capacity in production planning” (Kim et al. 2008).

Despite the plethora of research on the importance of matching load (tasks put on the weekly work plan) to capacity (available resources), no clear metrics were derived to assess capacity planning in conjunction with the Last Planner System (LPS). This study proposes six metrics to assess the performance of capacity planning to guides last planner in managing and controlling production and workflow.

3 METHODOLOGY

Planners cannot manage what they cannot measure. Furthermore, measurement cannot happen without having proper metrics. In some instances, construction companies are overloading their resources and sometimes the resources are not being efficiently employed. Thus, the need for metrics, to help us better visualize how we are loading our resources, arises. Furthermore, we realize that there are not enough metrics in the field of planning that aid in adequately describing the state of capacity planning on a certain project. Accordingly, in an effort to better understand and attempt to find a proper solution to the problem of matching load to capacity, we devised six metrics that will serve as being somewhat descriptive of the state of planning on a project in general, and capacity planning in particular.

Before coming up with the metrics discussed in this paper, this study distinguishes between three types of activity clusters as shown in figure 1. Within each cluster, there are two colours, red and green. The green pebbles represent normal activities while the red pebbles represent required activities (i.e. critical activities).

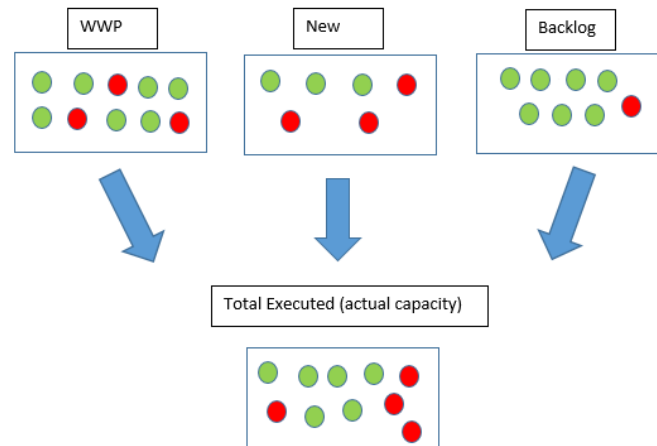


Figure 1 - Activity Clusters

The first cluster, as depicted in Figure 1, is the WWP cluster, where WWP stands for Weekly Work Plan. This group of activities consists of all the tasks that have been committed to be completed that week. The second cluster of activities is called New which are tasks that need to be executed during the week as pre-requisites or co-requisites to other tasks. Notice also that some tasks are required, in other words critical, (red) while others are not (green). The third cluster, Backlog, is representative of the activities that make up the backlog. These are the activities that are assigned when the team has completed the activities that they have committed to complete and they have extra resources to work more.

Furthermore, Figure 1 shows a fourth cluster of activities, Total Executed, which is the actual activities that have been executed that week (i.e. the actual capacity). The three clusters mentioned above contribute to the Total Executed cluster of activities. The tasks that have been executed in that week constitute the actual capacity and the tasks that have been chosen to be on the weekly work plan are the chosen load.

4 RESULTS AND DISCUSSION

4.1 Results

Six new metrics were created as described below. Note that these metrics are to be used for measurement on a weekly basis when applying the LPS.

The first metric is called the Capacity to Load Ratio (CLR). This metric is a comparison of the chosen load with the actual capacity. It is calculated by dividing the total number of activities executed this week by the number of activities on the weekly work plan (WWP), i.e. the activities the team has committed to completing this week. It is a retrospective metric which aids in tracking how close the team is in adequately employing resources. The CLR is calculated using equation (1) below.

$$CLR = \frac{\textit{Total Executed}}{\textit{WWP}} \quad (1)$$

The second metric is the CLR man-hrs. It is the same as the CLR described above with one difference; the CLR calculated in equation (1) is at the level of activities while the CLR man-hrs is at the level of the man-hours required to complete the activities. It is calculated by dividing the quantity of man-hours it took to complete the activities that have been executed this week by the quantity of man-hours required to complete the activities committed on the WWP. The CLR man-hrs is calculated using equation (2) below.

$$CLR\ man - hrs = \frac{Actual\ man - hours}{WWP\ man - hours\ Worked} \quad (2)$$

The third metric is called the Required Capacity Ratio (RCR) which represents the fraction of completed activities that are required (i.e. activities that are critical). It is calculated by dividing the required activities that were completed by the total number of activities that were executed, as shown in equation (3) below.

$$RCR = \frac{Required\ Executed}{Total\ Executed} \quad (3)$$

The fourth metric is called the Required Percent Complete (RPC) which represents the percentage of required tasks that have been completed. It is calculated by dividing executed required activities by the total critical activities this week, as shown in equation (4) below.

$$RPC = \frac{Required\ Executed}{Total\ Required} \quad (4)$$

The fifth and sixth metric are complementary and related. They are both used to assess the deviation from the WWP. The Weekly Deviation (WD) gives us an indication of how far the team has deviated from the WWP, and the direction of the deviation (i.e. if $WD < 0$ then the team is under loading their resources, if $WD > 0$ then then the team is overloading their resources, and if $WD = 0$ then then the team has matched the load to capacity). The Weekly Deviation Ratio (WDR) is the WD normalized by the WWP for comparison purposes. The WD and the WDR are each calculated by using equations (5) and (6) respectively.

$$WD = WWP - Total\ Executed \quad (5)$$

$$WDR = \frac{WWP - Total\ Executed}{WWP} \quad (6)$$

Table 1 summarizes all the metrics with their respective equations and descriptions, and Table 2 lists the variables required to calculate these metrics.

4.2 Examples and Discussion

To describe the use of the metrics suggested in this study, sample calculations were developed. The following examples serve to help the reader understand the application and the importance of the newly introduced metrics. The data summarized in Table 3 is used as input for the metric calculations that follow. The data is assumed to capture the capacity planning data comparing commitment planning to actual data at the end of the week. Note that activities with an asterisk sign (*) are required activities.

Table 1 - New Capacity Planning Metrics

Metric	Formula	Description
Capacity to Load Ratio	$\frac{Total\ Executed}{WWP}$	Number of executed activities vs. number of committed activities.
Capacity to Load Ratio man-hrs	$\frac{Actual\ man - hours}{WWP\ man - hours\ Worked}$	How many man hours have actually been expended vs. the hours required to complete the WWP.
Required Capacity Ratio	$\frac{Required\ Executed}{Total\ Executed}$	From the total executed tasks for that week, how many required.
Required Percent Complete	$\frac{Required\ Executed}{Total\ Required}$	Out of all required tasks for this week, how many have been executed.
Weekly Deviation	$WWP - Total\ Executed$	How far from the WWP we have deviated and in what direction.
Weekly Deviation Ratio	$\frac{WWP - Total\ Executed}{WWP}$	Normalized WD for comparison.

Table 2 - Variables included in the calculation of metrics

Variables	Description
WWP	Weekly Work Plan, i.e. the activities on the weekly work plan that have been committed to be completed for that week.
WWP man-hours	The quantity of man-hours required to complete all the activities on the weekly work plan for that week.
Actual man-hours Worked	The quantity of man-hours that was actually expended that week to execute the activities that were actually completed.
Required Executed	The critical activities that were executed that week (i.e. all red circles in Total Executed Cluster).
Total Executed	The activities that were actually executed that week (i.e. all circles in Total Executed cluster).
Total Required	The critical activities that are on the WWP, the backlog, and the new required activities for that week (i.e. all red circles in the 3 clusters).

Table 3 - Sample Data for a Week ((* stands for required activities)

Activities	A*	B	C*	D	E*
Man - hrs/activity	100	200	250	150	300
% Comp. (actual)	100%	19%	7%	100%	3%
% Comp. (WWP)	100%	100%	100%	0%	0%

4.2.1 CLR and CLR man - hrs

$$CLR \text{ man - hrs} = \frac{(1 * 100) + (0.19 * 200) + \dots + (0.03 * 300)}{100 + 200 + 250} = 0.57$$

$$CLR = 2/3 = 0.67$$

Considering CLR alone, which yielded a value of 67%, it can be said that the team was somewhat close to matching the load to available capacity. But looking at both CLR and CLR man-hrs, the latter yielding a value smaller than the former, shows that analysing activities is not enough. Measuring CLR in terms of man-hrs can show a different angle to that of CLR. Thus, both metrics are required to properly assess resource/task allocation.

4.2.2 RCR and RPC

$$RCR = 1/2 = 0.50, \quad RPC = 1/3 = 0.33$$

RCR yields a value of 0.5, which means that 50% of all executed tasks this week are required. Alternatively, RPC yields a value of 0.33 which means that 33% of required tasks have been completed. If we look at RPC alone, it raises the question of why has only a percentage of the required tasks been executed. Has the team wrongly allocated capacity or have the constraints for these tasks not been removed? Here, we can look at RCR. Since RCR yielded a value different than one, this means that part of the allocation of resources went to completing tasks that were not required. Thus, from these two metrics, last planners can assess if they are adequately allocating their resources to made ready tasks.

4.2.3 WD and WDR

$$WD = 3 - 2 = 1, \quad WDR = (3 - 2)/3 = 0.33$$

In this sample calculation, WD yielded a positive value, which indicates that the team has over committed, thus overloading the available resources ($WD > 0$, which means that $WWP > \text{Total Executed}$). Furthermore, notice that WDR is less than 1. This metric can be used for comparison across weeks and across projects.

5 CONCLUSION

The need for proper and reliable planning is essential for project success. Capacity planning has received good attention in the construction community but few metrics exist to assess its performance. The new metrics introduced in this paper will help in informing planners and last planners about the status of load vs. capacity, the matching between the two, and the reliability of capacity planning on a project.

Six metrics related to capacity planning, to be calculated on a weekly basis, were introduced in this study. The CLR (capacity to load ratio) measures the capacity available (tasks actually completed) versus the chosen load (tasks committed to be completed that week); the CLR man-hrs is the same as the previous metric except that it measures man-hours (i.e. man-hours actually expended vs. man-hours required to complete the committed tasks). The third metric is RCR which gives the planners an indication of how many tasks were required out of all those executed this week, and the fourth metric is RPC which depicts the percentage of required tasks completed this week. The last two metrics are WD which is deviation from the WWP, and WDR which is the normalized version of the WD (for comparison across multiple weeks and/or across different projects).

Further research on this topic and the testing of these metrics to prove their reliability in attempting to visualize the problem of capacity planning, is required. The authors are in the process of applying these metrics on actual projects to assess their utility and highlight major issues in capacity planning.

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PHASE SCHEDULE IMPLEMENTATION AND THE IMPACT FOR SUBCONTRACTORS

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Abstract: The hiring of subcontractors for construction is widely adopted in the construction industry, so a good relationship between the subcontractors and contractors is essential for the success of the project. However, there is still a need to analyze how the subcontractors can improve their performance based on a collaborative planning process and their relationship with all participants in the project. This paper aims to discuss the impact of the Phase Schedule in the production planning and control focusing on the subcontractor's viewpoint and how this process assists their performance and participation. To do that, an in-depth case study was developed from April to November 2016, involving the implementation of the Last Planner System focusing on the Phase Schedule technique, including cycles of monitoring through performance measures, as well as data collection through interviews, focusing on the perception of subcontractor's and contractor's concerning the impact of using Phase Scheduling in the planning process. The results show the reinforcement of teamwork and the sense of collaboration identified during the implementation lead to a positive participation and performance of the subcontractors in the Phase Schedule planning process.

Keywords: Last Planner System, Phase Schedule, Subcontractor, Collaboration.

1 INTRODUCTION

Rahman et al. (2014) argue that the project participants understand that sharing of knowledge and information is one of the key elements of a successful contractual relationship. Manu et al. (2015) state that to achieve success in future projects, a trust-based collaborative environment is required to facilitate high levels of information sharing and to secure commitments of the supply chain from the very early stages of a project. Therefore, communication with, support and training of the subcontractors are important factors in the project environment (Jang et al., 2007).

On the other hand, Lordsleem (2002) argues that there is a difficulty for the subcontractors to achieve the goals of production planning imposed by the contractors, because most of the time, they do not participate in the discussions about the work flow and duration of the activities in an earlier stage. Thus, the Phase Schedule can be an alternative technique to improve the relationship between the team involved in each phase of the project.

The Phase Schedule is a level of planning in the Last Planner System which is the link between work structuring and production control (Ballard and Howell 2003). It is a collaborative planning process where project performers work together to design the

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process to deliver a milestone (Tsao et al. 2014). Ballard and Howell (2003) indicate that the Phase Schedule proposal is to integrate long-term and short-term planning by generating inputs for medium-term planning and consequently increasing its efficiency.

To achieve the Phase Schedule's goals, active participation of the subcontractors has fundamental importance, since the collaboration to develop the plans and the transparency of the information for all involved can contribute to a better work flow and more reliable plans. While studies have been focused on the process and benefits of the Phase Schedule, little is known about how this planning process influences the practices and performance of the subcontractors in the project. Therefore, the main objective of this paper is to understand the impact of the Phase Schedule on the subcontractor's practices and how this process assists the performance and participation of the subcontractors in the project. A single in-depth case study was carried out to achieve this objective.

2 PHASE SCHEDULE PLANNING LEVEL

According to Ballard and Tommelein (2016), Phase Schedule has the functions of specify handoffs and conditions of satisfaction between processes within phases. Ballard (2000) argues that Phase Schedule is collaborative planning between the team that will do the work in the phase that extends through the lookahead window. It uses the technique of a pull planning, which is also a part of LPS, and it is used to develop a plan for doing work at any level of task breakdown (Ballard and Tommelein, 2016). This planning is used to develop a more detailed work plan that specifies the handoffs between the specialists involved in that phase (Ballard and Howell, 2003), then each assignment is subjected to constraint's analysis to determine what must be done to make it ready to be executed (Ballard 2000). It encourages project performers to have earlier conversations about how to handle physical interfaces and constraints between components (Tsao et al. 2014).

The main findings identified by Knapp et al. (2006), which involve several Phase Schedule sessions, indicated that the teams involved understood better their project, their individual roles and what was required for success on the project better. Hamzeh et al. (2008) affirm that it is important to employ collaborative Phase Schedule to incorporate inputs from all the project stakeholders in the lookahead process and then it becomes more reliable. Kalsaas et al. (2009) observed that it is relevant the participation of the subcontractor's site representative in the Phase Schedule meetings.

Two of the methods and metrics used to analyze countermeasures to prevent reoccurrence are Percentage of Constraints Removal (PCR), which is the number of constraints removed with the total number of identified constraints, expressed by a percentage and Percentage of Plan Completed (PPC), which is the number of planned activities completed with the total number of activities planned, expressed as a percentage, and the causes of non-compliance of the activities related to the non-removal of the constraints and activities planned.

3 RESEARCH METHOD

The case study was developed during the construction of a clinic facility, from April to November 2016, located in the city of Salvador, Bahia, Brazil. This was the first and only experience of the general contractor with the Phase Schedule technique over the period of this study. The project team had already used elements of the LPS, such as visual

controls, daily huddles, analysis of breakdowns and PPC metric. The definition of the subcontractor in the project was made by the owner and general contractor.

The implementation of the Phase Schedule was undertaken through trainings, Phase Schedule meetings and the monitoring of the implementation through performance measures. These meetings were attended by the project engineering team, subcontractors and the research team. A total of five cycles of Phase Schedule implementation and monitoring was developed during this period. The following construction phases were involved: foundation, structure, masonry, electrical and plumbing installation, facade, ceiling plaster board and drywall system. The meetings occurred at the construction site and lasted for an average of two hours, except the last one that lasted in one hour, probably because of the learning effect of those involved.

As the focus of this paper is the understanding and the evaluation of the impact of the subcontractor due to the Phase Schedule implementation, sources of evidence were used for this analysis, including interviews, results of the performance measures, document analysis and participant observation. The interviews were carried out in order to understand the perception of the subcontractor and general contractor. Questions related to the training and pre-discussion for the Phase Schedule meetings, the development of meetings and the planning and monitoring of the constraints and activities, and difficulties, benefits and feedback for continuous improvement were posed.

A total of four subcontractors involved in the Phase Schedule implementation were interviewed, including the formwork subcontractor, the rebar subcontractor, both for foundation and structure service, the electrical and plumbing installation subcontractor, the ceiling plaster board and drywall system subcontractor. In addition, to gain the contractor's view point, the foreman and the project engineer were interviewed.

The results of the performance measures were used to evaluate the direct impacts that such implementation had on the performance of the subcontractors. The following measures were used as main source of quantitative data: PCR and PPC. This data was collected through the monitoring of the constraints and activities planned in the Phase Schedule meetings, which were supervised by the managers from the project using worksheets during the lookahead and the weekly work plan meetings.

The participatory observation occurred during the Phase Schedule meetings and along with the monitoring of the constraints and planned activities. During the Phase Schedule meetings, it was possible to qualitatively evaluate the interaction and participation of all those involved. In the monitoring of the constraints and planned activities, it was possible to analyze if the constraints identified during the meetings were sufficient to make the activity ready to be executed and if the activities planned were in the right sequence and duration of execution. This data was analyzed in an integrated way with the interview in order to gain a better understanding of the effectiveness of the process and impacts on the subcontractors.

To make the data analysis more objective, two constructs were defined as following:

- a) Subcontractors Performance: aims to evaluate to what extent the subcontractors were able to meet the activities planned and to keep to their commitment to remove the constraints that could interfere in their tasks or subsequent tasks. The main source of evidence used was direct observation, data analysis of the worksheets and measures results, as well as interviews.
- b) Subcontractor Participation: aimed to evaluate their involvement and learning with the Phase Schedule practices and their participation in the discussion before and during Phase Schedule meeting in order to reach the goals established by the

master plan. The main source of evidence used was direct observation, and interviews.

4 RESULTS AND DISCUSSION

4.1 Implementation of the Last Planner System focusing on the Phase Schedule

The implementation of the Last Planner System with focus on the Phase Schedule started with the phase analysis from the master plan in which the milestones were defined by the general contractor. In the Phase Schedule meeting, the activities were planned using the “back to forward” technique, starting from the milestone initially defined. This planning seeks to identify in each activity its constraints, execution duration, the start date and the team required to do the work. The formalization of this planning happened by transferring all the information to a worksheet for the monitoring of the constraints and activities planned. This planning control of activities takes place during the lookahead plan and weekly plan meetings. The weekly plans were discussed with the foreman and sometimes with subcontractors.

4.2 Results of Indicators: PPC and PCR

The results obtained by the indicator of Percentage of Constraints Removal (PCR) are shown in the Figure 1, in which the axis are the percentage and the construction phases analyzed in the Phase Schedule meetings. This figure expresses the percentage of each subcontractor's and contractor's constraints that should be eliminated compared with the percentage that actually was eliminated, calculated by the PCR.

The number of constraints at the Foundation phase was lower than the other phases, so it was easier for monitoring the lookahead plan, resulting in a 100% of the PCR. Unlike the Foundation phase, the Structure phase had few constraints not removed, and the main causes were related to the delay of the material supply, lack of labour force from the rebar subcontractor and changes of plan from the contractor.

To Ballard and Tommelein (2016), it is important to identify the departments and individuals who will be the go-to guys for each type of constraint, thus most of the constraints identified on the Phase Schedule implementation were the responsibility of the general contractor; however, the subcontractor's constraints also had strong influence on the overall performance. For instance, in the Masonry Phase Schedule meeting, the electrical and plumbing installation subcontractor was responsible for only 3% of the constraints. However, due to the fact the electrical and plumbing subcontractor was hired late, this affected his ability to meet the deadlines established and to remove his constraints, causing a major change of plans. This change-over caused a non-removal of several constraints assigned for the general subcontractors, affecting the PCR result. The change of plans also influenced in the Facade phase, causing a non-removal of the contractor's constraints.

Another issue identified during the monitoring of the constraints from the Drywall/Ceiling Plaster Board phase was that some of the contractor's and electrical and plumbing's constraints were in fact from predecessor activities; so, this required a new analysis for better definition and detailing of the activity.

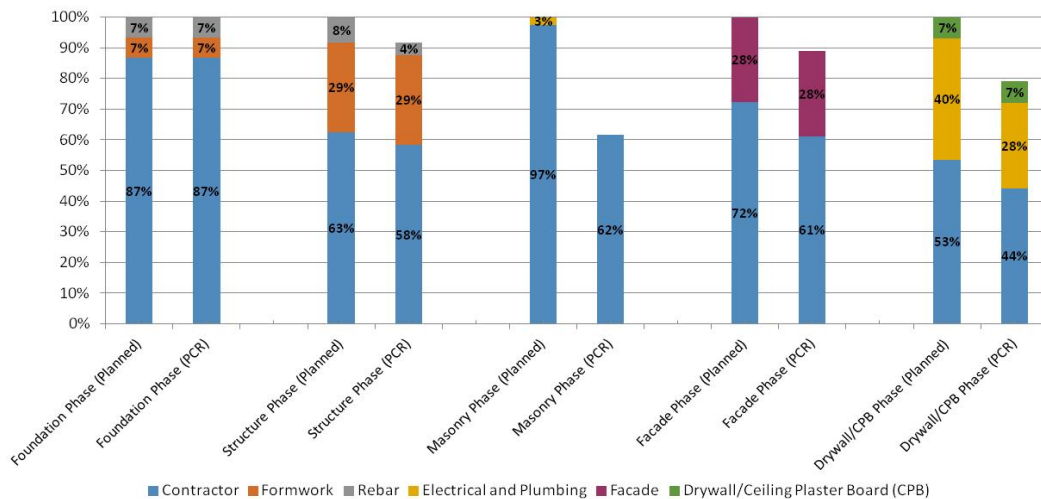


Figure 1 - Percentage of Constraint Removed (PCR) by construction phases analyzed in the Phase Schedule meetings

The PPC results from subcontractors and the whole project are presented in Figure 2. The subcontractor's PPC were found by selecting only activities which were their responsibilities. The Phase Schedule meetings occurred in the weeks 1, 6, 15, 20 and 23, as highlighted in the figure.

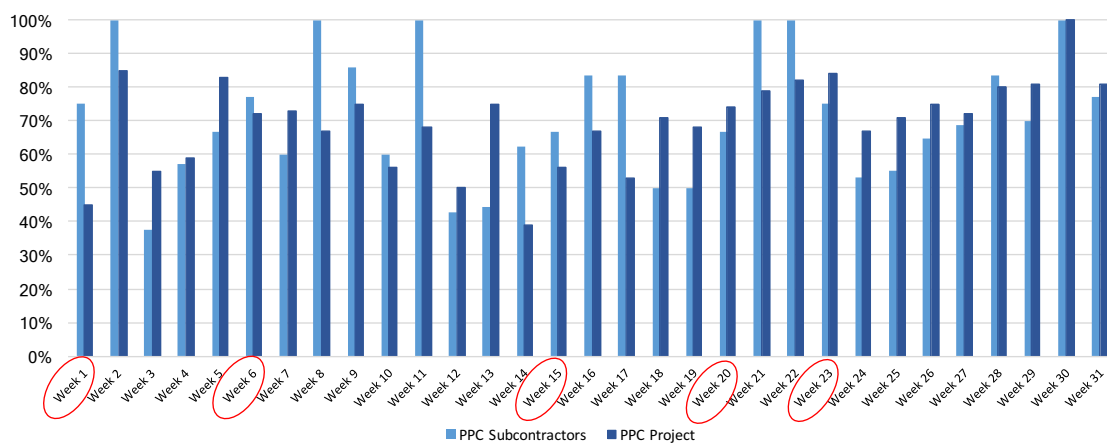


Figure 2 - Percent Plan Completed from Subcontractors and whole project

Based on the weekly PPC result, there is an improvement in the performance of the PPC in the following weeks after the Phase Schedule meetings. This happened probably because those involved had more time to remove the constraints identified. Some Phase Schedule meetings happened in the week before the start date of some activities of the phase, despite the literature which indicates that for the reliability of the planning system, the lead times for acquiring information, materials, labor, and equipment need to be considered (Ballard 2000). However, the main cause of the delay of the definition of the Phase Schedule meeting was the late hiring of the subcontractor by the owner.

The main causes for non-compliance of the activities planned from the weekly PPC were predecessor delay (workflow), change of plans, shift of the teamwork to one service planned to another and lack of subcontractors' commitment. According to this, the main causes of the subcontractors' PPC were predecessor delay (workflow) and change of

plans. This can indicate that the change of plans at lookahead schedule level has significant impact on the performance of the weekly PPC results.

It is also observed that the average of the subcontractors' results is close to the average of the contractor's, most likely to the general contractor effectiveness for monitoring the subcontractor's constraints and the subcontractors' commitment to accomplish the weekly activities; however, there was a significant difference in the weeks 2, 8, 11, 17, 21 and 22 because the number of subcontractors' activities were much lower than the contractor's. The low results in the weeks 18 and 19 are due to the non-removal of the electrical and plumbing subcontractor's constraints, causing the non-compliance of the weekly activities.

4.3 Impacts of the Phase Schedule Implementation on subcontractor's practice, performance and participation

The main findings of the interviews are presented at Table 1. From the four subcontractors interviewed, only the drywall subcontractor had previous experience with Phase Schedule.

Table 1: Positive aspects and challenges of the Phase Schedule case

	Positive Aspects	Challenges
Training and pre-discussion	Preparation and pre-discussion of the schedule and its use as a guide in the Phase Schedule meetings	Difficulty in visualizing the method that will be used
Phase Schedule meetings	Support from the engineering team (facilitators) for a better understanding of the methodology Transparency because of the visual resources (post-its and board with the weeks) Clarification and collaboration of existing interference and joint identification of constraints Experiencing the methodology in one meeting improves the performance in the following ones	Initial difficulty with "back to forward" planning Long time of the meetings (about two hours) at the beginning Many activities for discussion at the same meeting
Monitoring of constraints and planned activities	Self-reorganization and interactive teamwork at the field	Late hiring of subcontractors

In general, the Phase Schedule technique was a new and positive experience that facilitated the development of the field activities. The main positive aspects mentioned by the subcontracts were the improved transparency of information, the opportunity to understand the phase and the possibility of collaboration to identify the best way to execute the task and according to the milestone. These findings corroborate with Kalsaas et al. (2009) study which postulates that this sort of planning process increases the understanding of the tasks for all participants.

The main challenges faced by the subcontractors were the long duration of the meetings in some cases and the high number of activities to be planned. Knapp et al. (2006) highlights that the size and length of the phase selected is very important because when the phase is too large and complex it makes the session less effective.

Concerning the Performance construct, analyzing the PCR and PPC data, the subcontractors achieved good results in both indicators (the average of PCR was 84% and the average of PPC for subcontractor was 71%). These results indicated that the mapping

of the constraints along the Phase Schedule meetings contributes effectively to a better understanding of possible limitation of the tasks, and addresses issues that need to be resolved before the tasks hit the construction stage (Tsao et al., 2014).

These constraints mapping also contribute to increasing the perception of responsibility of the subcontractor for removing the constraints in order to reduce the uncertainties in the field and to be able to meet the final date planned in the Phase Schedule. However, the late contracting of subcontractors had a direct impact on the ability to meet deadlines (removal of constraints). Ballard and Tommelein (2016) argue that is an area of weakness when specialty contractors are engaged late in the project and do not have sufficient understanding of the work to contribute effectively to planning. Despite this, according to the subcontractors' perception, the monitoring of the activities was well done by the contractors, encouraging them to accomplish the deadlines.

Concerning the participation, the subcontractors presented a low level of resistance related to the adoption of the Phase Schedule practices, such as the pre-discussion, including an improved detailing and duration of the tasks, and throughout the meeting, providing the information required. Also, one good practice identified was related to the sharing of the lessons learned in previous meeting among the participants. It was observed that those who participated in more than one meeting improved their participation at each stage.

The general contractor foreman mentioned in his interview that a greater sense of collaboration in the field was created, reducing the transfer of responsibilities, since everyone was aware of their commitments and the importance of teamwork to reach the goals. The visualization of the whole project during the Phase Schedule meetings facilitates the reorganization of the subcontractors' team in the field, when a delay or uncertainty has happened, without changing the deadline. One advantage of this planning is to create a team able to respond flexibly to differences between assumptions about how the future will turn out and what actually happens (Ballard and Tommelein, 2016).

One of the subcontractors interviewed mentioned that it was very important to have the opportunity to discuss the deadlines of the project in a collaborative way, instead of the traditional package of activities already planned by the general contractors. This highlights the importance of the collaboration characteristic of phase schedule.

5 CONCLUSIONS AND FUTURE RESEARCH

This paper aimed to understand the impact of the Phase Schedule in the practices, performance and participation of the subcontractors in the project. Based on the results, the reinforcement of teamwork and the sense of collaboration were identified during the implementation, which was corroborated by the perception of the interviewees. The participants in the meetings expressed their preoccupation to accomplish their agreements established at the Phase Schedule meetings. For instance, when there was a delayed activity which involved more than one subcontractor, they tried to work out solutions together, showing a sense of belonging and responsibility related to the project.

Through the indicators (PCR and PPC) it was possible to understand the performance of the subcontractors from a quantitative perspective. However, there are still opportunities for better definition of measures that could analyze the impact of the Phase Schedule as a whole to improve the workflow and the reliability of the plan. Also, corroborating with Emdanat and Azambuja (2016), new studies are required which have

the objective of aligning the short-term work execution planning with the overall Phase Schedule and master schedule targets. A second stage of the present work has been developed to identify measures that can reduce the gap of this knowledge.

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GUIDELINES FOR DEVISING AND ASSESSING VISUAL MANAGEMENT SYSTEMS IN CONSTRUCTION SITES

Caroline Valente¹, Fernanda Brandalise², Marinna Pivatto³, and Carlos Formoso⁴

Abstract: Visual Management (VM) has gained a prominent place in the Lean Production Philosophy, and is strongly connected to the core principle of increasing process transparency. However, the use of VM in construction sites is still relatively limited, and there is not much literature on the implementation of this principle. This paper proposes guidelines for devising and assessing VM systems in construction sites. It is based on a set of benchmarking studies, and on an empirical study conducted in a housebuilding firm that is widely recognised as a leading company in the implementation of Lean Construction in Brazil. Initially, an overall assessment of the VM system implemented in one construction site was conducted. Then, a more focused analysis was made on the installation of drywall internal partitions. The main contributions of this investigation are related to the need of integrating visual devices in the managerial routines of the company, as well as to the difficulties of providing autonomy to the production crews, and the need of decentralized production controls.

Keywords: Visual Management, Transparency, Production Planning and Control.

1 INTRODUCTION

Process transparency can be defined as the ability of a production process (or its parts) to communicate with people (Formoso et al., 2002). This is achieved by making the main process flows visible and comprehensible from start to finish, through organizational and physical means, measurements, and public display of information (Koskela, 2000). If process transparency is successfully implemented, most problems, abnormalities, and types of waste that exist can be easily recognized in order to allow remedial measures to be taken (Igarashi, 1991). Galsworth (1997) defines visual system as a set of visual devices (indicators, signals, controls and guarantees) that are intentionally designed to enable the sharing of information between people. Tezel et al. (2016) define Visual Management (VM) as a sensory strategy for information management. It includes messages communicated through any of the five senses - taste, touch, smell, and hearing as well as sight (Galsworth, 1997). Ewenstein and Whyte (2009) suggest that visual objects may either be (i) unavailable to be changed (“frozen”), or (ii) amenable to be changed (“fluid”), often as part of collaborative processes. These categories correspond, respectively, to static and dynamic visual devices, as described by Bititci et al. (2015) and Tezel (2011). Another distinctive aspect of VM is that it is intended for a group, and not just for an individual. Whereas in

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a conventional workplace most messages are transmitted by specific information channels, such as meetings and memos, in visual factories an information field is created, extending access to information to a large number of people (Greif, 1991).

Tezel et al. (2016) proposed a taxonomy of functions for VM, including transparency, discipline, job facilitation, and on-the-job training. Recent research also suggests that VM systems can mitigate problems related to the management of complex production systems (Viana et al., 2014), and contribute for a cultural change in the organization (Valente and Costa, 2014). In fact, besides increasing process transparency, VM involves other Lean Production core principles and practices, such as reducing variability (Formoso et al., 2002), and continuous improvement (Bernstein, 2012).

Although a growing number of visual management practices in construction have been reported in the literature, the application of those practices in construction sites is still very limited: visual devices are mostly used in site offices to support managerial decisions, and only health and safety "frozen" warning boards are usually found in construction site working areas (Tezel et al., 2016a). Moreover, research on the process of devising and implementing visual management systems is relatively scarce (Tezel et al., 2015). Recent research has mostly focused on the definition of categories for existing visual management practices (Tezel et al., 2016b) or on the impacts of visual systems devised for specific purposes, such as production planning and control (Brady, 2014), or material supply (Arbulu, 2008; Costa and Burgos, 2015). In fact, the introduction of visual devices is often viewed as something intuitive and based on common sense (Beynon-Davies and Lederman, 2016), without considering the demand for information in a systematic way, or the mental models of potential users.

Nicolini (2007) states that producing some visual devices require a great deal of "non-visual" work that is often hidden, and that ends up being neglected by the research initiatives on this topic. Such hidden work is part of existing managerial processes, and is fundamental to perform other tasks that are necessary for creating a transparent environment, such as processing and analysing information, and devising improvement measures. Nicolini (2007) also suggests the somewhat paradoxical possibility that visual practices are by definition not only visual, and that the visual part is, in fact, only the emerging tip of a much bigger iceberg.

Moreover, visual management can be regarded as a leaner way of knowledge management (Rooke et al., 2010). According to Eppler and Burkhard (2007) the creation and effective transfer of knowledge through visualization involve five perspectives: (i) what kind of knowledge is visualized (content); (ii) why this knowledge should be visualized (purpose); (iii) for whom this knowledge must be visualized (target group); (iv) in what context this knowledge should be visualized (communicative situation: participants, place, media); and (v) how knowledge can be represented (method, format). These issues are connected to the hidden work involved in visual management.

This paper proposes guidelines for devising and assessing visual management systems, understood as sets of visual practices that should be integrated to managerial processes. These guidelines are meant to be a prescriptive contribution, i.e. it should be used as a reference for companies that intend to develop or refine visual management systems to support production management in construction projects.

2 RESEARCH METHOD

Design Science Research was the methodological approach adopted in this investigation. It is a way of producing scientific knowledge that involves the development of an artifact

to solve a real problem (Holmström et al., 2009). This investigation was divided into two stages. The first stage consisted of a set of benchmarking studies, in which the visual management systems of five companies outside the construction industry were analysed. Four of the companies were from the manufacturing industry, and the fifth one developed digital solutions (Table 1). These companies were chosen because they had very advanced visual management systems, some of them very well integrated to managerial processes. Each visit involved direct observation of production facilities, and one interview with a manager directly involved in the visual management system.

Table 1: Industrial sectors and interviews carried out in benchmarking studies

Company	Industrial Sectors	Interviews
A	Gear and Couplings	Industrial Manager
B	Rigid and Flexible Packaging	Process Engineering Analyst
C	Agricultural Machinery and Equipment	Process Engineer
D	Soft Drinks	Continuous Improvement Assistant
E	Digital Solutions	Head of Operations

The second stage of the research project consisted of an empirical study carried out in a construction company (named Company F), in which the visual management system adopted in one construction site was assessed. This is a large housebuilding company from Brazil, with branches in 17 different states. Company F develops and builds commercial, residential (mostly for the higher middle-class) and, more recently, health-care projects. This firm was chosen because it is well known as a leading company in Brazil on the implementation of quality management and lean construction practices. In fact, it was included as one on the best practicing companies on visual management in Brazil in a report produced by Tezel et al. (2010). The empirical study was carried out in a health-care construction project, a short-stay hospital located in Porto Alegre. This project was chosen because it was considered to be the most advanced one in terms of implementation of Visual Management in the Porto Alegre Metropolitan Region. This empirical study was divided into two phases.

The first phase consisted of an overall assessment of the visual management tools that had been implemented in the construction site. Six site visits were undertaken, in which a wide range of visual devices was assessed. Some visual devices were excluded from this study, such as visual indicators located in the site management office, mostly used in the production planning and control process, as well as boards that displayed very simple, "frozen" information (e.g. safety warnings), as the main focus of this assessment was the support provided by visual management in the execution of construction processes. A protocol was devised for guiding data collection related to each visual device, including the content, type and function of information displayed, the target group, the visualization format, the management area assisted by it and if it was static ("frozen") or dynamic ("fluid"). The main outcomes of this phase were the identification of improvement opportunities related to the existing visual management system adopted by the company, and an assessment of the degree of integration of the visual devices to existing managerial systems.

The second phase consisted of a detailed analysis of the visual management devices that supported the installation of drywall internal partitions. The main reasons for choosing this process was: (i) it plays a key role in site installation, due to the large number of interdependences with other processes; and (ii) it uses mostly industrialized components, and has a relatively short lead time, creating improvement opportunities that can be rapidly implemented.

Multiple sources of evidence were used in this empirical study: (i) interviews (40-60 min) with two site managers, the foreman, a technical assistant, interns, four workers involved in material supply, and two warehouse keepers; (ii) direct observation of the construction site (13 visits), including visual devices and production operations; (iii) analysis of documents (conventional production plans, visual schedules, inventory sheets, standard operating procedures and flowcharts); and participant observation in a planning meeting. Based on the data collected in this investigation, some improvement initiatives were developed by the company, and the results were also observed by the research team. The results of this study were discussed with representatives of Company F in three discussion meetings and two seminars.

3 RESEARCH FINDINGS

3.1 Benchmarking studies

Some visual management best practices were identified in the five benchmarking studies. Firstly, in all five companies' visual devices were highly used to support rituals of daily meetings that usually take place in the morning, before the start of the work shift, and lasts from five to thirty minutes. The agenda usually consists of: follow-up of the previous day production, problems occurred in the latest shift, the current day's schedule, weekly indicators analysis and action plans for performance improvement. Those companies also used visual charts that are made visible to all workers and keep the information available and accessible at a glance to users, providing rapid feedback. Another best practice was the effort to standardize processes and operations, not only for value-adding activities, but also for inspection, logistics and safety operations. Finally, high importance was given by the five organizations to the use of A3 reports as a tool for problem solving and communication. All of them developed A3s to solve and document production and administrative problems, contributing to mitigate system's complexity. In some of the companies, the A3 chart had standardized sections.

3.2 Overall assessment of visual management devices

Figure 1 presents the classification of visual devices adopted by Company F, according to the functions performed and type of information used, based on the classification proposed by Eppler and Burkhard (2007). This information provides insights on how visual devices are integrated to existing managerial systems.

Regarding the functions of each visual device, Figure 1(a) indicates that more than half of the visual devices performed functions of identifying or informing something, which refers to the most basic types of visual tools (indicators or signs). Only 13% of tools were used for data or activity control functions, and only 5% were intended to guarantee an action by using an error-proof device. Hence, the adoption of more powerful tools, such as visual controls and guarantees, was identified as an improvement opportunity, in order to increase the impact of visual devices in work standards.

Concerning the type of information displayed, more than half of the devices were intended to identify or inform. A large percentage (31%) of devices portrayed information that responded to a "what?" question, followed by devices that answered "where?" (23%) and "who?" questions (16%). One surprising result was the very short percentage (1%) of visual tools associated to a "why?" type of question. Answers to this type of question usually relate to the reason or purpose for a particular action or attitude, which often refers to the company's beliefs, values, and culture. The lack of this type of information on visual

devices can be related to the typical role of task execution played by the labour force in the construction industry, assuming that it is not necessary to know much about the purpose of things.

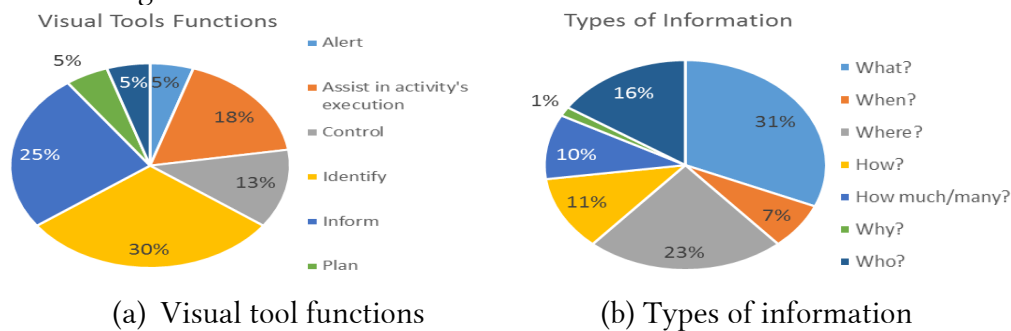


Figure 1: Classification of visual tools according to the functions performed and types of information associated

The relatively low level of participation of workers in the visual management system was also made evident by the source of the information to be disseminated in visual devices. As shown in Figure 2, most visual device information was produced by the site managerial team. Workers were rarely involved in the conception, or updating of visual devices, despite the fact that they had useful information for production management. Consequently, the site management team had to spend a considerable amount of their time in production control activities, which is contradictory with the idea that process transparency should be used for increasing the autonomy of the labour force.

Based on a comparison between the practices of this company with the ones analysed in the benchmarking studies, it is possible to identify two spirals in visual management. A positive one is when controls become simpler and problems are more easily detected, which enables the production crews themselves to perform those controls. In that case, there is more autonomy and responsibility for production crews, reducing the burden of control for the site management team, who can spend more time in studying, evaluating, and rethinking processes in order to make them more transparent and improve performance. In the negative spiral, if the processes are not transparent, problems are more difficult to be identified and controls are more complex and time-consuming, demanding much effort from the site management team. This hinders production teams from having autonomy to perform these controls and take responsibility for detecting problems. In that situation, the site management team becomes overwhelmed with controls and there is not much time left for process improvement, making them even less transparent.

Around half of the visual devices were related to production planning and control, including productivity evaluation tables, and daily activities sheets for labourers. Twenty-two percent of the devices were concerned with quality management, such as work standards, inspection sheets and quality policy panel, although none of them visually displayed data on defect rates or abnormalities. Some information deficits were identified in other managerial processes, such as safety, waste detection, and logistics management. Regarding safety, although workers were encouraged to report near-misses, most visual devices were static, or displayed accident rates and action plans after accidents. In addition, although some visual practices were fairly well connected to the production planning and control and quality management processes, the integration between visual devices and some other managerial processes was relatively weak. As a large number of visual devices were static and had only informative or indicative character, little feedback could be pulled out from them to support problem-solving or mitigate complexity.

Moreover, none of the visual devices was designed to support the creation of knowledge at the level of construction workers.

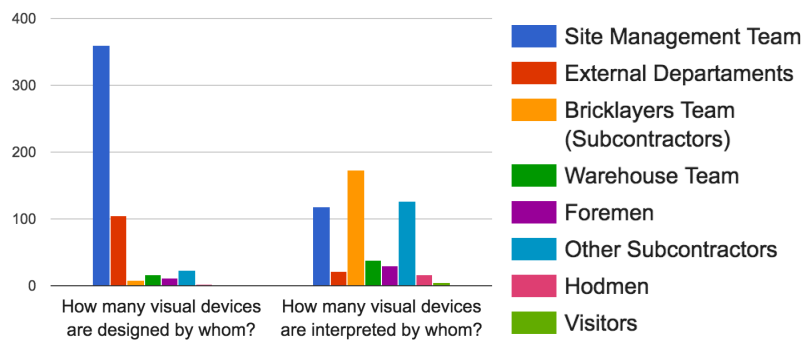


Figure 2: Graph of participation of agents at site's visual management system

The results presented above can assist the company in adjusting its visual management system in two complementary ways. Overall, it seems to be important for Company F to seek a balance on the use of visual devices among different managerial processes and to use visual devices that offer more support for production control and improvement. It would be better to have a smaller number of dynamic visual devices that effectively support decision-making and encourage reflection and collaboration, rather than having a large number of devices, most of them with a low impact in production management.

3.3 Analysis of the Drywall Process

Company F has implemented several visual devices for this process, such as physical prototyping, templates, inspection sheets, standard operating procedure flowchart, kanban for supplying materials, visual schedule for each floor, and material control sheets. Some of these visual devices are dynamic, such as inspection and material control sheets. Another good practice was the fact that some of those visual devices were well integrated. For instance, the physical prototype was used, among other things, to adjust the amount of materials for each kanban. By contrast, some problems were detected in the kanban system. Due to an implementation problem, cards were sometimes used simply as inventory distribution sheets. Some of the information was not very clear for the labourers in charge of transportation, and the batches were not adequately distributed in each zone of the building.

Based on discussions carried out in this investigation, the site management team decided to improve the kanban system. Figure 3 presents the new format of the card, which is more intuitive, and easier to understand than the previous one. Some additional controls were included, such as the amount of materials that left the main storage area. However, some problems related to leftovers or lack of material persisted, mostly due to mistakes in the preparation of transportation batches, and poor communication between team members. Due to the changes introduced, mostly concerned with giving more autonomy to workers, some improvements were identified: 6% reduction in gypsum plasterboard waste; reduction in the time spent counting components, higher productivity of the material supply teams, better organization of inventories, and increase in the motivation of the employees. It is worth noting that the material supply team spent 33% of their time waiting for the panels to arrive in the elevator, due to interference from other material supply operations. Thus, more time should be spent in standardizing and coordinating logistics operations.

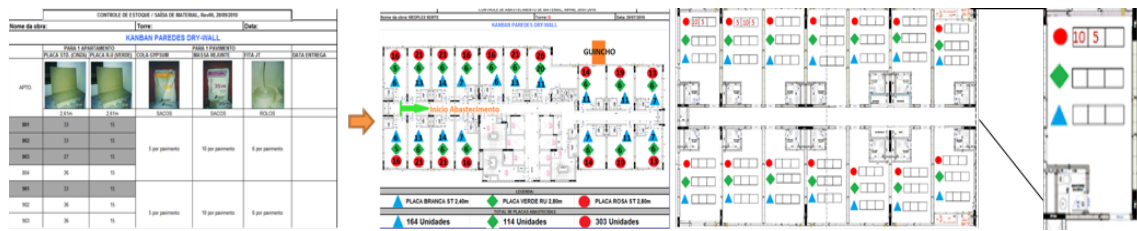


Figure 3: Old version (left) and new version (right) of kanban

4 DISCUSSION AND CONCLUSION

Based on the literature review, in the benchmarking studies, and especially in the empirical study carried out in Company F, a set of guidelines for designing, implementing and assessing a visual management systems have been proposed: (i) *Support communication rituals in collaborative meetings*: visual devices should be associated to learning initiatives and moments of reflection. When a visual device plays this role, it becomes important to people and relevant to the process. Stopping in front of the performance board or visual device, even for a few minutes in a daily ritual, is a strong evidence that this artefact is useful; (ii) *Ensure rapid feedback*: a visual management system should provide timely information and quick feedback so that corrective actions can be taken; (iii) *Encourage the joint processing of information*: a visual management system should support collaborative activities in organizations. Some visual devices can be used as catalysts to facilitate a variety of tasks, from the generation of ideas to decision making, planning, knowledge sharing and learning (Eppler and Bresciani, 2013); (iv) *Consider the mental models of the users*: the assumptions, beliefs, generalizations, illustrations, and previous experiences that influence the behavior and understanding of the users should be considered in the design of visual management systems. This reduces the amount of information to be provided in visual devices, and make them easier to be understood by users; (v) *Contribute to a cultural change*: a visual management system can change the way employees feel about their work, contributing to increase morale and motivation, by promoting collaboration, decentralizing decisions, and increasing the degree of autonomy among production teams; (vi) *Mitigate problems related to system complexity*: complex systems are unpredictable environments, full of uncertainty and variability. Some visual devices can provide some support to deal with this complexity by sharing the right information on time and removing information barriers in the work environment.

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PRODUCTION SYSTEM DESIGN TRACK

Track Chair:

Frode Drevland

Norwegian University of Science and Technology

COMPARING PRODUCTION DESIGN ACTIVITIES AND LOCATION-BASED PLANNING TOOLS

Clarissa Biotto¹, Mike Kagioglou², Lauri Koskela³ and Patricia Tzortzopoulos⁴

Abstract: What are the differences between production system design and work structuring? And between phase scheduling and work structuring? Which lean planning tool is better suited for each one of these design processes: line of balance, takt-time planning or flowline? This paper aims to answer these questions through a comparison and deeper understanding of production design processes, as well as the potential uses of location-based tools for production planning and control in each design effort.

The method used is the literature review analyses on main lean terms and tools applied for production system design. With a better comprehension of the terms and tools, it is expected that academics and lean practitioners will be able to apply lean construction in a more aware and sensible manner. The results will also support researcher's decision about the most suitable lean tool to apply in the case studies in different production design processes.

Keywords: Production design, phase scheduling, work structuring, line of balance, flowline, takt-time planning.

1 INTRODUCTION

The production system management is divided in three major activities: design, operation and improvement (Koskela & Ballard 2003). In lean construction literature, the Production System Design (PSD) also refers to Work Structuring (WS) (Ballard et al. 2001). Although it occurs before the construction act, it is known that, during the production system operation, some production system design activities also take place, e.g. the Phase Scheduling (PS). It occurs because information becomes available and accurate for decision-making just after the beginning of construction. Whether PSD, WS or PS, these design processes have different features, uses and scopes, which are not very clearly described in the literature.

In the lean literature, there are some tools for production design that express the work structure in a visual fashion, such as line of balance (LOB), flowline (FL) and takt-time planning (TTP). These tools use the locations in a building/facility as the unit basis for production planning and control, structuring the work in different ways. For that reason, it is also important to clarify these differences among them, and the potential use of these tools.

The aim of this paper is to present brief descriptions and comparisons about production

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design, such as PSD, WS and PS, as well the tools used to devise them, namely, LOB, FL and TTP. This literature review is part of an ongoing doctoral research, in which papers were used to track how the lean tools and processes are being applied in academia and industry.

Through the clarification of production design processes and planning tools, it will be possible for construction managers to choose the most suitable tool for each design process in development, based on the accuracy of information, the stakeholders' commitment and level of uncertainty in the construction project.

2 LITERATURE REVIEW

2.1 Production System Design

In manufacturing industry, the production system design is the study of alternatives of production organization in order to choose the most appropriate strategy to achieve the desired results (Meredith & Shafer 2009).

In construction, the design of the production systems has three main goals (Koskela 2000): 1. Deliver the project; 2. Maximize value; and, 3. Minimize waste. PSD represents the most basic form and opportunity for minimizing the effect of variability on production, at the same time it contributes to achieve the major project goals (Ballard et al. 2001).

Usually, PSD refers not only to the work structuring, which is a necessary activity to study the workflow, but also, to a set of decisions that cover the whole project strategy. PSD should take place, necessarily, before the construction stage in order for the project team to be aware of alternatives for production organizations and its consequences for budget, time, and workflow. One of the PSD outputs is the master plan that will be used when the system starts its operation (Schramm et al. 2004). Then, the project team will be able to adapt the production system in case of variabilities and uncertainties, i.e., minimizing their effects on production, and delivering value for client.

2.2 Phase Scheduling

Phase Scheduling, also known as pull planning, is a collaborative design activity to structure the process of a project phase and produce a plan for completing it (Ballard 2008). PS aims to maximize the value generation among the stakeholders and client through a transparent and collaborative process of decision making, in which people involved can use sticky-notes (amongst other means) on a wall (or other physical and digital media) to plan their activities, define the network of activities and the handoffs, insert the buffers, and also, to guarantee the completion of the work on time (Ballard 2008).

In order to plan a phase, the PS participants use the work structuring to breakdown the phase activities into processes and operations, and then, define the handoffs between the crews of sequential activities, and between project phases.

2.3 Work Structuring

The term Work Structuring was introduced in construction by Ballard (1999) to designate the production system design. However, there are some differences of focus between the two. Work structuring can be defined as process design (Ballard 1999). It is “the development of operation and process design in alignment with product design, the structure of supply chains, the allocation of resources, and design-for-assembly efforts” with the goal of making “work flow more reliable and quick while delivering value to the customer” (Ballard 1999).

Work structuring is used before the production stage, but it can be used any time during the construction (Ballard 1999). It breaks down the product and the process into parts, sequences and assignments to realize the work flow with less variability, to reduce waste while increasing the value (Ballard 1999). To achieve this goal, the work structuring deals with three main concepts:

- **Production unit** – “a group of direct production workers that do or share responsibility for similar work, drawing on the same skills and techniques” (LCI, 2004 cited in (Tsao 2005);
- **Work chunk** – “A unit of work that can be handed off from one production unit to the next” (Tsao 2005);
- **Handoff** – “The combined (1) completion of a work chunk by a production unit that allows a subsequent production unit to further transform the work chunk or execute a different work chunk as planned, (2) declaration of completion of the work chunk by the production unit and release to the subsequent production unit, and (3) acceptance of the released work by the subsequent production unit” (Tsao 2005).

Based on these concepts, work structuring tries to answer the following questions (Ballard 1999): 1. In what chunks will work be assigned to specialists?; 2. How will work chunks be sequenced?; 3. How will work be released from one production unit to the next?; 4. Where will decoupling buffers be needed and how should they be sized?; 5. When will the different chunks of work be done?

2.4 Discussion about Managerial Activities in Lean Construction

Comparing the Production System Design with Phase Scheduling and Work Structuring, it seems that the first one focuses on strategic decisions about the construction project with concerns about project’s viability, budget and lead time, which are consequences of the production system organization. In contrast, the PS tries to ensure that phase activities are clearly defined in handoffs for participants and the phase lead time fits into the master schedule. On the other hand, WS focuses on the process view and it is used in both design processes, PSD and PS, considering the information available for the decision making to break down the work in work chunks, handoffs, and production units, and in order to make the workflow smooth (Figure 1).

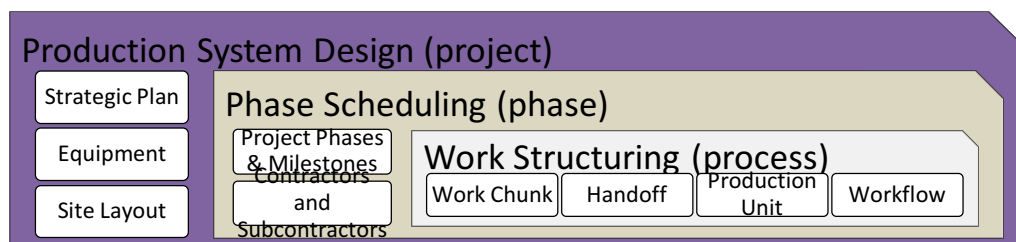


Figure 1: Work structuring is part of the decision scope of production system design and phase scheduling.

2.5 Location-based Planning Tools

There are different types of methods to plan construction activities: those based on activity or those based on location. Examples of methods to plan construction based on activity are the well-known Critical Path Method (CPM) and PERT. Both methods are frequently criticized by lean researchers, due to their incapacity to deal with the construction complexity.

Methods originally developed in the manufacturing industry were adapted for construction, such as Line of Balance, Flowline and Takt-time planning. The adaptation occurred by changing the vertical axis unit: from units produced to location (Kenley &

Seppänen 2010). The term location-based schedule was proposed by (Kenley 2004). It occurred due to the construction industry having resources, namely manpower and equipment, flowing through the fixed location units, differently from the manufacturing, where production units flow through the fixed resources.

2.5.1 Line of Balance

Line of Balance (LOB) is a planning technique developed by Goodyear Company in the 1940s and then used in the manufacturing industry for repetitive process. Next, it was developed for an industrial program by the US Navy in the 1950s (Arditi et al. 2001). Currently, the line of balance is also used by the construction industry, especially in repetitive projects, such as high rise buildings, tunnels, roads, and so on.

The LOB is a diagram that represents units in the vertical axis, and time in the horizontal axis. Initially, the tasks were represented as dual parallel lines. As the LOB is based on activity-on-arrow (AOA) networks, the task lines represent an activity between two event nodes (the delivery of production unit) (Yassine et al. 2014), hence, the line slope means the delivery rate. Because this method is focused in the delivery of completed units, the delivery rate starts counting “when the first unit has been finished” (Yassine et al. 2014).

The LOB technique allows the project team to achieve continuous workflow and uninterrupted flow for crews through the location units. This technique is appropriate for planning projects with repetitive nature by taking advantage of continuity of work (Mendez & Heineck 1998). The main idea in the LOB is that all activities can be performed in only one production rate, i.e. a parallel programming between the activities (Mendez & Heineck 1998) to reduce the work in progress.

The LOB is being used to devise the production system design, as well as the master plan of construction projects (Kemmer et al. 2008; Schramm et al. 2004). It also can be detailed in different forms, i.e. the time units can be days (Valente et al. 2014) or weeks (Seppänen et al. 2010) according to the level of uncertainty in defining the tasks duration.

2.5.2 Flowline

Flowline is a term coined by Mohr (1979), however, the method was developed earlier by Selinger (1973) and (Peer 1974). The flowline consists from a derived method from the Line of Balance, however, the activity is represented by a single line, which Kenley and Seppänen (2010) consider a much cleaner representation than line of balance. In order to visualize the crews’ workflow, the activity flowline can be broken down into crews’ lines (Kenley & Seppänen 2010).

The flowline can also be designed for normal construction projects, rather than the repetitive ones, by breaking down the project locations in equal sizes or work content (Kenley & Seppänen 2010). As the flowline is rooted in activity-on-node (AON) representation, which is used to draw the CPM network, the tasks represents the start and end of a process and the logical link among tasks (Yassine et al. 2014). For that reason, the slope of a line represents the production rate, which is the total quantity of units divided by the total duration (Yassine et al. 2014). The task is graphically represented by starting in the point of the first unit location (Y-axis) and start of duration (X-axis); finishing in the point of the last unit location (Y-axis) and end of duration (X-axis) (Kenley & Seppänen 2010).

2.5.3 Takt-time Planning

The takt-time planning (TTP) in construction is derived from the takt time used in lean manufacturing to plan the production system by setting its rates according to the demand

rate. The use in construction started recently, with some works on its application in the development of the production system design, more specifically, the Phase Scheduling (Frandsen et al. 2013; Linnik et al. 2013).

Frandsen et al. (2013) define Takt time as the “unit of time within which a product must be produced (supply rate) in order to match the rate at which that product is needed (demand rate)”. The main aim of the TTP is to design the production system for continuous workflow, keeping the trades in a balanced pace of work (that match the demand rate) through a sequence of zones (Frandsen et al. 2013).

The zones are “physical and clearly defined locations” to avoid ambiguity about location boundaries, the same as in the Line of Balance (Frandsen et al. 2015). In a production plan devised using the TTP method, the trades must complete their work in the assigned zone in an amount of time set by the takt time (Frandsen et al. 2015).

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 (Frandsen et al. 2013). All these steps are devised with the participation of trades and general contractor in an iterative fashion, and decision are made collaboratively by communicating and exploring production systems alternatives (Frandsen et al. 2015).

2.6 Discussion about Location-based Planning Tools for Construction

When comparing the three methods for construction planning, all have a number of similarities: they aim for continuous workflow and for setting a unique production rate for activities in order to reduce the WIP. However, as visual tools, they have different graphical representation of construction activities (see Figure 2).

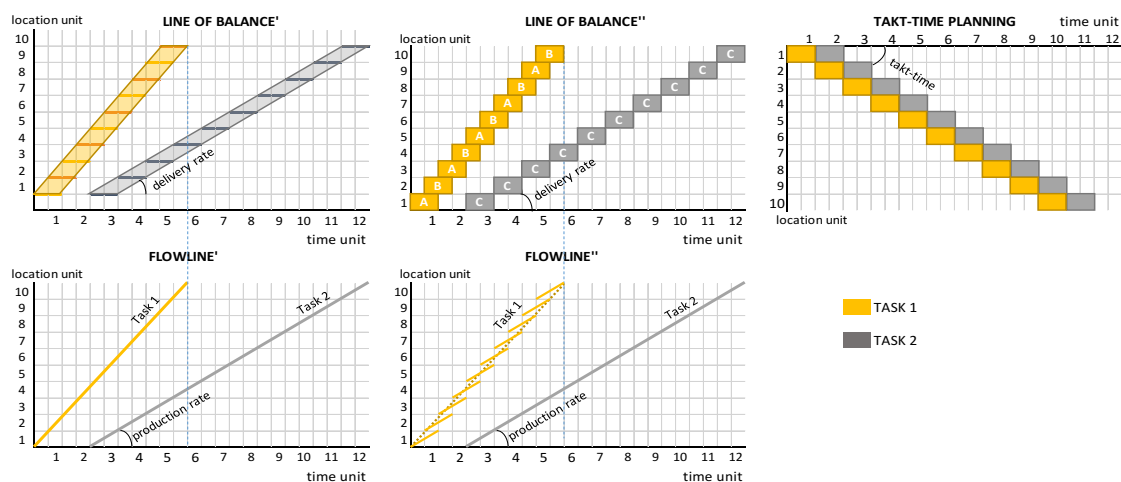


Figure 2: Different construction planning techniques based on location.

In the LOB method, workflow is visualized by dual parallel lines that represent an activity. The crews’ workflow became clear in the current LOB, by using boxes with the name of the crew. In turn the flowline represents an activity by a single line starting in the beginning of first day and finishing at the end of the last day.

In relation to the lines/boxes slope, Su and Lucko (2015) point out that the line of balance presents the delivery rate, whilst the flowline shows the production rate. The difference between them are: the delivery rate starts counting after the first unit completion, whilst the production rate starts counting from the beginning of activity execution (Su and Lucko 2015). In TTP, the boxes slope represents the takt-time, or customer demand rate, or phase demand rate when applied in the phase scheduling.

Buffers are used in different ways: the LOB uses time buffers between critical activities,

as well as the flowline. Further, the TTP incorporates buffers in the crew’s production capacity (i.e., the activity cycle time is shorter than the takt time) (Frandsen et al. 2015). Although Frandsen et al. (2015) expose that LOB uses buffers only between activities, Valente et al. (2014) used buffers inside the crew’s production capacity, yet, not balancing the workers operational time. A comparison is presented in Table 1.

Table 1: Comparison among the lean tools for construction planning.

	Line of Balance	Flowline	Takt-time Planning
Crews’ workflow visualization	Formerly: No Currently: Yes	Depends on the level of plan detail	Partial (crews can work in two locations at the same time, or executing work backlog)
Task visualization	Formerly: two parallel lines; Currently: boxes	One line	Boxes
Task duration per location	Location quantities divided by standard crew’s productivity	Location quantities divided by standard crew’s productivity	Equal to takt-time or shorter
Tasks representation	Formerly: Start and finish dates of first and last units; Currently: start and finish dates by unit	Start date of the first unit and finish date of the last unit	Start and finish dates per unit
Use of buffers	Buffers inside the work package duration; Buffers between critical activities	Buffers between activities	Buffers inside the work package duration: difference between takt-time and cycle time
Pace achievement (balancing the lines)	Adding or reducing the number of crews to execute an activity; Changing the crews’ composition and amount of service inside the work package	Changing the crews’ composition	Changing the crews’ composition and amount of services inside the work package; Distributing the workload among crew’s members; workable backlogs
Slope of line represents	Delivery pace	Production pace	Takt-time: available production time divided by demand
Level of detail of plan	Flexible	Flexible	High
Collaboration	Varies according to the level of plan	Varies according to the level of plan	Highly necessary

Project uncertainties also influence the way these methods are implemented. In low complexity projects, or in projects with known partnerships, the uncertainty is lower and the interdependencies are known. In this scenario, buffers between activities can be reduced, and TTP can be applied. However, in scenarios where the project has high uncertainty, it is recommended to protect the production from cascading delays, that could be avoided by allocating buffers between activities, such as the LOB and Flowline do it.

3 CONCLUSIONS

In this paper, the authors compared the lean construction activities to design a production system, and the mainly location-based tools to represent the work structured. It became clear that the WS is the design of construction processes which can be used by both PSD and PS. The level of detail of the WS varies according to the information availability whether the moment of decision making.

Comparing the three location-based methods, it was found that the line of balance and flowline are very similar tools, and both evolved in construction, becoming flexible to be applied in any level of uncertainty of work structuring. Both protect the production system against variability and delays through the allocation of buffers between activities. Both methods try to achieve the same production rate, however, without forcing it, as the Takt-time planning does. The latter is the most recent method applied in construction and it requires more work backlog in order to avoid the crews' idleness or demobilisation. Crews must work in the same pace or shorter than the takt-time. No buffers are allocated between activities, which increases the risk of cascading delays in projects with high level of uncertainty. It has been used in phase scheduling, and collaborative participation of contractors to develop it is necessary.

A final summary of these comparisons is presented in Figure 3, where the location-based tools are positioned according to their potential use in production system managerial activities. Differences among the tools were identified for lean construction practitioners to be able to choose the most suitable one according to the project context. The results will be used in an ongoing research about integrating the design and construction planning and control system in projects with overlap between these stages.

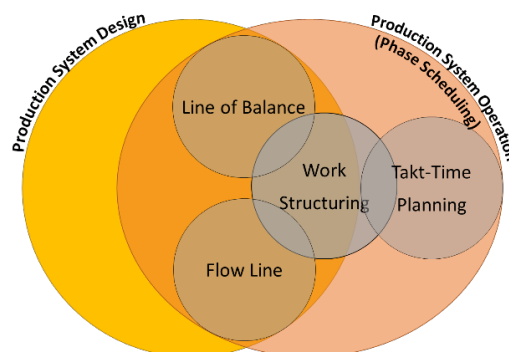


Figure 3: Position of lean tools in relation to planning activities in lean construction management.

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STANDARDIZED WORK: PRACTICAL EXAMPLES IN A BRAZILIAN CONSTRUCTION COMPANY

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Abstract: Standardized Work, Heijunka and Kaizen are the basis of the Toyota Production System (TPS) model and provide stability to its pillars. As many tools adapted to Lean Construction, the Standardized Work can also be applied in AEC Industry to increase productivity, reduce waste and define a standardized procedure for the activity.

Recently, the high variability in execution, cost and team member's productivity have caught the attention of the company's construction managers. There is also a high difference between workforce budgeted cost and actual cost, related to a lack of knowledge of the daily routine. The Standardized Work's goal is to identify the roots of these differences, reduce the variability of the main construction work packages, and know the work packages of the Last Planner. The purpose of this article is to present the results of these studies and the improvements identified, such as the increase of the productive time of the teams, the increase of productivity, the reduction of waste, and characterization and standardization of the activities.

This paper contributes to the understanding of Standardized Work and show the application on a construction site. In addition to showing the main results of each work package, the main goal is to exemplify the collection and tabulation of data.

Keywords: Lean construction, standardization, production, job-sequencing, continuous improvement.

1 INTRODUCTION

The Toyota Production System (TPS) was created in Japan between 1984 and 1975 to be a differential in the production of automobiles, offering greater products variety, greater quality, lower cost, and more efficient lead-time.

Standardized Work, Heijunka (continuous flow), and Kaizen (continuous improvement) compose the basis of the TPS system (Ohno, 1997). These three elements look for the complete elimination of waste and sustain the two pillars of the TPS model.

According to TPS, the Lean Philosophy has two pillars: Jidoka (autonomation) and Just-in-Time. The autonomation is the capability of the worker identify and correct abnormalities on the production line. In its basis, the Standardized Work establishes a standard to the execution of an activity and it allows the employee of the production line to have all the information needed to identify and eliminate possible anomalies. It also sustains the pillar Just-in-Time, offering stability to the process so the takt-time is regularly fulfilled (Ohno, 1997).

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The Standardized Work is frequently addressed by the manufacturing industry and it has been extensively researched over the years. However, this subject still has its deficiencies within the AEC Industry, mostly due the high variability within projects and work packages on a construction site. A few case studies from construction contractors were reported, such as Mariz et al (2012), Mariz and Picchi (2013), and Fernandes et al. (2015), however there are no significant results as in manufacturing industry.

It is important to emphasize that the Standardized Work tool is applied to a production cell looking forward to improve productive time and to eliminate waste in order to improve the whole process. Despite of focusing on one stage of the lead time, the Standardized Work should aim for the systematization of the set of production cells through the Value Stream Mapping (VSM) to ensure that one stage does not disturb the other.

To evaluate each work package's execution cycle and the team productivity, each task of the cell's production process is timed and classified by following the definitions established by Carvalho et al (2004):

- **Productive Time:** the tasks that add value when the activity execution occurs compose the Productive Time. For example, laying the tile adds value to the installation of porcelain or ceramic flooring, and laying the brick adds value to the execution of masonry wall.
- **Auxiliary Time:** it corresponds to the time spent with tasks that do not add value, but are inherent to the activity. These tasks comprehend the preparation to those that add value, thus they should be optimized. Usually, the Auxiliary Time corresponds to the preparation of materials and tools, organizing and cleaning the workplace, and assembling scaffolding, that is, the set up activities.
- **Non-Productive Time (NP Time):** it corresponds to the tasks that do not add value and that are not inherent to the activity execution, thus, it corresponds to waste and it should be reduced or eliminated. Usually, the Non-Productive Time corresponds to waiting for material, tools or project information, rework, displacement, and stops for any reason. The Non-Productive Time may correspond to 20-25% of the teams' working hours.

According to Freitas et al. (1994 cited in Carvalho et al., 2004), it is important that the teams have time to rest, such as snack and bathroom breaks, within the daily journey in order to guarantee the accuracy of what was proposed with what normally take place on site. As the construction workers have high workloads within their daily journey, the resting time tend to increase their productivity.

In conclusion, the main goal of this paper is to present the results of the application of the Standardized Work tool in three multifamily residential projects of a construction company located in Fortaleza, Brazil. The company aims to identify the adding value, auxiliary and non-adding value tasks from the main construction work packages and increase productivity by eliminating waste.

The secondary goals of this research are to establish a standard execution process to the main work packages of the Line of Balance (LOB), increase productivity by reducing wastes, improve work safety and workplace conditions, and update the company's planning and budgeting.

2 METHOD

The methodology applied in this research was adapted from the methodology proposed by Mariz and Picchi (2013), and it has five main steps:

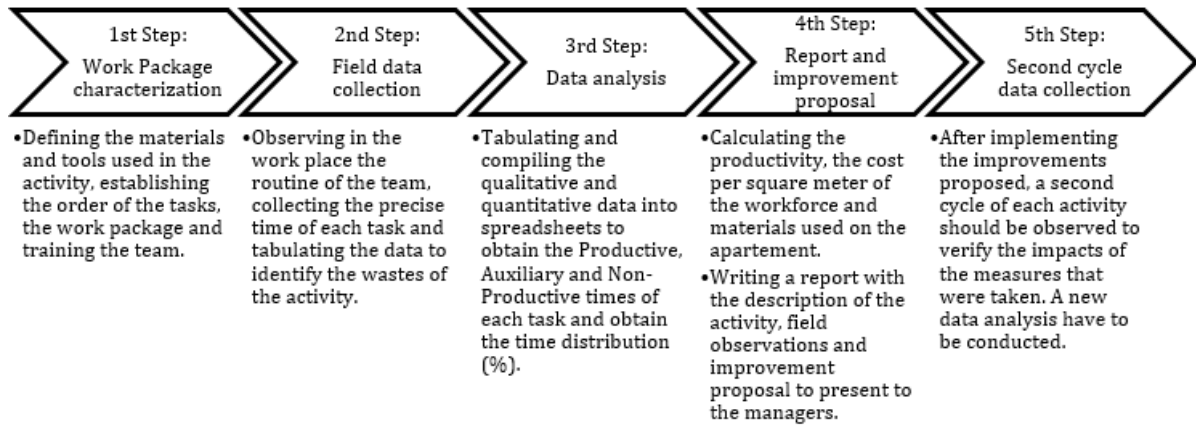


Figure 1: Research methodology

3 CASE STUDY

The proposed improvements are needed to increase productivity and quality, reduce costs and eliminate waste. These improvements may be creating routine cards (with daily goals), acquisition of new tools or features to improve quality, rethinking the inventory plan, retraining the team, etc.

The work packages analysed within this study were waterproofing with acrylic membrane, masonry walls, concrete subfloor (dry and wet areas), porcelain and ceramic floor tile, and gypsum block walls. The data gathering was conducted during the execution of the working packages within the apartments, due the repeatability of the activities.

3.1 The Company

The construction company is located in Fortaleza, Brazil, and it has more than 800,000 m² of constructed area of high standard residential buildings in different neighbourhoods in Fortaleza. The company was founded in 1977 and it started its lean journey in 2004.

Since 2004 it has been developing new tools and practices, and strengthening the relationship with Universities in order to fulfil the Lean Construction gaps and adapt the manufacturing industry tools to the construction sites.

The Standardized Work tool has been applied since 2014 in several construction work packages followed within the Line of Balance (long term planning). A peculiarity of the AEC Industry is that the 'factory' moves to a new site, while the product stays. Because of this characteristic, the study was conducted in three different construction sites of residential projects during distinct construction phases.

3.2 Case Study Development

According to the methodology explained previously, all work packages observed had the minimum information needed to begin the data collection. Which were the tasks sequencing well defined, materials and tools were available at the apartment (shielding

production), and the teams were previously trained to execute each activity. The work package was established in common sense between the teams and work supervisors. This is a very important step thus the improvements of the Standardized Work tool may only be applied if there is an initial standard to be improved.

Each activity was analysed individually through the timing of each cycle activity. The data collected was inserted on a spreadsheet (Table 2), adapted from Mariz and Picchi (2013). For being distinct work packages, the number of team workers may vary, but usually two professional workers (mason, bricklayer, carpenter, etc.) and one hodman (apprentice) compose a team. It is important to observe and collect data from all professional workers, knowing that, in an ideal situation, they should have 100% of their working hours spent with adding value activities. The hodmen (or non-professionals) were not analysed during this case study.

Table 2: Process Study Sheet adapted from Mariz and Picchi (2013)

Hour	Time interval	Executed activities	Comments	Place	Productive, Auxiliary or Non-Productive Time?
13:29:37	00:51,3	Layering brick	2° brick 3ª layer	AP 800	Productive
13:30:28	00:42,5	Stop	Talking	AP 800	Non-Productive
13:31:11	00:49,8	Layering brick	3° brick 3ª layer	AP 800	Productive
13:32:01	00:39,0	Layering brick	4° brick 3ª layer	AP 800	Productive
13:32:40	01:10,2	Stop	Looking for bob	AP 800	Non-Productive
13:33:50	00:14,7	Brick alignment	Verifying alignment	AP 800	Auxiliary

After data tabulation, the activity quantitative and qualitative analysis were conducted, evaluating the time distribution within the main tasks, the productivity, the materials and tools supply during the execution, the ergonomics and shielding production, the need to acquire new tools, and, finally, the activity cost analysis, determining the work and material cost per square meter.

The activities conducted by the work teams are evaluated accordingly to the time distribution of the tasks observed and characterized as Productive, Auxiliary or Non-Productive, as shown on Figure 2.

Time Distribution

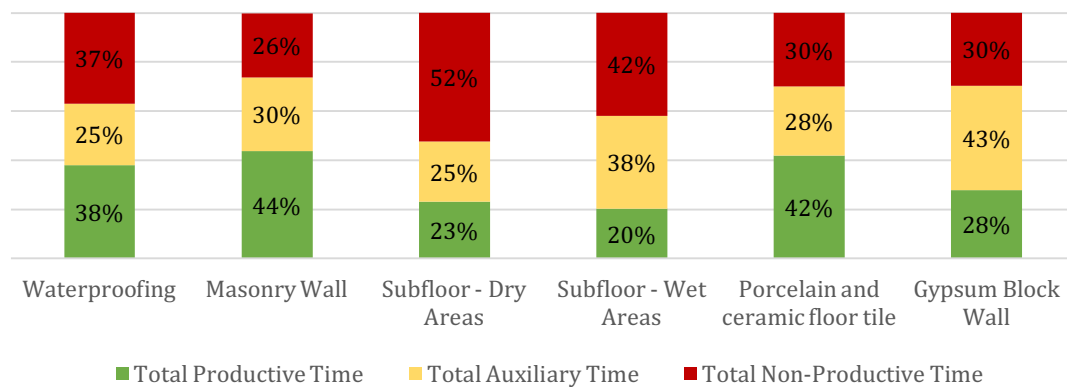


Figure 2: Productive, Auxiliary and Non-Productive time distribution (1st Cycle)

As some of the activities observed had a lead-time that could not be reduced, such as masonry (the lead-time need to be synchronized with the concrete structure rhythm of 8 days/floor due safety and construction process restrictions), the changes and improvement proposed had different goals for each activities.

For example, the improvement proposed to the masonry work package was to redirect the mortar distribution logistics to reduce the Non-Productive Time due waiting for material. Meanwhile, the improvement proposed to the gypsum block work package was to replace the hacksaw with a circular saw to improve the block cutting task and reduce the Auxiliary Time.

Thus, to these situations, the improvements proposed reduce the main wastes of Lean Construction such as displacement, rework, stocking and material waste. The inventory plan is evaluated to verify if it meets the team needs, if the material pallets are obstructing their passage or disturbing the normal activity execution.

One of the results of the Standardized Work is the Routine Card (Figure 3) that helps the team to control its daily tasks and the production rhythm, to program the Mortar Kanban request of each shift and the best sequencing of the activities through the apartment. In addition, the ergonomics of the tasks execution is analysed and it is observed if there are tools that may simplify the work and the sequencing of the activities.

The last step of the Standardized Work tool is the data collection of a second cycle, with the improvements implemented after the first analysis. This step allows evaluating quantitatively and qualitatively the response of the team about the improvements, in case of the application of the Routine Cards, Lean Construction tools training, time cycle reduction, Non-Productive activity elimination, etc.

Activity: Concrete Subfloor - wet areas				Activity: Concrete Subfloor - wet areas				Activity: Concrete Subfloor - wet areas			
DAY 1 – Mason 1				DAY 4 – Mason 1				Mortar Kanban Request			
Morning				Afternoon				*Check the need before requesting			
Schedule	Task	Local	Icon	Schedule	Task	Local	Icon	Day	Schedule	Icon	Type
07h30-07h45	To prepare material	-		12h30-14h00	To execute the concrete subfloor	Kitchen		Day 1	07:30		3
07h45-09h30	To execute the wallboard	Balcony		14h00-14h45	Cleaning and organization	-		Day 1	12:30		5*
09h30-09h45	Bathroom time	-		14h45-15h00	Bathroom time	-		Day 2	07:30		10
09h45-11h30	To execute the wallboard	Balcony 01		14h45-16h00	Supervisor checks the product	-		Day 2	12:30		9*
				16h00-17h15	To move to the next apartment	-		Day 3	07:30		9
								Day 3	12:30		5*
								Day 4	07:30		6
								Day 4	12:30		2*

Figure 3: Routine Card of the Concrete Subfloor - Wet Areas Task

As shown on Graphic 4, the Standardized Work intends to reduce Non-Productive time of the work package through the actions previously mentioned. During the first cycle of Porcelain and ceramic floor tile's team, it was observed that the team spent too much time with Non-Productive tasks, because the hodman waited the team run out of mortar and tiles before replenishing. In addition, the tile boxes were misplaced within the floor plan, thus the team needed to move them several time. After establishing the team daily routine, the Routine Cards were presented to the team and each member's responsibilities and tasks within the activity execution were clarified. During the second cycle it was observed that the Productive Time increased from 42% to 65% and the Non-Productive time reduced from 30% to 13%.

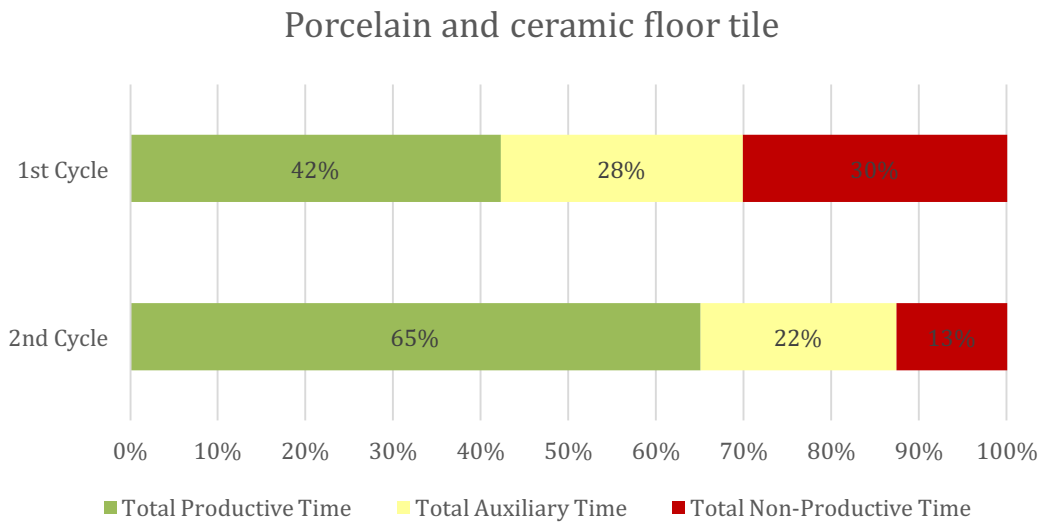


Figure 4: Comparison of time distribution for two observations of Porcelain and ceramic floor tile

After the data analysis, the Standardized Work report is presented to the Construction Site Management team in order to implement the improvements proposed.

4 RESULTS

The results of this case study can be summarized to the work packages characterization and the cost study to update the budget database. This type of record promote the continuous improvement for the next projects, once the Standardized Work Reports were compiled into a collection distributed to all Construction Sites Management Teams and to the Project Management Team (responsible for elaboration of each projects Line of Balance and Construction Budget).

The main results of the six activities mentioned previously were summarized on Table 3. It is important to notice that, the company's goals are keeping the Non-Productive Time within 20-25%, the Auxiliary Time within 15-20% and the Productive Time within 60%.

Table 3: Case Study Results (part 1)

Activity	Results	Indicators
Waterproofing with acrylic membrane (1 mason / 1 hodman)	It was observed that the workers did not have a proper place to store their tools, thus to reduce displacement, a toolbox was made. In addition, two small stools were built to improve their posture while executing some of the tasks. Finally, the team routine was established and registered on the Routine Cards.	NP Time: 24% 16,04m ² /day/person

Table 3: Case Study Results (part 2)

Activity	Results	Indicators
Masonry wall (2 mason / 1 hodman)	During the first cycle, it was observed that the team was not using the kanban for mortar properly, resulting in constant waiting for mortar, increased by the high demand for the rack lift for transportation of concrete. After a new training about the Kanban and rethinking materials flow within the construction site, the stops reduced from 25% (1st cycle) to 15% (2nd cycle). The productivity has increased 20% and there was a 25% difference between the workforce budgeted cost and real cost.	1st Cycle NP Time: 26% 11,84m ² /day/person 2nd Cycle NP Time: 20% 14,20m ² /day/person
Concrete Subfloor - dry areas (bedroom and living room). (2 mason / 1 hodman)	The stops, related to waiting for mortar, corresponded to 42% of the time for dry areas. The second cycle was not observed, but the improvements represented a 25% increase on productivity. The concrete subfloor for dry areas had a real cost 37% higher than the budget due a greater material consumption (the budget considered a subfloor thickness of 3 cm but the real thickness is at least 7 cm).	NP Time: 27% 30,19m ² /day/person
Concrete Subfloor - wet areas (bathroom, kitchen and balcony). (2 mason / 1 hodman)	The stops, related to waiting for mortar, corresponded to 52% of the time for wet areas. A Routine Card determining when to place the kanban for mortar and the volume of mortar needed was delivered to the team. The second cycle was not observed, but the improvements represented a 10% increase on productivity on wet areas	NP Time: 45% 15,82m ² /day/person
Gypsum Block Wall (1 mason)	The second cycle was not observed, but the improvements proposed will be applied on the next project. It was noticed that the workforce budgeted cost is 40% higher than the real cost, while material cost show no important difference. The Routine Cards for the next project predict a 25% decrease on Non-Productive Time (from 28% to 21%) and an increase of the Productive Time from 27% to 42%, by reducing stops and displacement. The productivity is expected to increase 15%.	NP Time: 28% 25,80m ² /day/person

5 RESEARCH FINDINGS AND CONCLUSION

The Standardized Work Tool has been one of the main Lean Construction Initiatives within the company activities since 2014. The activities evaluated have achieved expressive results, both within a quantitative level as well as within a qualitative level.

The main benefits were reducing Non-Productive and Auxiliary Times, increasing productivity and reviewing the company's budget database, readdressing teams to tasks

that suited their characteristics, improving the work place safety and quality, and giving the team the opportunity to participate on the improvement proposal, creating value for the internal customer.

It was observed that the team productivities have increased within 15-20% through elimination of Non-Productive activities and reduction of time spent on Auxiliary activities. In addition, the creation of a job sequencing through Routine Cards reduced the work variability and improved its productivity.

The Standardized Work results also showed that the team sizing methodology should be reviewed in order to reduce the idle work force, as well as the man work cost budget methodology should be reevaluated.

The most important characteristic of the Standardized Work and job sequencing is that it can be continuously replicated in other activities and different construction types. In addition, all the results are compiled in a report, which is available to the company's and construction site's managers. Thus, the next steps within the company are updating the budgeting indexes with the real material and man work costs for each activity and replicating it to all work packages from the line of balance.

It is important to replicate the results and improvements proposed on the company's future residential or commercial projects and to feed continuously the Standardized Work's reports with the new collected data in order to establish a database consistent with the company's practices and construction techniques.

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LEAN EQUIPMENT INSTALLATION – POTENTIALS OF USING TAKT PLANNING

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One of the major OEMs (Original Equipment Manufacture – Car Manufacture) in the automotive industry has successfully implemented Takt planning in several of their plant construction projects. This has allowed them to do quicker handovers as well as the possibility to do partial handovers. The efficiency and transparency of this process can even be further improved when the installation of production equipment follows the same method, this enables the OEM to reduce the overall time required for the project delivery. This paper shows the advantages of using Takt Planning in the equipment installation phase. A case-study shows the first experience using Takt Planning and the existing connections to the building construction site. This paper is focused on Takt planning and highlights the potentials of lean equipment installation as well as showing the first results of an implemented real case.

Keywords: Takt Planning, Production System, Equipment installation, production, client.

1 INTRODUCTION

Takt Planning is a Lean Construction method which is used in construction projects for organizing the construction site. It is a takt time and takt area based method (Haghsheno 2016) for the realization phase of construction projects. In recent years, several papers have looked at Takt Planning in construction (Frandsen et al. 2013) (Frandsen et al. 2014) (Faloughi et al. 2015) (Frandsen & Tommelein 2016), nevertheless no work has looked into the use of this methodology for equipment installation. Takt Planning and Takt Control as a method within the research field of Lean Construction was successfully implemented in several plant constructions of a major OEM in the automotive sector. This car-manufacture started the Takt Planning approach within first construction projects by enabling and training construction companies.

The Results in these projects show a stable and continuous workflow on site led by the Takt time with high transparency of achieved goals. This more efficient way of building, and the possibility of planned partial handovers show the time potentials in the end of a construction project by using buffers. While there is no need to use these buffers by the general contractors, these time potentials could be used by the equipment installation of the production line.

After the successful and early handover to the equipment installation in this project, potentials in building the production line has been seen in using the same methodology for the installation of the equipment. In the third lighthouse project the company implements the three level model in Takt Planning and Takt Control (Dlouhy et al. 2016)

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with their general contractors (SE Partner) for the installation of the production line. These next step is part of the value chain for delivering the value of the customer. Detailed needs and dependencies are shown by using the same method.

So, the question of this research is: could the Takt planning approach for installation of equipment be used and what are the effects? Are the results and potentials like transparent time buffers verifiable in installation for equipment?

2 DEFINITIONS AND FOUNDATIONS

In the presented example, the method of Takt Planning and Takt Control (Haghsheno et al., 2016) is used in the system of the Three Level Model (Dlouhy et al., 2016). Haghsheno et al. (2016) describe a prophase before the Takt Planning called process analysis in which the project is structured and the sequence of trades is defined. In this phase, the customer has the biggest influence on the project and its outcome. Within this phase, the client defines the areas with high priority and the handover accordingly. Afterwards in the Takt Planning phase, the calculation of the Takt area depending on different performance factors of trades is done. The performance factors are based on each working step. The working steps are clustered to work packages and afterwards accumulated into waggon of the train. Also, the leveling of work packages is important for the efficiency of the system (Binninger et al., 2016). These theories are adapted to the needs of the equipment project team. Therefore, the terms and goals are different to major construction sites.

The Takt Control for equipment project team uses the same Takt Control boards as the construction team. This leads to more transparency and understanding between the different phases.

2.1 Definition of Lean Equipment

Why is Lean Equipment part of Lean Construction? Lean Construction is the adaption of the Lean Principles named by Womack, J. & Jones, D. (1996) to construction. They analyzed production processes of the Toyota Production System. But until now the building of production lines was not part of the methodic approach in production.

Construction processes are using different or modified methods to implement Lean principles like Last Planner System, Location Based Planning System or Takt Planning and Takt Control. In production, the product is flowing and value adding process by machines and workers are immobile. In construction, the products are immobile and the value adding process by machines and workers is flowing. Keitel (2008 p. 3) describes construction and equipment installation (plant construction) as a “transient single piece production”.

2.2 Different Types of Projects

- Greenfield Project - Building of a new “State of the Art” production line
- Brownfield Project – Building a new production line in an existing production environment.
- Blackfield Project – Building some parts of the production line in shut down time of production

2.3 Challenges in the normal Equipment Process

It is common in equipment installation to have more than one general contractor (SE-Partner). Three and more contractors are usual to bigger plant projects. The total number of subcontractors could be up to more than 150. These companies are normally not connected to each other nor are they aligning their time and work planning. Dependencies between each of them are given by interfaces in the production line and the amount of work. Space for transportation and storing is lacking.

- Transparency for solving interface problems by the team is impossible in single team scheduling.
- Bottlenecks in time and laydown areas or material are not seen before. Steering the workflow and controlling the quality of work is getting more complicated and harder day by day.
- Structured coordination between SE-Partners during the realization is very hard to align.

2.4 Status quo in the Installation Process

The equipment installation of highly automated production lines is, when regarding one robot, repetitive work. In a body shop, a robot station could be including two equal robots and infrastructure. In a production line, there are between 100 and 300 stations. That means 200 to 600 robots are part of the equipment installation.

Workers in the installation are well educated and specialized. The use and coordination of the rare experts and their knowledge is getting more important to save expensive labor hours and time in the construction process.

3 THE REAL CASE STUDY PROJECT

3.1 Research Method

The research method is focusing on a real case study. The implementation of the Takt Planning method was driven by the client. He and his Lean Construction team used the same method, strategy for implementation and training like they did for construction projects:

- Short introduction (1hour) to the SE-Partner by the Clients Project leader.
- First Workshop (2 days) with all SE-Partners, client project team, Lean Construction Experts. First day: Lean Simulation and teaching the three level model. Second day: Training Takt Control and Start Takt Planning for the project. Definition the interfaces between Construction and Equipment Team.
- First Takt Planning for every SE Partner (contractor) internally
- Link the 3 different schedules together in one master schedule.
- Align these schedules with all parties.
- Cycled adaption of the Takt schedule.

The potentials and results are in the stage of pre-realization planning. Therefore this research paper is based on the estimated and planned effects of applying the three-level method. The realization must be analyzed separately.

3.2 Project Description

The relevant car-manufacture made a very late decision to change the product line for one of their older well established production facilities. The change in product was severe, and especially in the Body-in-White (BIW – a special Body Shop) production facility the changes were massive. The BIW process is the first major step of three that makes up the manufacturing of a car. During this step steel, aluminum and in special cases carbon fiber are joined together to form the structure or skeleton of the car. Joining is done by automated robots. For this specific project a normal Brownfield project was not an option due to the short timeline as well as the complex changes required to the existing production lines.

A Greenfield project was decided for the new BIW production facility. The late project change decision caused the project to be immediately one year behind the reference schedule. A BIW project is comprised of two major phases, the design phase and the realization phase. Both phases require about 18 months for execution, spanning a total of three years. For the relevant project, only 24 months were left. Catch up during the design phase was done by a copy and paste method from a similar product line to speed up the process in the design phase. The problem area and the focus of this paper is the equipment installation phase.

The equipment installation phase for a BIW project consist of three major sub-phases. These sub-phases are the mechanical installation phase, the electrical installation phase and the commissioning phase.

- During the mechanical installation, sub-phase all production hardware is installed and mounted. The hardware includes robots, welding equipment, welding fixtures and material handling equipment. This sub-phase is scheduled to be 4 months long.
- During the electrical installation, sub-phase all production hardware and equipment are electrically installed by connecting all the relevant power and communication cables. This sub-phase is also scheduled to be 4 months long.
- The final sub-phase is commissioning. This sub-phase is considered the most important and most value-adding phase of the three sub-phase. During this time, all Programmable Logic Controllers (PLCs) and robots are programmed to autonomously operate the production facility. This sub-phase is scheduled to be 10 months long and is the least flexible phase in terms of optimization.

One chance to reduce the overall realization phase is to optimize the mechanical and electrical installation sub-phases, this is where lean equipment comes into consideration.

The BIW project was awarded to four different SE Partners, each responsible to complete a different section of BIW production facility, including both the design and realization phases. A SE Partner is a production line design and build company that assist OEMs with project realization. The work content was split as follows:

- SE Partner A was responsible for all the smaller strategic sub-assemblies,
- SE Partner B was responsible for the main lines that brings the sub-assemblies to the main car body,
- SE Partner C was responsible for all the material handling systems, and
- SE Partner D was responsible for the final line where hang-on-parts like doors are fitted.

The work content split caused several interfaces between the four SE Partners. This means that a SE Partner is not only dependent on himself, but they also depend on the working schedule and completion of each other.

In the equipment installation phase, there is normally not much attention given to interfaces between contractors. It is expected that the SE Partners will have casual interaction between each other and follow a relaxed installation approach method, working around the problems of each other. When the timeline is significantly reduced, like it is with this reference project, there is no chance to do this anymore.

The situation and the project face two major problems:

- Problem 1 was that there is currently no way to optimize the mechanical and electrical installation sub-phases significantly so that more time can be allocated for the commissioning sub-phase.
- Problem 2 was that there is no efficient method in BIW planning to synchronize the installation activities between the four SE Partners.

Assuming the results will be similar, it is predicted that the mechanical and electrical sub-phases can be significantly reduced as well as complexity for interfaces between the SE Partners decreased. The following part of the paper, document the Project preparation.

3.3 Case Study Result

The results shown in figure 1 and 2 are done in the first 3 steps of the implementation. So, every SE-Partner did the first Takt Planning for himself. Then the Takt schedules were connected and aligned. As figure 1 demonstrates, the Takt Planning was used in 5 steps:

1. List all activities and state their duration.
2. Divide layout into smaller workable sections.
3. Calculate the days per activity and area.
4. Divide activities into daily tasks and color code.
5. Populate timing plan with a Takt schedule.
6. Align the Takt schedule with all others SE-Partners (not in figure 1)



Figure 1: Steps 1 – 5 of Takt Planning in Lean Equipment Installation

But there are more soft advantages coming with this approach. The Takt schedule is a kind of communication interface to identify early collisions and bottlenecks between contractors. That enables a common understanding of the project's possibilities and challenges. While the Takt schedule is departed in short Takts, it is easy to track and control a lot of works. Therefore, shorter feedback loops give the possibility to react quicker. This collaboration has the chance to grow, with a higher level of communication and transparency.

4 DISCUSSION AND CONCLUSION

As mentioned in this paper, the results are estimated and planned and not yet realized. The equipment installation is still in process. The theoretical potentials should be proven in various projects. But the method shows equal potentials and gives the opportunity for time savings in installation projects like in this installation of a production line. The realized time saving needs to be quantified by the Takt Control of the project. This should be documented and analyzed to get specific data and KPIs for Takt Planning and Takt Control in equipment installation.

The discussion, if contracts for further projects include aspects and services for Takt Planning and Takt Control.

In fact, the method should be implemented in projects even earlier than the realization phase. Even in the planning phase, information and data out of Takt Planning could be very important.

The major results are equal to the potentials of Takt Planning in construction. The method is useable in a similar way in equipment installation. So, time buffers are verifiable in installation for equipment. For the clients value a transparent value stream from construction over equipment installation to the start of production shows a lot of potentials in reducing variances, reducing interphases, increasing flow and making transparent value adding decisions.

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A FRAMEWORK OF FIVE-STREAM PRODUCTION SYSTEM FOR MEGAPROJECTS

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Abstract: Construction projects, particularly megaprojects, tend to frequently fail in satisfying their budget, schedule, quality, and safety objectives. Two of the most notable systems that have been developed to enhance project performance are the Last Planner® System and Location-Based Management System. This paper builds on combining these two systems through proposing an integrative production system that can play a significant role in enhancing project performance, especially in the case of megaprojects. The proposed production system incorporates five cohesive streams: production planning, material flow, Built in Quality (BIQ)/Information flow, tracking flow, and safety flow. This paper discusses each of these five streams, at five different implementation levels throughout the project lifecycle, in the context of an ongoing successful megaproject. Finally, the paper concludes by listing four main success pillars that are needed for the proposed production system to flourish.

Keywords: Lean construction; Production system; Megaprojects; Case study; Integrated Lean Project Delivery® (ILPD)

1 INTRODUCTION

While the construction industry makes up a significant portion of the U.S. economy, it is fraught with waste and inefficiencies. Despite mounting technological developments, construction productivity has decreased by nearly 30% between 1964 and 2011, while non-farm industries have more than doubled their productivity over the same period (Hanna et al. 2016; Ibrahim 2016). Because of the declining productivity, around 45% of construction projects are not delivered on time (Hanna 2016). Such losses are even more visible in megaprojects. Recent studies have demonstrated that for megaprojects: 1) 98% experience cost overruns or delays, 2) the average cost increase is 80%, and 3) the average schedule slippage is 20 months (Changali et al. 2015). Such losses and failures have urged the development of new construction production systems that aim at eliminating the incorporated waste and maximizing the value of the construction process, most notably

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the Last Planner® System (Ballard 2000) and Location-Based Management System (Kenley et al. 2006). This paper builds on the combination of these two systems (Seppänen et al. 2010) through proposing an integrative production system, consisting of five cohesive streams. This production system is presented in the context of the Van Ness and Geary Campus (VNGC) Hospital project, located in San Francisco, California.

2 PROJECT CONTEXT

The VNGC hospital project is an ongoing megaproject that is being executed through an Integrated Lean Project Delivery® (ILPD) system that is supported by employing an Integrated Form of Agreement (IFOA) and profit sharing. The fundamentals of the employed project delivery system are further explained by Lichtig (2005). The project scope is building a LEED Silver, fifteen-floor hospital that will create 779,508 square feet of diagnostic, treatment, and inpatient bed space, as well as 210,290 square feet of parking space. Through this project, Sutter Health (the owner of the project) will provide 274 licensed patient beds and 435 parking spaces. The total budgeted cost of the project is \$2.03 billion, with a duration of 68 months, ending in the first quarter of 2019.

The superior performance of the proposed production system is illustrated through the notable performance of the VNGC Hospital project. At the time of writing this paper, the project has been on schedule with a cost performance index (earned labor hours per actual ones) of 1.25. Also, the project team has successfully increased its contingency budget, through savings, by 28.6% so far. Moreover, the project has been achieving remarkable safety performance; for example, its average worker compensation cost per labor hour has been \$0.06 per hour, as compared to an industry average of about \$1 per hour. Following is a holistic overview of the project's production system that has enabled such performance, as captured by numerous project-site visits and extensive interviews of the project team.

3 PROJECT PRODUCTION SYSTEM

An illustration of the production system, as applied in the VNGC Hospital Project, is depicted in Figure 1, showing its five streams in each of its five implementation stages.

The proposed production system is designed with the main objective of ensuring predictable and streamlined workflow for complex projects. To do so, the production system is structured into five cohesive streams, each of which is divided into five different implementation levels. This design is intended to promote whole-system thinking, emphasizing that all resources are tied to the same physical output. This is particularly important in the case of megaprojects, in which project participants usually tend to optimize components in isolation, thus hindering the whole project, if these components are not designed to cohesively work with one another. Following is a further explanation of each of the five streams, starting with the production planning stream.

3.1 Production Planning

The proposed production planning incorporates the Last Planner® system's stages, with the addition of the "production strategy" stage that corresponds to the "review and optimize" implementation level. Further explanations of the five implementation levels of production planning are presented in the succeeding paragraphs.

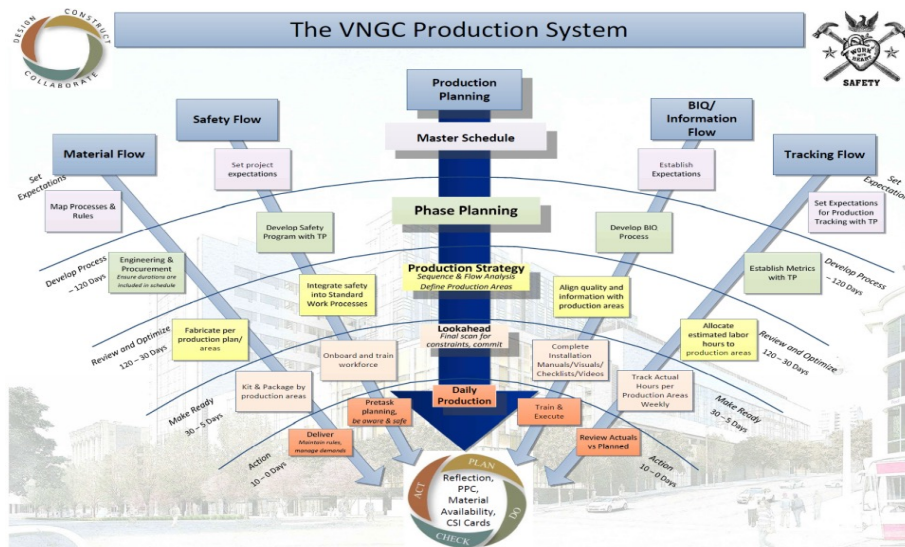


Figure 1: The proposed production system as applied in the VNGC Hospital Project

3.1.1 Master Schedule

In the first implementation level, entitled "set expectations," the production planning process is implemented by developing a master schedule incorporating the main project milestones. At this level, the main goal is identifying the goals that satisfy the client's expectations, and reflecting these goals in the project's master schedule. It is critical at this stage to integrate all the relevant estimator's information, since project leaders need such information to comprehend how project drivers and constraints affect planning. Therefore, during this stage, the project team should consider the provided project documents, performance goals, conditions affecting methods and sequence, interface with existing occupancy, special equipment and resources, initial approvals, and long-lead items. The project team should use its relevant experience and refer to comparable project phasing and durations as a guide while reflecting the project goals in the project's master schedule.

3.1.2 Phase Planning

In the second implementation level entitled "develop process," the production planning process is implemented by developing phase planning. The goal of this stage is to establish the project phases and their milestones, while making them visible through handoffs. This goal is achieved by performing five steps. First, the project team coordinates to establish major phases of work while focusing on design and construction phases, agency reviews, long lead items, and system turnovers. During this step, the project team works together in making the relationships of required work between trade partners visible. Second, the project team cooperates in identifying milestones for each phase as well as the conditions of satisfying them. Third, the project team works together in recognizing the work streams (activities by discipline or system) within the developed phases. Fourth, the project team collaborates in highlighting the expected outcomes for segments of works. Fifth, the project team checks and verifies the practicality of the phase planning efforts. Throughout phase planning, it is critical to implement a pull technique, actively engage key trades, and make sure that project superintendents validate the phase plan.

3.1.3 Production Strategy

In the third implementation level entitled "review and optimize," the production planning process is implemented by developing a production strategy. The main goals of this stage

are implementing sequence and flow analyses, defining production areas, and designing production using takt-time principles to achieve stable and predictable construction workflow. These goals are achieved by performing four steps. First, for each phase, the project team investigates different production strategy alternatives, and concludes by choosing a preferred strategy. Second, in accordance to the selected production strategy, the project team works on defining general work sequence (in terms of different disciplines). Third, the project team works on clearly defining production areas, so that these areas have almost similar scope. Fourth, the project team implements takt-time planning so that all trades can move through the project at the beat of the same drum. In the VNGC hospital project, at the time of writing this paper, there were 36 work-teams moving through 110 defined production areas at nearly the same rhythm.

3.1.4 Lookahead

In the fourth implementation level entitled "make ready," the production planning process is implemented through performing lookahead. To ensure that the planned work is ready to be executed, all constraints are reported and the team works together on solving them. To do so, different team members commit to being the champions of solving specified constraints, and the status of each constraint is regularly reported to the whole project team. For successful application, the project team must lookahead far enough to prevent production interruption, while making the whole process visual and collaborative.

3.1.5 Daily Production

In the fifth implementation level entitled "action," the production planning process is implemented through planning and controlling daily production. This stage incorporates two steps. The first step is daily huddling to quickly and effectively adjust for variances. This step is critical as it fosters a collaborative culture onsite while effectively ensuring that all the tasks for that day are constraint free, and that each task is a reliable commitment. The second step is swarming to solve any unforeseen constraint. This step is vital to keeping the plan reliable. At the end of each day, the team records the completion of daily activities, thus enabling the calculation of percent-plan-complete (PPC) to verify the reliability of the plan. In the case of incompleteness, the area superintendents and the related trade partners' general foremen apply a five-why-process to pinpoint the root causes, and implement actions to prevent future incompleteness.

3.2 Material Flow

To achieve predictable and streamlined workflow, the entire supply chain must be aligned with the production flow on site. In megaprojects, this task is extra challenging. The material flow stream of the proposed production plan is designed to resolve this challenge.

3.2.1 Setting Expectations and Rules

In this implementation level, the project team works on aligning the material flow to the production plan through linking deliveries to important milestones. Also, during this stage, the project team starts selecting vendors that align with the set expectations, and involving them in the process. Together, the team works on exploring how to optimize the use of pre-fabrication, as well as establishing a visible supply chain monitoring system that can easily reveal variances to plan. It is critical, at this stage, that the team does not jump into detailed planning until expectations are defined and aligned.

3.2.2 Engineering and Procurement

In the second implementation level, the project team focuses on sequencing and prioritizing engineering efforts in the order of fabrication and assembly. The main objective of this stage is empowering engineering to release complete and accurate information to fabrication, as well as optimizing prefabrication and component utilization.

3.2.3 Fabrication per Production Areas

In this stage, the project team aligns the fabrication sequence with the order of field installation/demand. The time buffer between fabrication and installation is sized to both minimize storage and reduce material shortage. Also, in this stage, the project team aims at achieving fabrication in a controlled environment to the largest extent possible.

3.2.4 Kitting and Packaging by Production Areas

In this stage, all materials are kitted and clearly labelled to match production areas. To complement the kitting and packaging of materials, any specialized tools, as needed, should be included. It is important to kit materials and deliver them on wheels to minimize dunnage and transportation waste.

3.2.5 Delivering, Maintaining Rules, and Managing Demands

In this stage, materials are delivered in the order of installation. All deliveries should be coordinated and recorded, and any unscheduled deliveries should be sent away if they have the potential of disrupting any planned deliveries. During this stage the team should work on eliminating waiting time and double handling.

3.3 BIQ/Information Flow

Another important aspect of achieving and maintaining predictable and streamlined workflow is having the right information available for the right people at the right time to enable building-in-quality from the first time. Following is a further explanation of the five implementation levels of BIQ/information flow.

3.3.1 Establishing Expectations

In this stage, the project team identifies the customers' quality expectations, and converts them to requirements. Also, the team identifies the related trade partners' superintendents, Quality Assurance/Quality Control (QA/QC) manager(s), and Project Managers (PMs), as well as special inspector(s), if applicable, and empowers them throughout the process.

3.3.2 Developing BIQ Process

After identifying the quality expectations as well as the key people, the team collaborates in developing a standard process that consistently produces work based on the identified customers' expectations and the countermeasures that can prevent past failures, as well as the approved drawings, specifications, and Testing, Inspection and Observation (TIO) requirements (if applicable). The objective of this step is to clearly map the trade process after capturing all the steps, lessons learned, and best practices to complete each step safely and successfully. During this stage, it is critical to interact and establish relationships with trade field-leads.

3.3.3 Aligning Quality and Information with Production Areas

During this stage, the construction team is provided with approved documents and field checklists that helps assure conformance to expectations, as per each production area. Then, the construction team reviews the scope, as well as the related process map and the

quality considerations identified for each step, and validates that the Inspection Request (IR) batches align with installation. Also, during this stage, the team works on eliminating any duplication while still meeting inspection requirements.

3.3.4 Completing Installation Manuals/Visuals/Checklists/Videos

During this stage, the construction team tests the developed BIQ plan, pre-inspection checklists, and implement improvements. If applicable, the team, additionally, finishes and distributes First Run Study (FRS) documentations. The objective of this stage is finalizing the confirmation that the deigned process aligns with the approved information.

3.3.5 Training and Executing

During this stage, the production team ensures that all field-workers have all necessary information developed in the implemented BIQ program, and are using the pre-inspection checklists as intended. During this stage, active interaction (e.g. weekly check-ins) with trade field-leads is essential to capture any variances to plan, and to make sure that appropriate learnings are shared and adjustments are made instantly.

3.4 Tracking Flow

Tracking performance is essential for achieving project success. Since the construction industry is labor-intensive, labor performance tracking is vital to ensure a smooth workflow, as well as to identify and reduce risks. In megaprojects, this task is extra challenging. The tracking flow stream of the proposed production plan is designed to resolve this challenge as illustrated in the following paragraphs.

3.4.1 Setting Expectations for Production Tracking with Trade Partners

In this stage, the project team defines expectations and set goals regarding production tracking. It is essential to engage all trade partners in this collaboration to clearly define expectations and incorporated assumptions, and to attain commitment from key members. For example, in the VNGC hospital project, this stage concluded that the team will track the project the way it will be built. In this sense, the team has committed that with the completion of each production area, the team will follow a defined assessment process to evaluate how this production area was completed, and asses the overall performance trend.

3.4.2 Establishing Metrics with Trade Partners

After setting the expectations for production tracking, the production team collaborates with each trade partner to establish clearly defined metrics. Overall, these metrics should be sufficient to evaluate the performance of on-site field labor, off-site fabrication labor, non-direct labor, trade specific productivity, and material tracking.

3.4.3 Allocating Estimated Labor Hours to Production Areas

In this stage, field leadership of the trade partners collaborate with the production team in allocating the estimated labor hours to the defined production areas. Together, they report these numbers using visual area maps.

3.4.4 Tracking Actual Hours per Production Area

In this stage, the field leadership of the trade partners collaborate with the production team in tracking the actual labor hours for each active production area.

3.4.5 Reviewing Actuals vs Planned

Having both the estimated labor hours as well as the actual ones for each discipline within the active production areas, the project superintendents and PMs collaborate with the

production team in assessing the achieved performance by comparing the actuals vs the planned. If this process reveals any insufficient performance, together the area superintendents and the trade partners' general foremen apply a five-why-process to pinpoint the root cause(s), and implement actions to prevent future failures. On the other hand, the main factors that have enabled remarkable performance are recorded as lessons learned to be shared throughout the project.

3.5 Safety Flow

In the proposed integrative project production system, safety is an equally vital aspect and is carefully incorporated in every step of production. Unfortunately, megaprojects often experience numerous safety incidents. Following is an explanation of the five implementation levels of the safety flow stream that is designed to face this challenge.

3.5.1 Setting Project Expectations

In this stage, the project team collaborates to form a dedicated safety core group. This safety core group collaborates with the project directors and trade partners' PMs to define measurable safety goals (such as lost time incident rate, total incident rate, and recordable rate, among others), as well as the targeted safety-related behavior and overall culture.

3.5.2 Developing Safety Program with Trade Partners

During this implementation level, the safety core group collaborates with the project's superintendents, foremen, and safety managers in four main tasks. First, the development and implementation of safety into the design phase. Second, the development and implementation of loss time prevention policies. Third, the development and implementation of procedures ensuring compliance with applicable rules and regulations of all federal, state, and local agencies. Fourth, the development and implementation of phase-specific safety enhancements.

3.5.3 Integrating Safety into Standard Work Processes

During this implementation level, all project superintendents work on integrating safety into standard work processes. In the VNGC hospital project, this is achieved through four avenues. The first is preconstruction meetings, in which superintendents identify safety concerns during production planning. The second is weekly (every Monday) site safety boost assembly, in which superintendents share with all the workers the relevant information about the identified hazardous activities occurring this week, and how to execute them safely. The third is weekly coordination meetings (every Friday) in which superintendents work on identifying safety concerns for the following week. The fourth is daily huddles, in which superintendents review daily safety issues with trade field-leads.

3.5.4 Onboarding and Training Workforce

During this implementation level, project superintendents and foremen work together on three main tasks. First, ensuring that all field staff are given basic and site-specific trainings. Second, making sure that all workers are aware of current hazards in the field and know where to go for additional information and help. Third, confirming that all staff have proper Personal Protective Equipment (PPE), and know how to use it. Additionally, it is critical to involve and fully engage new hires in the established safety culture. For example, in the VNGC hospital project, new hires are required to watch a short video about the project in which project workers, managers and executives welcome them while promoting the project culture, specifically safety culture.

3.5.5 Pre-task Planning

In this stage, everyone on the project must be actively using the developed safety-related resources. For example, in the VNGC hospital project, all field workers fill in safety-related information in the Pre-task Handbook to review activity-based safety protocols, and use Continuous Safety Improvement (CSI) Cards to recognize additional safety-related issues.

4 CONCLUSION AND RECOMMENDATIONS

This paper proposes an integrative production system for megaprojects. This production system consists of five cohesive streams, each of which has been explained throughout the paper in the context of the ongoing construction work of the VNGC hospital. It is vital to note that many success-pillars must be established for the proposed production system to flourish. The four most important pillars, as referred by the VNGC hospital project team, are: a truly collaborative culture that is based on respect for people and aligned interests, a people-empowering culture that fosters care and innovation, a continuous improvement culture that targets perfection, and colocation that promotes a collaborative problem solving culture. To promote these success pillars, the VNGC hospital project is being executed through an ILPD® system that is supported by employing IFOA and profit sharing. Moreover, to advance the success potential of the proposed production system, the VNGC hospital project has been implementing Building Information Modeling (BIM), not as a sixth stream, but as a tool of the production system that further enhances its performance and cohesiveness. It is important, however, to note that implementing such rigorous production system can result in making the project increasingly intolerant for variances and changes. This is a potential growth area for the proposed production system that should be addressed by future research efforts.

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SIMULATION OF PRODUCTION LINE IMPROVEMENT IN MODULAR HOME MANUFACTURING

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Abstract: The production of modular homes is highly variable, where the production time for a single home can vary significantly. Because there is a large amount of variation and customization in the home models built, operation time on the production line varies greatly, and considerable effort is needed for production line flow balancing. Simulation not only allows the manufacturer to identify areas of potential improvement on the line, but also helps to measure the likely success of proposed changes before investment in or implementation of these changes. In this paper, a case study is presented which uses simulation to evaluate the current-state performance of a wall panel production line, and to validate several proposed changes in terms of whether or not they will be effective and should be implemented.

Keywords: Production line performance, Simulation, Lean, Modular home manufacturing.

1 INTRODUCTION

Modular home construction plays a unique role in today's construction industry due to the associated potential for continuous improvement with respect to product innovation, quality, and efficiency (Moghadam et al., 2012). Modular manufacturers are continuously seeking ways to enhance their operations through the application of Lean manufacturing techniques; research and development (R&D) teams bring out new ideas to challenge the current practice. Testing and implementation plays a key role in establishing a culture of acceptance of new ideas and ensuring a successful Lean manufacturing transformation journey. However, the unknowns of any proposed methodology constitute a barrier to implementation because of the extra cost of the test run, as well as the potential for failure of newly adopted work procedures after a large capital investment. In this regard, simulation has proven to be effective in filling the gap between R&D and production line operation during the improvement process.

This paper investigates the use of simulation to model a wall panel fabrication line in a modular home manufacturing facility in order to assist management in identifying potential areas of improvement as well as to provide strategies for implementation of the proposed changes. A future-state simulation model is presented which can generate a preliminary validation report on the feasibility of the proposed methodology.

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2 LITERATURE REVIEW

The potential for the use of simulation in modular home production lines has been recognized and tested in other studies. Shafai (2012) notes the importance of avoiding overproduction, where using a pull system, establishing continuous flow, and eliminating waste are recognized as some of the salient Lean concepts to be leveraged. Because of the variability in the design and requirements for each house, relying on average task times for activities with high amounts of variation is found to be inaccurate, and instead the use of statistical analysis to develop a distribution for each task time is recommended. For highly variable tasks, Shafai (2012) notes that design properties influence the task duration. For walls, design properties may include the number of window and door openings, the length, and the number of studs. Regression analysis is typically applied to determine the statistically relevant design properties, and to find regression models for highly variable activities.

Moghadam (2014) also applies simulation to their study of modular construction manufacturing process improvement. They use simulation to evaluate the labour required in a modular construction manufacturing facility to meet a range of different takt time goals. Labour resources are categorized based on whether they have been cross-trained to work at different workstations or are only qualified to work at a certain workstation. In the research presented in this paper, while simulation is used to evaluate labour in relation to takt time, it is also used to evaluate semi-automated machinery.

Yu et al. (2013) assert that the first step in creating standardized work is to determine the takt time, which will set the pace for the production of the entire line. The takt time is the maximum time spent at one station, and can be calculated as the time available divided by the demand. They also note that the time required for a single task can vary drastically, pointing out that the use of a labour resource pool could help to decrease this variability.

The use of simulation for manufacturing as a general industry is also supported by McLean and Leong (2001), who support the position that while currently underutilized, simulation in manufacturing can help to decrease start-to-finish production time and increase the quality of the products produced. They mention that costs, time, and skill of employees are some of the reasons that simulation may not be currently used in these environments.

3 METHODOLOGY

In order to build a reliable and effective simulation model, site observation and time study are essential. Therefore, a study of the current work sequence is first carried out. Understanding the procedure is crucial for ensuring the accuracy of the data collection and evaluation. The level of accuracy of the data can vary based on the type of task being studied. It is thus important to design the data collection process based on the purpose of the output. In this case, the method used to understand the problem and the current state of production is to interview an expert on the given company's operations.

Next, the simulation model is built based on the collected information. The building of the current-state simulation model involves defining the targeted area for the simulation; constructing the simulation model; analyzing the model and its output; and determining potential areas of process improvement. The Cyclone template in Symphony is used to create the simulation model representing the current state, and then to apply any proposed changes in order to quantify the effects with respect to several different

metrics of the wall line's success, such as productivity and labour utilization. Symphony, developed at the University of Alberta, is "an integrated environment for building special purpose simulation tools for modelling construction systems" (AbouRizk and Mohamed, 2001). Cyclone is a general purpose template provided in Symphony that is especially useful for modelling continuous or cyclical events. The discrete modelling function in Symphony is used in this study to model the production line. Finally, the proposed improvements are tested by changing the simulation model accordingly and using the results to quantify the effects of the change.

4 CASE STUDY

4.1 Data Collection

Two different types of modular homes are constructed in the case facility—mini homes and modular homes—each of which has a range of sizes and many custom options that can be applied. Each mini home is a self-contained module, while the modular homes each consist of two modules that are later attached to one another on site.

In this case, it is assumed that data collection based on expert opinions will be accurate enough to determine the expected improvements based on the identified case changes. A person familiar with the plant activities is surveyed in order to determine a lower bound, upper bound, and most likely duration for the various activities as well as the current plant output for use in constructing and verifying the model. Because of this data collection strategy, triangular distributions are used in constructing the model. Using this data, the under-utilized wall production line is studied in detail through the use of simulation in order to test different proposed improvements and identify their effectiveness in increasing the production to a target of walls for four houses produced per day. Simulation allows the effects of any changes to the wall production line to be tested and analysed without disrupting the line or investing in costly equipment.

4.2 Current State Simulation Model

4.2.1 Side Lumber Construction Station

The side lumber station is one of the first stations on the line and is where the construction of the side lumber, referred to as the top and bottom plates, is done. This step involves attaching 16 ft lengths of lumber to reach the total desired length of the module. The assembly of these lumber pieces needs to be completed upstream of the construction of the framed exterior wall.

4.2.2 Openings Construction Station

This station is where the wall openings for doors and windows are constructed for the exterior wall panels. The number of openings per wall and the type and size of openings will vary based on the home type and the customer's preferences. The time required to construct each opening is based on the type of opening, (e.g., door, or small, medium, or large window). Triangular distributions are used to predict the durations. As is the case for the top and bottom sills, the construction of the openings will need to be completed before the construction of the exterior wall panel can be done.

4.2.3 Exterior Wall Panel Construction Station

Once the required openings and the top and bottom sill for the exterior wall panel have been constructed, the panel can be put together. This process involves installing studs

and the components for the openings. The simulation model will calculate how many studs and opening components are required and use these characteristics to calculate the time required to construct the wall. The fastening of the studs to the top and bottom plates is assumed to have a constant time but the total construction time for the wall will vary based on how many studs and opening components are in the wall.

4.2.4 Interior Wall Framing Station

The interior wall framing is carried out in the same manner as for the exterior walls, but they are usually significantly smaller. The time required for fabrication of each interior wall is calculated as the time required to attach each stud to the top and bottom plates, multiplied by the number of studs required for each wall. The number and size of interior walls will be determined by the model and size of the home, and will vary based on the customer's order.

4.2.5 Non-Conventional Interior Wall Framing Station

Irregularly shaped interior walls are included only in modular home models and include walls with curves, half-walls, or other shapes that cannot be produced at the same rate as regular interior walls. Therefore, the time required to construct these panels is highly variable. A triangular distribution is thus used to predict the time needed for the construction of each non-conventional wall.

4.2.6 Poly and Drywall Installation on Exterior Walls Station

At this station, the poly for the exterior walls is installed and, if time permits, some drywall is installed as well. As a general rule, it is assumed that drywall will only be installed until the other two parallel stations (the special shape wall construction and the interior wall framing) have completed their work for the given unit being produced, so that the wall erection will not be delayed.

4.2.7 Labour Assignment

There are 7 workers assigned to the wall manufacturing line. The current-state labour requirement of each station can be seen in Table 4-1. As can be seen, the sum of the labour requirements is greater than the amount of workers. This is because not all the stations are fully utilized, so workers can be shared between stations.

Table 4-1: Labour resources per station in the current state

Station	Number of labour resources	Station	Number of labour resources
Side Lumbers	1	Exterior Wall Panel Framing	2
Openings	1	Special Shape Interior Walls	1
Interior Wall Framing	2	Exterior Wall Drywall and Poly	2

4.3 Simulation Model

The current-state model representing the construction setup described is constructed, and its reliability tested by comparing the outputs from the model to the actual measurements obtained from the plant operating with the modelled layout. The current-

state model also provides the basis for comparing changes in the future-state models to see how different proposed improvements will affect the entire wall production line.

The current-state model is run for one year and, since it is a stochastic model, multiple runs are used (500 runs). The main model creates the house orders at an inter-arrival rate of 5, and with 50 house orders per month. Each house is then defined as either a mini or modular model. The other characteristics, summarized in Table 4-2, are then set. The layout of the main part of the simulation model can be seen in Figure 4-1.

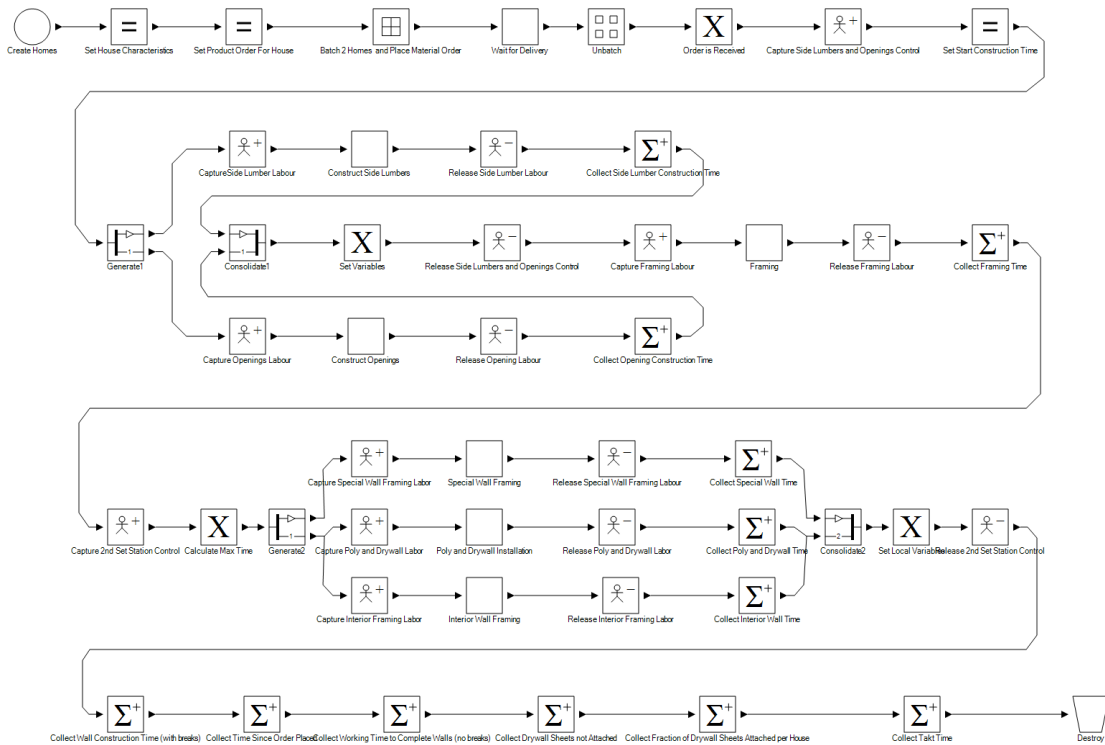


Figure 4-1: Current-state wall panel simulation model

Table 4-2: Variables used in the simulation model

Characteristic Variables	Time Variables
length of the home	time to construct side lumbers
number of doors	time to construct openings
no. of windows (small, medium, and large)	time to complete exterior wall framing
type of home	time to construct special walls
wall height	time to install poly and some drywall

Each station is simulated so that the required labour is reserved during the time for the task, and released when done. The duration of the task is then calculated depending on the distributions and assumptions in relation to the characteristics of the house, as described above. Priorities are assigned for the labour based on which tasks are most important, as determined through consultation with experts at the plant. The current-

state simulation results are presented in comparison with the future-state simulation model in the following section.

4.4 Future-State Simulation Model

4.4.1 Labour Change

To decrease the task times of the exterior wall framing and opening component construction stations, the first change to the simulation model is to add another labour resource to each of these stations in order to increase the rate at which work can be completed. The labour at the exterior wall framing station is increased to three workers, and the labour at the openings construction station is increased to two. It is assumed that the task time, not including setup time, will decrease in proportion to the increase in assigned labour resources, i.e., if the labour resources are doubled, the task time will be halved. The statistics from running the simulation model with the proposed labour assignment show that the takt time can be reduced from 3.975 hours to 2.941 hours. This improved takt time will allow the line to produce the walls for about 2.55 houses per day; however, the statistics also show that the exterior wall framing station still sets the takt time for the wall production line and, in order to further increase production, the task time needs to be further reduced. Table 4-3 summarizes this approach.

Table 4-3: Statistics from the labour change simulation model (six workers)

Statistic	Current State		Future State	
	Mean	Std.	Mean	Std.
Opening station construction time (hours)	2.537	0.030	1.267	0.015
Side lumber station construction time (hours)	0.218	0.006	0.218	0.006
Exterior wall framing station time (hours)	3.975	0.078	2.941	0.050
Special shape wall construction time (hours)	0.465	0.081	0.474	0.080
Interior wall framing station time (hours)	1.805	0.043	1.786	0.043
Exterior poly and drywall station time (hours)	1.807	0.044	1.811	0.042

4.4.2 Equipment Change

One option to further decrease the task time of the exterior wall framing station is to invest in semi-automated equipment. If the company were to invest in a semi-automated machine for the exterior wall panels, it is estimated based on the simulation results tabulated above that the time required to install each stud could be reduced from two minutes to thirty seconds, and that the labour requirement at this station could be reduced by one worker. The statistics found by running the simulation model with these changes show that the takt time can be reduced further to an average of 1.857 hours, which equates to four houses' walls produced per day, and would ensure that the plant can achieve the targeted average production. A summary of this approach can be found in Table 4-4.

Both of the two approaches are recommended to company management. Given that adding labour resources as a means to improving productivity is reactive and may not yield a desirable result, proactive solutions to eliminate non-value-added activities using

semi-automation are preferable. On this basis, efforts are also made to implement lean principles in order to upgrade existing processes.

Table 4-4: Statistics from the equipment change simulation model

Statistic	Current State		Future State	
	Mean	Std.	Mean	Std.
Opening station construction time (hours)	2.537	0.030	1.268	0.016
Side Lumber Station Construction time (hours)	0.218	0.006	0.217	0.006
Exterior wall framing station construction time (hours)	3.975	0.078	1.640	0.023
Special shape wall station construction time (hours)	0.465	0.081	0.469	0.080
Interior wall framing station time (hours)	1.805	0.043	1.796	0.045
Exterior poly and drywall station time (hours)	1.807	0.044	1.807	0.046
Takt time (hours)	3.975	0.078	1.857	0.043

4.5 Model Validation and Verification

This model is verified both subjectively by the authors, as well as through the independent validation and verification approach (IV&V), as described by Sargent (2007). Individual station times are checked by an independent party familiar with the operations at the manufacturing facility to ensure that they are both feasible and appropriate. Another form of validation applied involves checking the takt time against the expected value. The target takt time at the manufacturing facility for which the model is designed is currently about two homes per day. To meet this target the wall line needs to have a takt time of about three-and-a-half to four hours. As seen in Table 4-3 and Table 4-4 above, the takt time for the current state provided by the model is 3.975 hours. This check serves as verification that the model is producing approximately the same volume as the plant in actual practice.

5 CONCLUSIONS AND RECOMMENDATIONS

While some changes to production lines, such as labour reallocations, are easy to make and reversible if they do not produce the expected results, others, such as investing in large equipment or reducing overall labour resources, are not. Simulation allows these changes to be tested before they are made to determine their likely effect on the production line. For the labour change and semi-automated equipment scenarios investigated in this research, it can be seen that the production per day can be increased by 34% by changing the labour assignment and 79% by investing in semi-automated equipment for the exterior wall framing station. Since the production goal of the company is to produce the walls for four houses each day, this simulation allows them to see that adding labour to the production line will not achieve this goal. With this information, they can see that investing in equipment to aid in the production of the walls is a better alternative to reach their production goal. This information is important since a common solution in the industry is to add more workers in order to increase production, though this may not be the most effective solution.

The company has since invested in lasers to decrease the measuring time for locations of wall studs, which is an alternative method to decrease the stud installation time, as recommended by the research team and achieved through the application of semi-automated equipment in this simulation. This shows that the conclusions drawn through this work can be useful for decision support in practice.

An important consideration is that the takt time for modular homes is much longer than for mini homes. To arrive at a more reliable measurement that is less dependent on the type of home, each modular home order could instead be switched to an order for two “boxes”, which are closer to the size of one mini home, and the takt time goal and calculations could be based on the time per box and not per home. Also, as the data used in this simulation was based on expert opinion and since triangular distributions were used, the accuracy of the model could be improved if a detailed time study of the activities were to be carried out and if distributions were to be fitted to the sampled data.

In future research, analysis should be carried out to further balance the production line, such as tests to determine whether more value can be added to the walls at the stations with extremely short task times, in order to decrease the task times for downstream stations.

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COLLABORATIVE TAKT TIME PLANNING OF NON-REPETITIVE WORK

Iris D. Tommelein¹

Abstract: This paper describes an approach for takt time planning (TTP) that was developed and tested on a pilot project in California. A companion paper by other authors describes their approach for TTP that they applied in a different project type-, commercial-, and geographical context. The aim of these papers is to articulate TTP methods used so as to allow for comparison, refinement, and improvement.

The here-described approach was piloted on the gut-and-remodel of a small healthcare project. The owner chose to deliver this project using an Integrated Form of Agreement (IFOA) contract. Accordingly, the project team members working together as trade partners were driven to explore opportunities to use lean practices.

The researchers offered the IFOA team an action research opportunity to study together, not so much *if*-, but rather *how* takt time might be used to plan and execute their work because, at first glance, units of repetitive work were not obvious. The researchers embedded with the team developed a TTP approach on the basis of "work density" and then successfully used it on two project phases.

The contribution of this paper is that it presents a characterization and proposes a formalization of a method for collaborative TTP of non-repetitive work. This may inform the use of TTP on other projects, as well as serve as a basis for comparing and contrasting takt time- and other planning methods.

Keywords: Lean construction, collaborative planning, takt time planning (TTP), work structuring, work density, Last Planner System (LPS)

1 INTRODUCTION

Takt is increasingly being used to structure construction work and thus "shape" schedules of work anticipated and control of work being executed (e.g., Linnik et al. 2013). Use of takt imposes a rationale and methodological structure that aims to achieve continuous flow in the schedule. This is done by using capacity buffers and defining clearly delineated handoffs between trades, thus marking schedule control points that can help increase predictability in system performance.

This paper details a takt time planning (TTP) method for work structuring that was piloted on a project in the San Francisco Bay Area. A companion paper (Binninger et al. 2017) describes a takt planning method in use in Germany. In subsequent work, the authors of these papers will present a framework for characterization of takt planning methods, and illustrate its use in comparing their methods as described. Frandson et al. (2015) already compared TTP with Location Based Management (LBMS). Further comparison of these and other planning methods is warranted.

The word "Takt" or "Taktzeit" in German means "beat," the regularity with which something gets done. Since "Takt" in German, like "beat" in English, by definition pertains to time, saying "takt time" is redundant; this notwithstanding, the latter is commonly said.

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When takt is used in a lean context, it is interlinked with many other lean concepts, such as continuous flow, standardization, load leveling, predictability, etc. Takt refers to the heartbeat of assembly lines in the Toyota Production System. Once a beat is suited to each line and set (different lines each having their own beat), lines can move in sync with one another in a continuous flow process. Whether at Toyota, in new product development and manufacturing at large, or in construction, takt may be defined as: *the unit of time within which a unit of production must be produced (supply rate) in order to match the rate at which that product is needed by the customer (demand rate)* (after Hopp and Spearman 2011 p. 467-468). So-defined, takt is a design parameter that may be used in production in manufacturing, construction, or any other setting.

The approaches used in industry today and conceptualizations of the use of takt appear to vary. With this paper and ongoing study the author aims to create conceptual clarity and highlight distinctions between takt planning methods and the contexts in which they apply. This paper lays out methodological steps, based on the fundamental concept called “work density,” used to define takt in a production system’s design. These steps detail the method for collaborative TTP of non-repetitive work that the researchers developed and piloted while embedded with a team delivering a small project in California.

2 TTP ROOTED IN SPACE SCHEDULING

The author’s study of TTP is rooted in her research on “space scheduling” (Tommelein and Zouein 1993 p. 266) that stemmed from the observation that the resource “space” is omnipresent yet—paradoxically—often overlooked in construction management. Many of today’s construction management books still consider only 5 resources (i.e., time, money, manpower, machines, and materials) and overlook space. Yet, space is the 6th resource to be managed, not only in the process of layout planning (e.g., while locating temporary facilities such as material laydown yards and equipment) but also of scheduling. Line-of-Balance methods (LOB) (e.g., Lumsden 1968) to plan production of repetitive units, tend to treat space as a scalar (1D) variable and thereby abstract away significant complexity encountered when managing 2D or 3D space (e.g., Riley and Sanvido (1995) studied patterns of flow). With the advent of computer tools such as BIM, space has become more “visible” and easier to draw management attention to. Many software tools exist today to show in 3D and simulate in 4D how site space use in and around the facility being built evolves during construction (e.g., Navisworks, Synchro). TTP is a kind of space scheduling.

After describing the context of the pilot project, we present the rationale and methodological structure of the approach we used to shape this project’s construction space schedule on the basis of takt.

3 GEOGRAPHICAL AND PROJECT CONTEXT

We developed the here-described approach for collaborative TTP on a 700 m² (7,500 ft²) gut-and-remodel healthcare project. This project, located in the San Francisco Bay Area, was constructed over the course of about 12 months in 2012-2013 at a cost of about USD 3 million (Dunnebier et al. 2014). The owner, Sutter Health, chose to deliver this project using an Integrated Form of Agreement (IFOA) contract. Jointly with the owner, designer, and general contractor (GC), the IFOA project team comprised specialty contractors, several of which had previously worked together on other projects. Team members were thus driven to collaboratively explore opportunities for using lean practices.

The researchers, Iris Tommelein and graduate students—in early planning of the project Josh Mohayai and soon thereafter Adam Frandson—offered the IFOA team an action research opportunity to study together, not so much *if*, but rather *how* takt time might be used to plan and execute their work because, at first glance, units of repetitive work were not obvious. The researchers embedded with the team ended up developing an approach and successfully using it on two out of four project phases, namely above-ceiling work and in-wall work (Frandson and Tommelein 2014).

The project scope included demolishing the existing interior of about half a floor in the facility and then constructing a new interior. The work was planned in phases: (1) demolition, (2) framing and above-ceiling work, (3) in-wall work, and (4) finishes. All work had to be done while maintaining the structure as well as the live fire sprinkler system, and maintaining full operation of the remainder of the facility. This constrained site access, forced some work to be done at night, and restricted some day-time work (e.g., drilling to mount anchors in concrete floor slabs was permitted only at certain times so as to not disturb healthcare providers and patients during their business hours).

4 THEORETICAL FORMULATION

4.1 Takt Time in Manufacturing vs Takt Time in Construction

While in manufacturing, the assembly line for the product being built keeps moving and workers are more-or-less stationary (nevertheless moving with the line while performing their task), in construction, the product (facility) being constructed is stationary and workers move from one location to another to perform their task *in situ*.

The speed of the line and the corresponding rate of work at stations must be designed so that each worker at each station can complete what is assigned to them and still have some time left within the takt time given. Under ideal circumstances, each station's task will be reliably 100% done within the allotted takt. Of course, in a world subject to variation, one can never be 100% sure so when a deviation from the standard task occurs, the "time left" serves as a capacity buffer. This buffer ensures that each worker has some time remaining within their takt, in case they notice a condition that warrants pulling the andon for others to come to their assistance, and address the condition without having to stop the line. Determining the appropriate task to be done at each station and thus the capacity buffer is key to the production system's design, because when the "time left" is insufficient, workers must stop the line to manage the situation.

Translated from manufacturing to construction, TTP seeks to define spaces (we call these spaces that are tied to a takt time "zones") in a facility as it is being constructed so that each trade can get their work reliably done in each zone, according to their planned sequence of work, in an amount of time (takt) that is the same for all trades who need to work in that zone. Just like a line's takt will likely vary from other lines' in a single manufacturing plant according to the tasks performed at the various stations in each line, takt and the corresponding zones will likely vary from one phase of construction to another on the same project.

4.2 Takt Time Planning is a Work Structuring Method

Generally speaking, TTP is a work structuring method. Work structuring means breaking an entire project into smaller pieces (so-called "chunks") so that these pieces will be manageable. Ballard (1999), Ballard et al. (2001), and Tsao et al. (2004) defined work structuring as addressing the following questions:

1. In what units (chunks) will work be assigned to production units?
2. How will work chunks be sequenced?
3. How will work be released from one production unit to the next?
4. Will consecutive production units execute work in a continuous flow process or will their work be decoupled?
5. Where will decoupling buffers be needed and how should they be sized?
6. When will the different chunks of work be done?

Manageability of the pieces may be assessed based on the degree to which certain production system objectives are met. Structuring of work using TPP has as objectives:

1. Have trades work in a way they prefer.
2. Aim for constant crew sizes and continuous work flow (i.e., no work interruptions).
3. Avoid trade stacking (i.e., only 1 trade works in any 1 zone at any time).
4. Use timely on-takt handoffs.
5. Balance the whole while pushing for speed.

4.3 Finding Repetition in Non-Repetitive Work based on Work Density

Answers to the work structuring questions will affect the various production system parameters that act as throttles in the system. These parameters pertain to the product to be constructed and to the process (means and methods) used for construction, namely:

1. Components and characteristics of the product to be constructed, describing the work to be done as typically shown in plans and specifications, perhaps in a BIM.
2. Worker trade skills, informing what work can be done by an individual worker (e.g., a specific journeyman or apprentice) or crew that will be designated in the weekly work plan to complete an assignment.
3. Alternative breakdowns of the scope of work, e.g., by trade (boundaries of work between trades, based on union jurisdictions or other drivers) and sequence.
4. Alternative means and methods available to each trade to do their work.
5. The number of trade resources that can be assigned when using specific means and methods, and corresponding space and time needed to complete work.

The setting of these parameters defines chunks of work and how they will flow or not (e.g., when decoupling buffers are added). A chunk is work of a certain scope that will be performed by a crew of a certain configuration (number of crew members and their individual and combined skills), using certain means and methods. Aiming to meet the stated objectives, the goal pursued in TTP is to define chunks to be done in certain locations (zones), so that all chunks can be performed in the same amount of time (takt) and in a sequence that emulates continuous flow.

An ideal flow may present itself as a Parade of Trades (Tommelein et al. 1999) moving through space with one trade following the other in sequence, all marching to a drum beat, and—ideally—with no variability. However, it is unlikely that all construction work can be cast in such a mold. If it can be, then creating a TTP is relatively straightforward, but how to develop a TTP when work is not repetitive in that way? Linnik et al. (2013) broached this topic. The manufacturing analogy is to decide what work can be done on any one of several specific lines vs. done off-line (e.g., workable backlog in the Last Planner System). A related system design question is: At what speed should the line (Parade) progress? The speed needed to match the project requirements may not be achievable when one or

several bottleneck trades limit the pace for everyone. Adjustments to dependencies and sequencing of trades in the Parade and potential investments (e.g., alternative means and methods) then need to be considered to alleviate the bottleneck.

The approach we used is based on a mathematical concept, what Tommelein (in Dunnebler et al. 2014) called “work density” expressed in unit of time per unit of area. It is a trade-specific characteristic defined as follows: *Given a certain work area, work density describes how much time a given trade will require to do their work in that area, based on the product design and the scope of work done by that trade for a given task in the schedule (thus depending on work already in place and work that will follow), the means and methods the trade will use to do their work while accounting for their crew’s capabilities and crew size.* Work density thus captures what will be done, by whom, when, where, and how. (Note that “work density” differs from “schedule density” defined in the context of change and delay analysis for productivity loss claims, e.g., Finke 2000. It also differs from workhours/location as used in LOB and LBMS because units of area are not necessarily the units of space that will be used in the TTP.).

4.4 Collaborative TTP Method

The 5 steps of the TTP method we formulated and tested on a pilot project (Dunnebler et al. 2014) and later used on projects similar in size and context, is based on the cycle of work structuring (Figure 1).

Step 1 - Collect Data: The researchers collected data from the team by construction phase several weeks before each phase’s start. Tommelein and Ballard (2017) define “In the hierarchy of task breakdown, a phase is part of a project, the hinge point in regard to specifying what needs to be done vs. how to do it. It is a time period of a project, starting at a defined

milestone, during which a specific group of activities is scheduled to be accomplished (e.g., building design, completion of foundations, erection of exterior walls, building dry-in), leading to the accomplishment of a defined end milestone. A phase comprises processes.”

1.1 A description of the overall scope of work shown graphically, e.g., using drawings or BIM (Figure 2), and written in specifications to represent the product to be constructed. This product data is produced by designers prior to the start of construction, possibly reflecting input provided by contractors or suppliers.

1.2 A delimitation of the scope of work that will be done by each trade and, for each one, a description of the means and methods, sequence in which they want to work, and resources they plan to use.

On the pilot project, we collected this data from each trade foreman directly responsible for managing work (or supervisor, when the foreman was not yet identified or available). We asked them to bring a hard copy of the plan showing their scope (trade-specific plans look different from architectural plans, e.g., showing fabrication and installation detail), had them verbally describe the way(s) in which they wanted to approach their work while coloring-up the plan, using a different color for each chunk of work they expected to be

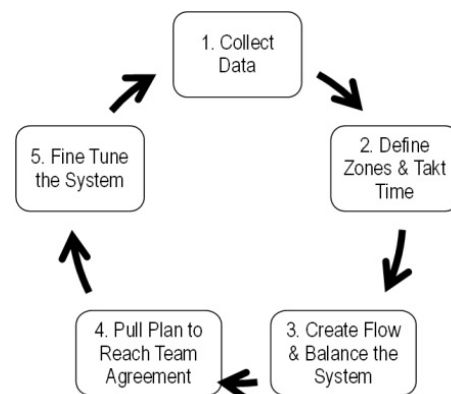


Figure 1: Process Steps for TTP (after Ballard and Tommelein 1999)

able to complete in each successive 2-day time interval (shown in sequence on Figure 3). This time interval and coloring describe work density.

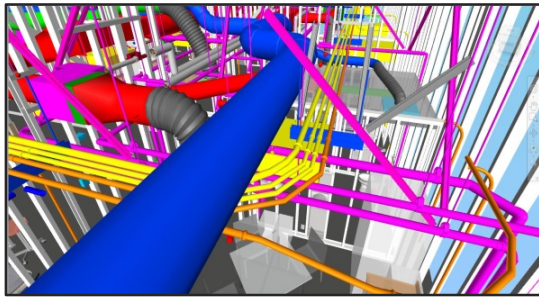


Figure 2: Building Information Model of Interior Overhead Space on Pilot Project

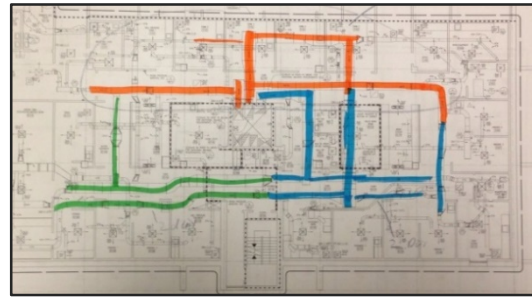


Figure 3: Input from Mechanical Trade using Work Chunks of 2-Day Takt, Sequenced Orange, Blue, then Green

A key part of the discussion is to have the foreman consider and articulate alternative approaches, and—if time permits—capture those in alternative color-ups. Clarity on a set of alternatives offers flexibility later in the TTP process, when the inputs from all trades get combined into the phase plan, and trade-offs may have to be made across trades.

Step 2 - Zones and Takt Time: The design of zones and takt is an iterative process.

2.1 After obtaining color-ups from each trade, the researchers overlaid these with a grid pattern to compute work density. Figure 4 schematically illustrates greater work density in increasingly darker colors for each trade (4.a mechanical, 4.b framing, and 4.c electrical). The number inside each grid cell is the time the trade needs to complete their work in the corresponding area (cell), given their assumed means and methods as well as crew sizing.

2.2 Subsequently, the researchers defined a zoning (a zone is a grouping of grid cells) to superimpose on the grid cells so that all space is covered and no zones overlap. Figure 4.d exemplifies one such zoning, with cells grouped into zones numbered [1] through [7].

The time each trade needs to complete their work in each zone is computed by adding up the numbers in the cells included in each zone. For example, in zone [5], mechanical needs $2+1=3$ time units, framing needs $1+2=3$, and electrical needs $6.8+0.9=7.7$. Figure 5 charts this data by zone, using a column for each trade. It shows peaks and valleys in work density. A perfectly balanced system would have columns of equal height.

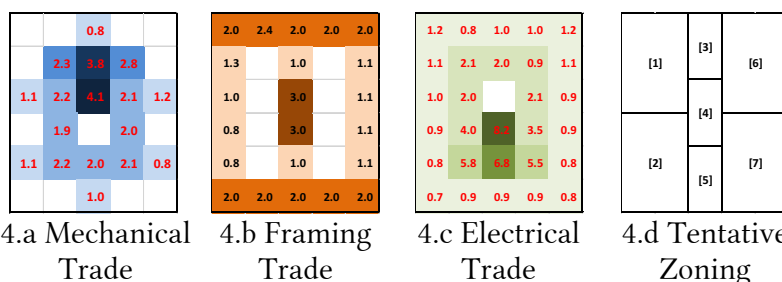


Figure 4: Work Density for Different Trades and Zoning

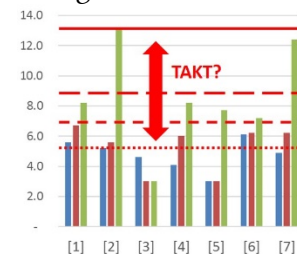


Figure 5: Time needed per Zone per Trade

2.3 Finally, the researchers chose a takt through trial-and-error (ongoing research is looking into how to systematize this step) by setting an upper limit on the time for trades to complete their work in each zone, allowing for some- but not too much underloading (capacity buffering).

The researchers repeated steps 2.1, 2.2, and 2.3 while considering alternative crew sizes, means and methods, task allocation, and the like, so as to alter the work density and thereby make columns more even in height. This repetition ended when a takt-zoning combination was found to be satisfactory.

Step 3 - Create Flow and Balance the System: The researchers used the work flows shown in color-ups, to the extent possible, to illustrate how each trade’s work would progress over time with work structured using a 2-day takt and Figure 4.d’s zoning. They shared the resulting “schedule mock-ups” (Figure 6) with the trades to get feedback and buy-in.

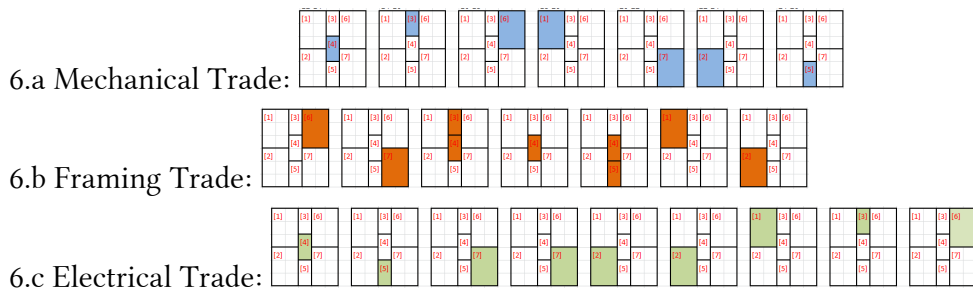


Figure 6: Patterns of Work Flow per Trade in 2-day Takt with Zoning

Steps 1, 2, and 3 prepared each trade to come to the phase planning meeting with their preferred plan and alternatives, as well as understanding of their plan flexibility based on advantages of doing work one way vs. another.

Step 4 - Pull Plan to Reach Team Agreement: At the team’s phase planning session, the researchers explained to all what they had learned from the color-up sessions and shared their analysis of takt-zoning alternatives. The team’s discussion that followed, on the timing of work within the milestones delimiting the phase, revealed concerns but also possibilities. E.g., considering the in-wall phase, the framer proposed to prefabricate wall sections to above-ceiling and convinced trade partners of the value of having all space to themselves to work fast, and then clear the way for everyone else. Shared understanding informed the subsequent pull planning effort, during which the trades meshed their patterns of work flow (Figure 7). The result was a takt plan, albeit not necessarily an optimal one since many zones are not worked in (zones left white are waiting on workers).

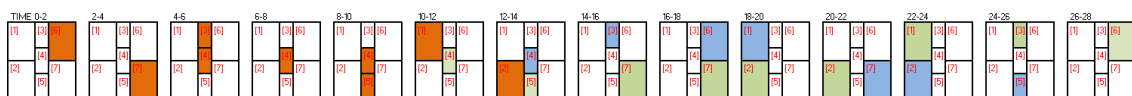


Figure 7: Meshed Patterns of Work Flow by 2-day Takt with Zoning

Step 5 - Fine Tune the System: Finally, trades added to this takt phase plan work to be done in areas other than those zoned (e.g., underfloor, on roof) as backlog to fill “time left.” Dunnebie et al. (2014) and Frandson and Tommelein (2014) expand on the practical implementation of this takt plan. In summary, the work structuring done based on takt-zoning resulted in phase plans that were successfully used with the Last Planner System.

5 CONCLUSIONS

This paper outlined the rationale and methodological steps for TTP piloted on a small healthcare project. Due to the non-repetitive nature of the work, the interdependence of scopes of work by different trades, and the small space available to work in, this TTP effort

had to be collaborative. The means and methods that each trade could use on the project and their possible production speeds, could not have been known a priori. For this kind of TTP, detail is needed that is not readily available as book knowledge.

6 ACKNOWLEDGMENTS

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SUPPLY CHAIN MANAGEMENT TRACK

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VALUE STREAM MAPPING: A CASE STUDY IN STRUCTURAL MASONRY

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Abstract: There is a growing interest in the Lean Thinking (LT) principles due to the high levels of waste in construction. Value Stream Mapping (VSM) is as an important tool for a systematic implementation of the LT. Few studies have addressed the application of VSM for improvements related to the execution of structural masonry, therefore this article presents an exploratory case study that aims to propose improvements for this process. Data was collected in a residential project, where the execution of structural masonry is the activity of greatest impact in the budget and schedule. From field observations, interviews and analysis of administrative documentation, the VSM of the current state was elaborated and analyzed through the LT. Improvements in the future VSM focused mainly in the elimination of transport and excess (inventory) wastes. A reduction of 45.5% in cycle time and an increase in Value Aggregation Time (VAT) from 32.45 to 60.55% is estimated. The VSM provided a systemic view of the value chain of the process, facilitating the identification of wastes, their origin and the proposition of improvements.

Keywords: Value Stream Mapping, Structural masonry, Lean Thinking.

1 INTRODUCTION

For a long time, Architecture, Engineering and Construction (AEC) industry has dealt with problems related to its low performance in production management, closely linked to the high number of wastes, as a consequence of the application of managerial methods oriented only by conversion activities (Koskela, 1992). There is thereby a growing interest of the academy and industry in the principles and tools of Lean Thinking (LT), referred to as an antidote to waste (Womack and Jones, 1996).

It is important to highlight that LT improvements in AEC industry must be preceded by a change in the way of thinking of those involved in the industry, rather than only applying isolated tools to solve specific problems (Koskela, 1992). In this context, VSM is a way for a systematic implementation of the LT principles, as it drives the improvements throughout the process flow (Picchi, 2003).

Previous studies have addressed the application of VSM in AEC industry, in processes such as design processes (e.g., Lima et al., 2010), house construction (e.g., Yu et al., 2009), drywall and ceramic application (e.g., Bulhões and Picchi 2011), ceramic masonry (e.g., Pasqualini and Zawislak, 2005) and concrete block (e.g., Al-Sudairi, 2007) masonry. However, there are few studies addressing improvements in the processes

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related to the execution of structural masonry through the use of VSM, as the focus is given to VSM measurement parameters (e.g. Ortiz et al., 2012a; Ortiz et al., 2012b).

This paper aims to propose improvements in the structural masonry execution process using VSM to identify wastes and elaborate a future state. This paper's main contribution is the reduction of wastes in the process flow, establishing an ideal situation in a setting where the budget and schedule are not flexible, provoking reflection of scholars and interested in Lean Construction for the application in others projects.

The scope of this paper is restricted to the structural masonry process in one of the seven towers of a residential project, considering the execution of a complete pavement as the batch, from the request of concrete blocks until the completion of the walls elevation. It is restricted to the proposition of a future state and does not include implementation plan. The process mapping considered the concrete blocks as the only material to be analysed.

2 LITERATURE REVIEW

2.1 Lean Thinking

Womack and Jones define Lean Thinking as a way of combating waste, making more with less effort, equipment, time and space, offering exactly what is desired by customers (1996). Its principles are the specification of value (offering greater added value for the customer), value chain identification (identifying and eliminating waste throughout the activities), flow (production without interruptions), pulled production (production according to demand) and perfection (continuous improvement through rapid detection and solution of problems in their root).

2.2 Value Stream Mapping

Value Stream Mapping is a tool that enables the visualization and understanding the material and information flow as the goes through its value flow. In order to obtain the continuous or pulled flow, a proposition of an ideal production chain can be made, getting as close as possible to produce only what customers need and when they need it (Rother and Shook, 2003). The focus is on eliminating wastes and, therefore, increasing the amount of time that effectively adds value to the process.

3 RESEARCH METHOD

An exploratory case study was chosen as the research strategy, an empirical investigation that analyse a phenomenon within its contemporary context, in which the researcher has little or no control over the events (Yin, 1994). It was necessary to explore the problems related to the unit of analysis: The execution of structural masonry on a floor, from the arrival of concrete blocks on site to the end of the last block row.

The structural masonry execution process was chosen because it is the most relevant activity in the budget and schedule of the project and, therefore, proposed improvements would generate a significant impact.

The study was carried out in one of the seven 14-storey towers of the project, with eight apartments per pavement. The selected tower was chosen as representative, since it started the services of structural masonry in the sixth floor by the time of data collection. The cycle times collected are an average of the execution's productivity in each tower floor, including the one, which the authors observed the execution.

The collected data included the triangulation from three sources: administrative documents (productivity, people and material request spreadsheets), 30 minutes unstructured interviews (with two interns, a crane operator, a construction technician, a foreman and a site engineer) and direct observation (measurements of cycle times and wastes). The period of data collection on site was comprised between November 7th and 14th of 2016. The historical data of the worksheets were tracked from the beginning of September until November 15th, 2016. The analysis focused on the identification of wastes and problems in the process, in order to propose improvements.

Construct validity was addressed by comparing the data collected with principles reported in Lean Construction's literature and data triangulation through multiple sources of evidence. With regards to the external validity, an analytic generalization is considered, in which the case study generates theoretical propositions that would be applicable to other contexts.

Rother and Shook proposed five steps to implement Lean Thinking through VSM: Select a family of products, map the current state, analyse the current state, map the future state and elaborate the work and implementation plan (2003). In this study, the authors selected a stage of the productive process of construction instead of selecting a family of products to initiate VSM as suggested by Pasqualini and Zawislak (2005). The selected stage was the execution of structural masonry.

4 CURRENT STATE MAPPING AND ANALYSIS

The current state mapping was elaborated with the purpose of applying the principle of the value chain identification, presenting a panoramic view of the stages, from the request of blocks to the last masonry row completion. Information about Cycle Time (CT), inventories, employees involved, problems affecting production and quality problems was collected during all process' stages. A working day containing 8.8 hours was adopted.

The process starts from the blocks request made by the project team, as shown in Figure 1. The construction technician checks the stock of blocks on site every Friday, compares it with the amount needed for the next week according to the bricklayers' productivity and makes the order, adding a safety margin of material sufficient for a week of work (1.5 to 2 pavement inventory per tower, depending on the block typology). The construction technician highlighted that the project team has already faced problems related to block's supplier reliability, such as: delay in block deliveries and dimensional variability not complied with Brazilian standards. As a result, the construction company replaced the blocks' supplier three times. Therefore, the technical team fears to be damaged again, mainly by the lack of material delivery.

One hundred and eighteen pallets of different block typologies are required for the execution of a complete pavement masonry, of which 22, 62 and 34 are, respectively, for the execution of the first, second to ninth and tenth to thirteenth row. Eight muck trucks deliver these pallets with a capacity of 16 pallets each, which supply the work throughout the week. The amount of trucks per day is variable as it depends on the availability of the supplier.

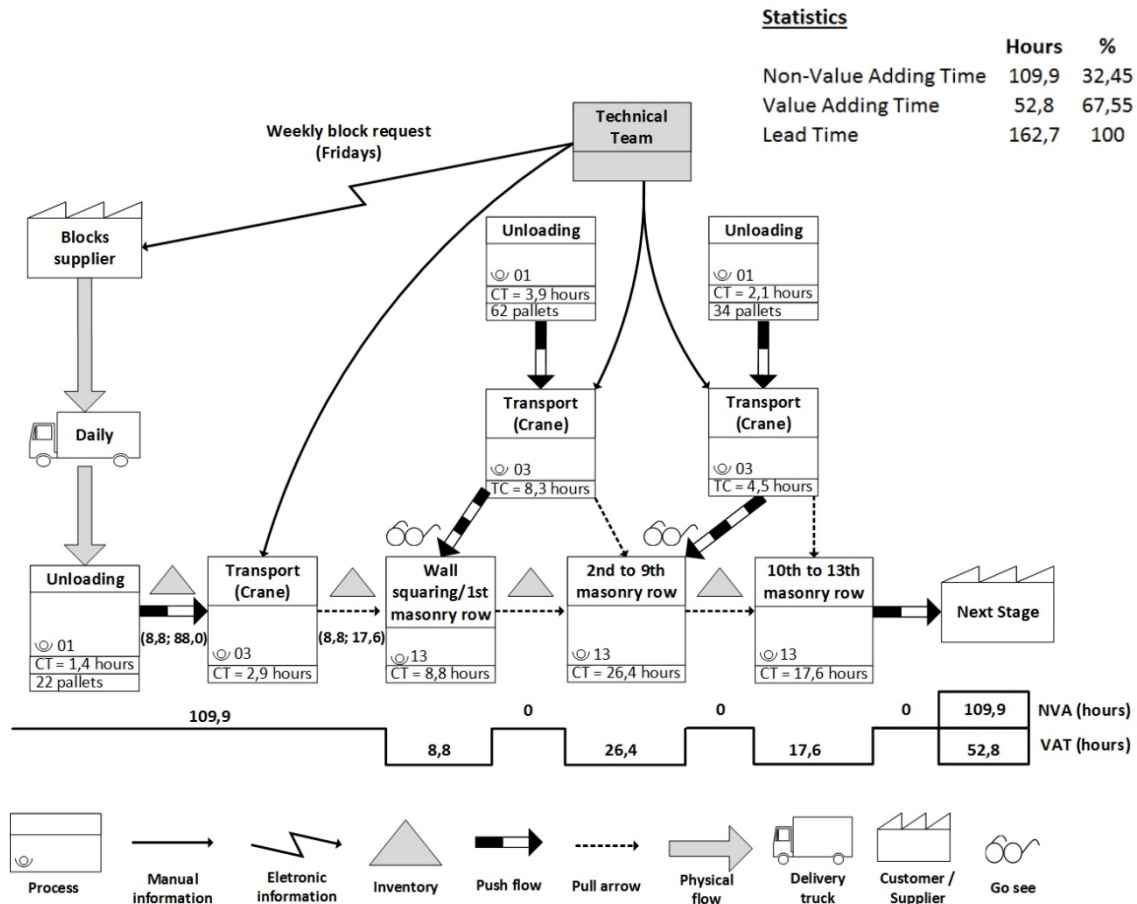


Figure 1: Current state map

After the arrival of trucks in the construction site, the unloading is carried out with the supervision of the stockroom assistant who indicates the place where the materials should be placed. It was observed that the blocks are unloaded where there is access to the trucks and space on site, i.e., there is no standardization or control of where the stock will be. In one hour, the supplier company's workers unload the 16 pallets. Twenty-two pallets are required for the first row of the masonry. For this reason, in the current state mapping the unload time for 22 pallets (1.4 hours) was considered as the initial process. Additional unloading happens simultaneously to the execution of the masonry.

After the block inventory is positioned on site, the vertical transport stage is started with the help of two cranes, which attend the simultaneous construction of seven towers. At this stage, both the production team and the researchers verified a production bottleneck. There was a delay in the blocks supply due to the way information flows to the crane operator, through verbal communication in real time. As a result, there was a decrease in productivity and even a total stoppage of some block laying team, reaching up to a 6-hour wait.

The signalman (the eyes of the crane operator) chooses the pallet that is more accessible to carry out after being informed of the need for material. Therefore, the first blocks that arrive on site are not always the first ones to be transported to the pavement. Therefore, the blocks inventory time on site can vary from one to 10 days, i.e., from 8.8 to 88 hours of work. The crane takes, on average, 8 minutes moving a pallet of blocks to a pavement. This moving time varies according to the positioning of the blocks (unloaded without much criterion) in relation to the crane and the tower.

The blocks required for the execution of the first masonry row are placed on the pavement, on average, 1 to 2 days before its use (waiting stock of 8.8 to 17.6 hours of work); because block layers fear that, the crane will not attend their real-time supply needs. Next, the step of wall squaring and first row execution is realized in the whole pavement (external and internal masonry). Through direct observation it was even found that there was not enough blocks on the pavement for this first stage, which is why the workers slowed down until the crane could continue with the supply.

During the execution of the first row, when the time is available, the crane transports blocks for the second to the ninth row to the pavement, exceeding the working hours.

The intern checks the walls' first row as the workers complete the rooms' walls of the apartments, i.e., this service is simultaneous to the elevation of the first row. The other rows' elevation is executed simultaneously to the supply of blocks by the crane. The blocks' supply is realized when time is available, as that two cranes are responsible for the supply of several materials for the seven towers.

It was observed that the masonry execution sequence in the pavement is variable, i.e., in some pavements, the masonry of the four apartments on one side is executed first, and then the elevation of the others is done. In other floors, the masonry of all apartments is executed simultaneously. There is, in this case, an opportunity for improvement related to the standardization of work.

From the collected data, it can be observed that lead-time (time from the start to the end of the process) is 162.7 hours, 109.9 hours (67.55%) of Non-Value Adding Time (NVA) and 52.8 hours (32.45 %) of Value Adding Time (VAT). The slab formwork assembling follows the masonry elevation completion.

5 FUTURE STATE MAPPING

During the data collection and analysis process, it became evident that the unloading of blocks and their transportation through the crane was generating a lot of waste of time and space. It was also contributing to the instability and uncertainty of the production. The project team also reported that this was the main source of problems on site.

With regards to the storage of blocks, the inventory waste reported by Ohno (1988) was identified, as the weekly order is made by adding a safety margin of material for a week of work. As a consequence, there is a material idleness for a period of up to 10 days, quality problems omission and delays related to the difficulty of transportation by the crane. The possibility of applying the principle of pull production was observed, reducing this safety margin to the equivalent of three working days as an initial attempt. For now, there is still insufficient trust in the supplier to order for only what is needed.

In this context, the use of a supermarket system was proposed (Figure 2). This type of solution is recommended for processes where it is not possible to produce directly in a continuous flow, that is, the delivery of one piece at a time is not realistic (Rother and Shook, 2003). The quantity of pallets to be ordered is communicated to the project team as the production pulls its consumption. This supermarket system eliminates the need for the construction technician to check personally all available inventories so that he can estimate the order to be made for the week, which eliminates the unnecessary movement waste.

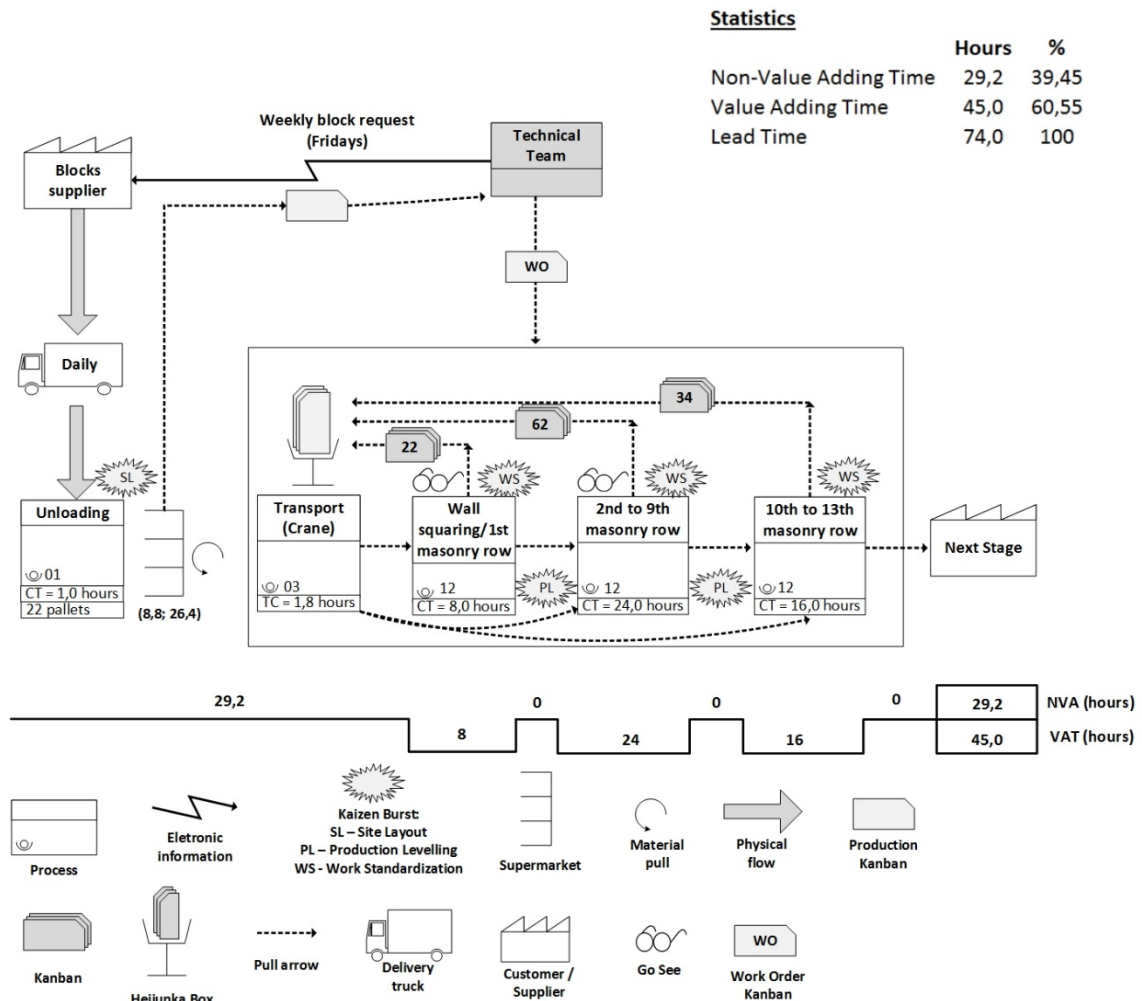


Figure 2: Future state map

With regards to the transportation stage, it is known that this is a necessary activity, but does not add value, as it is also one of the wastes reported by Ohno (1988). To reduce this waste, one of the recommendations is the reorganization of the site's layout (Rich and Hines, 1997). Therefore, the principle of perfection can be applied through an improvement in the construction site's layout, with the purpose of organizing the supermarket inventory by block typologies, sequence of delivery and proximity to the tower. This can reduce the cycle time of unloading, add value for the crane operator and his team and establish a flow, providing better transport conditions (a reduction of the crane TC is estimated for 5 minutes) and avoiding waiting of blocks on the pavement.

In the future state the crane could no longer operate through verbal communication in real time, but through a kanban system, previously placed in a heijunka box, a board that stores these cards which could be fixed to the base of the crane. The kanban system can be used by the production team to request the quantity, type, destination and delivery time of the pallets. In order to no longer have to make decisions about the urgency or priority of transport, the crane's signalmans would now meet the demand that is previously defined in the heijunka box (creating a pull production).

The masonry execution in the pavement starts from the request of production (kanban) delivered by the project team as work orders. These kanbans would contain

information about the pavement to be executed, due time, workers team and worker's payment.

Based on the principle of perfection (continuous improvement), production levelling and work standardization are proposed through block layers' training and use of poka-yoke tools.

By contacting the blocks supplier, it is proposed that previously cutted blocks are sent to the construction site in pallets. These blocks are used in several points of the walls for the fixation of the reinforcement and later the grouting. As a result, improved productivity can be achieved by reducing unnecessary movement wastes on the pavement, waiting time for cutting and reducing the production team by eliminating the cutter (a worker that only cuts blocks). An improvement of about 10% in the cycle time of the productive stages is estimated.

Through the proposed improvements, it is estimated that lead time will be reduced in 45.5%, from 162.7 to 74.0 hours, 45.0 hours (60.55%) of Non-Value Adding Time (NVA) and 29.2 hours (39.45%) of Value Adding Time (VAT). The main contribution in the reduction of time is the reduction of stock's idle time on site. With the mitigation of identified wastes, the masonry process presented a Value Adding Time that is expressively superior to the current state one, leading from 32,45% to 60,55%.

6 CONCLUDING REMARKS

Using VSM in the structural masonry process, this paper contributes to the literature on several fronts. First, it establish a future state that provides better conditions for the company. Second, it awakens the reflection of academics and practitioners for application in other contexts within the structural masonry construction system. Third, the use of VSM provided a systemic view of the concrete block supply chain, facilitating the identification of wastes and their origin, from the request of material to the execution of the last masonry row. Wastes related to excess inventory, material transportation, information flow, unnecessary movements, variability in team productivity and in the way of performing the pavement were identified.

The main proposed improvements are as follows: the reduction of block inventory, reorganization of the layout concerning the storage of blocks, the use of a kanban system to improve the crane information flow, supply of cutted blocks, work standardization and production levelling.

Concerning improvements implementation, an important issue is the awareness of the team. After that, future state map implementation could start with its division into pull loop and additional loops, as recommended by Rother and Shook (2003). The pull loop should be the first one to be improved, as its activities impact the previous loops. Masonry execution pulls the transport and request of blocks in the analysed process. Therefore, work standardization in the block laying process can be the first implementation effort. Then, production levelling should be easier. Thereafter, the times when blocks are needed are clearer, block inventory is possible to be reduced, layout can be reorganized and heijunka box can be implemented.

One limitation of this study is that the authors did not include the upstream supply chain stages in the analysis. Future studies should address the following: an analysis of the relationship between the construction company and the block supplier; block supplier internal processes and the cutted blocks supply. A more effective reduction of inventories requires commitment and a trust relationship with the supplier, leading to

the elimination of wastes. Moreover, future studies may include an implementation plan and feasibility tests for the proposed improvements.

7 ACKNOWLEDGMENTS

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JUST IN TIME IN CONSTRUCTION: DESCRIPTION AND IMPLEMENTATION INSIGHTS

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Abstract: The construction industry has long been plagued with productivity and waste management issues on construction sites, unmet deadlines, and client dissatisfaction over the quality of the construction delivered. Having greatly aided the manufacturing industry, this paper investigates how the JIT philosophy could help with these difficulties. The paper illustrates four scenarios of JIT implementation in construction according to the level of coordination required, on-site management, and information sharing. The methodology which consists of a systematic literature review on JIT in construction confirms the need to adapt this philosophy for an adequate deployment in this industry. It also confirms the close ties between JIT, lean construction, and prefabrication for successful construction project management.

Keywords: Just in time in construction, lean construction, prefabrication, systematic literature review.

1 INTRODUCTION

Several authors address the fact that productivity in the construction industry has improved significantly but is still lagging behind other industries (Pheng and Chuan 2001; Asri et al. 2016). A way to address this issue is to embrace the just in time (JIT) philosophy which consists of providing the right materials, in the right quantities and quality when it is needed in order to reduce waste and to provide maximum value (Tommelein and Li 1999; Tommelein and Weissenberger 1999; Vokurka and Davis 1996). More research indicates that JIT in construction consists of producing smaller batches of each component and sending them on site at the required installation time in order to reduce waste, diminish on-site storage space, and meet the deadlines and high standards of the construction industry (Cossio and Cossio 2012). The goal of the paper is to show how JIT may reduce costs, waste, and quality problems encountered in a construction project. To achieve this goal, different scenarios of JIT implementation are proposed determined by the level of coordination required, construction site management, and information sharing. The paper contributes to scholars by identifying elements that influence JIT implementation in construction and to practitioners by presenting requirements for its successful implementation. The paper contains six parts. An introduction, a systematic literature review (SLR), a discussion of results, a conclusion, references, and an appendix.

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2 JIT IN CONSTRUCTION: SYSTEMATIC LITERATURE REVIEW

In order to show how JIT can help to better deal with issues in construction, a scientific methodology called systematic literature review (SLR) is applied. The goal of a SLR is to “improve the quality of the review process by synthesizing research in a systematic and reproducible manner” (Tranfield et al. 2003). As these authors agreed, conducting a systematic review passes through three stages: planning, conducting, and reporting.

2.1 Planning the review

The first phase in the planning stage is to state the need for the review. This review is needed in order to present studies in which JIT has been implemented in a construction project. The studies will be used to equip practitioners with proper strategies of implementation and if not, to highlight gaps in those studies that could be filled in future studies. The second phase consists of preparing questions that should be answered by the review. For this research, the following questions are identified:

1. Is there a presence of JIT in construction mentioned in scientific literature?
2. Which shape does JIT take in construction?
3. Which indicators measure performance when JIT is implemented in construction?

The third phase presents the methodology used while conducting the review. Step one of phase three consists of an identification of keywords that will be used in the review. In the second step, a search in all engineering databases with established keyword combinations is done. The third step consists of an analysis of titles and abstracts of results. In the fourth step, articles that do not respect logical pre-established criteria are eliminated. The fifth step refers to a complete analysis and classification of the remaining articles.

2.2 Conducting the review

2.2.1 Identification of research

The databases used in the search of scientific articles are Compendex and Inspec from the research databases Engineering Village and Web of science. Engineering Village has been selected because it is an excellent choice for rigorous scientific research specific to engineering. Web of science has also been chosen because it covers a wide variety of scientific areas. The research coverage period has been left by default, from 1884 to 2016 in Engineering village and from 1900 to 2016 in Web of science in order to cover all potential articles. The research was done for the last time on September 27, 2016. Key concepts of the subject matter are “just in time” and “construction”. Synonyms found for each of them in the synonym database Thesaurus are "JIT" and "Build-to-order" for "just in time", and "building" and "prefabrication" for "construction" (an asterisk is used after *prefabricat* to search all words starting with *prefabricat* and finishing with all its suffixes). The research consisted of equations which are combinations of key concepts and their synonyms while specifying their appearance in the Subject, the Title or the Abstract. The nine research equations are as follow: “just in time” Near/6 construction, “just in time” Near/6 building, “just in time” Near/6 prefabricat*, “JIT” Near/6 construction, “JIT” Near/6 building, “JIT” Near/6 prefabricat*, “Buid-to-order” Near/6 construction, “Buid-to-order” Near/6 building, and “Buid-to-order” Near/6 prefabricat*. In all research equations, "Near/6" is used to specify the presence of at most six words between the two key concepts. After testing all combinations, the Boolean operator OR was used in order to present results of all combinations together. A third database from the International Group for Lean Construction (IGLC) was also used because IGLC has been working on the subject

for several years. IGLC conference papers relating to JIT in construction were searched on January 16, 2017.

2.2.2 Selection of studies

A total of 164 articles were found with Engineering Village, 227 with Web of science, and 83 with IGLC. In order to refine the results in Web of science, only articles from categories: operations research management science, industrial engineering, management, manufacturing engineering, civil engineering, and multidisciplinary engineering are kept since they relate more to JIT in construction. Of the 146 articles left in Web of science, 164 in Engineering Village, and 83 in IGLC, titles and abstracts are scanned by using five logical criteria. Articles kept are articles discussing only JIT in building construction, construction supply chain, tools used to implement JIT in construction, JIT success factors, and barriers to the presence of JIT in construction. This leaves us with a result of 23 articles from which critical information is extracted such as performance indicators used to measure the impact of the implementation of JIT in a construction project and tools used to undergo the implementation. Table 1 in the appendix summarizes the findings.

3 DISCUSSION

3.1 Reporting and dissemination

Analysis of resulting papers showed that scientific literature covers Lean in construction (eight papers) and JIT in construction (7) more than JIT implementation in construction (3). Indeed, few articles discuss an implementation of JIT in construction even though some of them underlined the impact of prefabrication and Lean techniques used on construction sites. No paper showed quantitative results on the impact of different levels of prefabrication as well as buffer stock and construction site organisation on the outcome of a construction. Eighteen out of twenty-three articles discussed JIT in construction, JIT implementation in construction along with Lean in construction and prefabrication.

3.1.1 Response to research questions

As the first research question concerned the presence of JIT in construction in scientific literature, we can now confirm that it is the case. The second question dealt with the form JIT typically takes in construction. The case studies from the SLR mention and describe how JIT has been applied in several construction projects whether big or small. However, Tommelein and Weissenberger (1999) and Pheng and Chuan (2001) maintain that in practice a buffer is necessary and its size should be determined strategically. In construction, JIT mostly covers the management of deliveries (Tommelein and Li 1999; Asri et al. 2016) and control of buffer stock levels on construction sites (Pheng 2001; Pheng and Chuan 2001; Ng et al. 2009; Roos et al. 2010; Amornsawadwatana 2011; Cossio and Cossio 2012) through a pull system (Akintoye 1995; Tommelein and Li 1999; Low and Wu 2005; Viana et al. 2015). Furthermore, the implementation of JIT principles in construction seems to require prefabrication (Cossio and Cossio 2012), Lean techniques, an integration of the materials procurement time frame with the construction project schedule, and evaluation of supplier performance to ensure quality of delivered materials while avoiding rework on site (Opfer 1998). Figure 1a presents the number of times these elements are mentioned to support an implementation of JIT in construction. Question three was about the indicators used to measure performance when JIT is implemented in construction. Figure 1b illustrates the number of times KPIs such as costs are mentioned to assess the results of an implementation of JIT in construction. The most frequently mentioned KPIs,

in descending order, are costs, productivity, project duration, amount of buffer stock, quality of construction, and waste quantity. Five out of the six KPIs are elements that impact only a portion of the building’s life cycle. However, the fifth KPI: quality of construction, which depends on client satisfaction, should have a greater weight since it lasts throughout the project's entire life cycle. Moreover, the adoption of JIT in construction seems to generate qualitative results such as better partnership between suppliers and contractors and improved system of deliveries (Cossio and Cossio 2012).

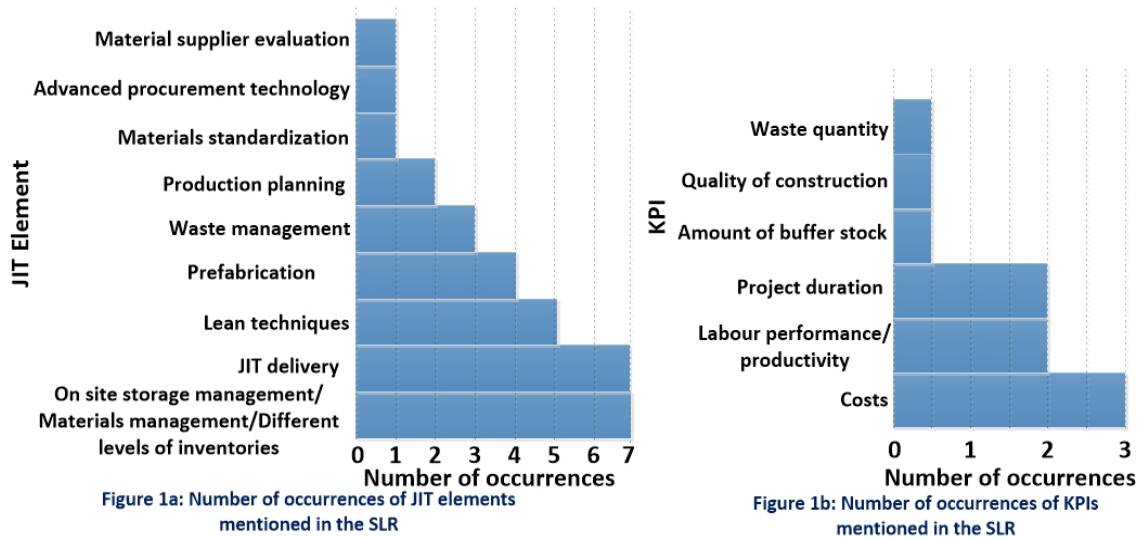


Figure 1: Number of occurrences of JIT elements and KPI mentioned in the SLR

3.2 Description of different implementation scenarios of JIT

According to the literature, JIT benefits on a construction project’s value chain depend on the prefabrication plant, the construction site, and the flows between them. As pointed out by Pheng (2001), one party trying to adopt a JIT philosophy while the other does not, will realize his efforts are futile and will not achieve the potential benefits. The situation is also depicted in Viana et al. (2015). Figure 2 illustrates four scenarios of JIT in construction. Scenario I shows that low information sharing between the plant and the site and low supply chain coordination are respectively less favourable to (-) prefabrication of components and (-) JIT deliveries while low construction site management suggests (-) low presence of Lean principles on the site. In scenarios II and III, one or two elements are less present, making it difficult to obtain gains on the overall value chain. Scenario IV illustrates the best scenario for JIT implementation in construction where high information sharing and high supply chain coordination are respectively more favourable to (+) prefabrication of components and (+) JIT deliveries while high construction site management suggests (+) the presence of Lean principles on the site.

Pheng (2001) states that prefabrication has come with “the hope of reaping the benefits of factory-styled operations” since it entails benefits such as improved quality, waste reduction, and faster erection of buildings. However, even if an efficient plant makes JIT deliveries, if there are no resources available to unload them on site, the truck and its driver will remain monopolized. Such a situation illustrates the need for JIT deliveries to ensure the fast erection resulting from prefabrication but also the need to use Lean in construction site activities to avoid waste of time (Friblick et al. 2009). For example, Khalfan et al. (2008) used Kanban, “one of the Lean approaches” in their construction project “to pull construction materials through their production systems on a just-in-time basis”.

Moreover, Lean tools such as 5S (Deshpande et al. 2012) are used to ensure that the construction site is well organized to improve performance of workers and optimal movements of materials on site. It can be concluded that successful prefabrication needs successful implementation of JIT while successful JIT implementation in construction requires adoption of Lean in construction site activities. However, the scenarios present some limitations. It is supposed that the plant is able to provide materials regardless of the demand and that it can manufacture different levels of prefabricated materials. These scenarios do not apply if the plant does not meet such expectations.

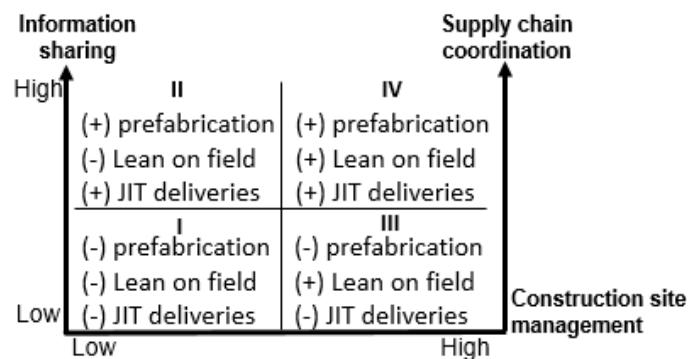


Figure 2: Scenarios of implementation of JIT in construction

4 CONCLUSION

The research showed through the SLR that JIT exists in construction, and helped identify the JIT elements applied as well as the KPIs used to measure the impact of their implementation. Moreover, the research proposed four scenarios to illustrate the influence of three JIT elements (prefabrication, JIT deliveries, and presence of Lean principles) on the successful implementation of JIT in construction. However, the aforementioned scenarios are purely qualitative. Future work will use activity-based software to simulate different scenarios presenting various levels of prefabrication, on-site buffer stock, and Lean on-site activities in order to obtain quantitative KPI measurements.

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6 APPENDIX

Table 1: Results of the SLR

References	Origin	Focus / KPI	Tools
(Akindoye 1995)	UK	JIT in construction/ KPI: -	Materials management, production planning
(Anglin et al. 1995)	US	JIT in construction KPI: Quantity of waste	Waste management
(Tommelein 1997)	US	Lean in construction (LC) KPI: Waste quantity, time saving	Lean techniques
(Opfer 1998)	US	JIT in construction/ KPI: -	Materials standardization, advanced procurement technology, material supplier evaluation
(Tommelein and Li 1999)	US	JIT in construction/ KPI: -	JIT deliveries
(Tommelein and Weissenberger 1999)	US	JIT in construction/ KPI: -	JIT deliveries
(Pheng and Chuan 2001)	SG	JIT implementation in construction, LC, Prefabrication KPI: Costs	JIT delivery, Lean techniques, on-site storage, waste management
(Pheng 2001)	SG	JIT implementation in construction, LC, Prefabrication KPI: Costs	JIT delivery, Lean techniques, on-site storage, waste management
(Low and Wu 2005)	SG	JIT implementation in plant, Prefabrication KPI: Lead time, machine setup time, quality	JIT vendor strategy, JIT production strategy, quality control strategy

Table 1: Results of the SLR (Continued)

References	Origin	Focus / KPI	Tools
(Horman and Thomas 2005)	US	JIT in construction KPI: Labour performance, productivity	Different levels of inventories
(Christensen 2005)	US	JIT in construction/ KPI: -	-
(Hamzeh et al. 2007)	US	LC/ KPI: Costs, time average inventory	Different level of inventory
(Khalfan et al. 2008)	UK	LC/ KPI: Waste quantity, costs, time saving	E-procurement system
(Zimmer et al. 2008)	US	LC/Construction supply chain KPI: Observations	Lean techniques, JIT delivery, material management, last planner
(Friblick et al. 2009)	SE	LC KPI: Costs, time saving, delays	Lean techniques
(Ng et al. 2009)	CN	JIT implementation in construction/ KPI: Project duration, amount of buffer stock	JIT delivery, on site storage management
(Amornsawadwatana 2011)	TH	LC/ KPI: Number of loading activities	JIT delivery
(Deshpande et al. 2012)	US	LC/ KPI: Costs, efficiency, waste quantity	5S
(Cossio and Cossio 2012)	MX	JIT implementation in construction, Prefabrication KPI: Project duration, costs, productivity, quality of construction	JIT delivery, on site storage management
(Tillmann et al. 2014)	US	LC/ KPI: Induction of desired Lean behaviours	Lean techniques
(Trivedi and Kumar 2014)	IN	LC/ KPI: Quantity of waste, costs, quantity of inventory	Pull system, continuous process flow, standardization
(Viana et al. 2015)	BR	JIT implementation in construction/ KPI: -	Production planning/JIT delivery
(Asri et al. 2016)	MY	JIT, LC, Prefabrication/ KPI: -	-

EXPLORING THE APPLICATION OF LEAN PRINCIPLES TO A CONSTRUCTION SUPPLY CHAIN

Rafaella Broft¹

Abstract: The characteristics known in construction are often seen as peculiarities of the industry and prevent the attainment of flows as efficient as in manufacturing. The construction industry knows two typical problems resulting from high levels of fragmentation and low levels of repetition: lack of control and decreasing performance. Despite the critical role of a client, parties on the supply side – the lower tiers of the construction SC – are believed to be able to develop into more integrated systems, independently from the demand. Contractors are willing to develop closer relationships, but implementing SCM seems a long-term, complex process and requires a certain level of understanding and therefore learning throughout the supply chain. Some characteristics of the industry are even believed and described a non-suitable base for implementing SCM. This paper sets out to explore possibilities and examines the results of a step towards successful SCM in construction. It describes the advantages of the application of some important Lean principles, by presenting the differences within the processes needed to produce one construction 'product' in two different ways – with a product- and project-focus. The two cases involve a supply chain, operating in the Dutch construction industry and representing long-term agreements between one main contractor and its most critical suppliers in housing. With the analysis, the paper provides the reader with the necessary insights to take an important step in implementing SCM in construction.

Keywords: Supply chain Management, lean construction, lead time reduction, value stream thinking, flow.

1 INTRODUCTION & BACKGROUND

Construction is a complex systems industry, managed through projects involving multiple, temporary, and transient organisations, complex contractual relationships and discontinuity of teams (Kumaraswamy et al., 2005; Pryke, 2012; Fulford & Standing, 2014). The management of these discontinuous exchanges in project-based industries is problematic due to the discontinuity of demand for projects, the uniqueness of each project in technical, financial and socio-political terms, and the complexity of each project in terms of the number of actors involved (Skaates et al., 2002; Crepsin-Mazet & Ghauri, 2007). The relationships required for the delivery of the constructed product among main contractors and suppliers are often weak and difficult to manage (King & Pitt, 2009) and the low levels of repetition increase the unpredictability of the flow of work (Vrijhoef, 2011). The consequences are poor production processes, limited ability or willingness to innovate, late project delivery and budget overrun (Morledge et al., 2009).

Several studies have underlined the need for radically different approaches to supply chain relationships that achieve 'customer delight' and minimise turbulence in stakeholders' relationships (Latham, 1994; Cox & Ireland, 2002; Pryke, 2009) and there has

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been a move towards better supply chain integration, and the formation of strategic partnerships and collaborative agreements between supply chain actors since (Akintoye et al., 2000; Holt et al., 2000; Briscoe & Dainty, 2005).

At the lower tiers of the construction supply chain, the supply side, however, there remains a paucity of properly documented examples of successfully implemented Supply Chain Management (SCM) initiatives (Cox & Ireland, 2002; Broft et al., 2016). Although fragmentation in construction originally occurred in response to highly variable workloads (Fulford & Standing, 2014), main contractors now increasingly depend on their suppliers, both for realising projects and for achieving the required performance in these projects – they require capabilities and knowledge which do not belong to their own core competences or in-house capabilities (Cox & Ireland, 2002; Green et al., 2005; Mbachu, 2008; Bemelmans et al., 2012). The increasing percentage of project turnover which is spent on buying goods/services does provide opportunities for collaboration and emphasises the importance of managing suppliers (Bemelmans et al., 2012). Contractors are willing to develop closer relationships (Ross & Goulding, 2007), but implementing SCM seems a long-term, complex process and requires a certain level of understanding and therefore learning throughout the supply chain. Some characteristics of the industry are believed and described a non-suitable base for implementing SCM (Cox & Ireland, 2006). This study sets out to explore possibilities and examines the results of a step taken towards 'successful' SCM at the lower tiers in construction.

2 CONCEPTUAL DEVELOPMENT

2.1 The Construction Supply Chain

In construction, a supply chain shows the following production-related characteristics:

- Converging logistics to a common and fixed point in the supply chain: the construction site where the 'construction factory' is located – the object is assembled from incoming materials, coming from different supply units, and through different services (Luhtala et al., 1994);
- Temporary and non-repetitive, or in other words, one-off construction projects that are produced through repeated reconfiguration of project organisations (Vrijhoef & Koskela, 2000). This takes along difficulties to production standardisation and modularisation, and limits gains of scale (Gosling & Naim, 2009). The organisations involved present high levels of autonomy;
- Multiple and concurrent projects, which produce significant implications at five categories: Capacity (balance the demand for accessing resources), complexity, conflict (unstable relationships), lack of commitment, and context.
- A number of studies have linked construction with the characteristics of the Engineer-to-order (ETO) production strategy (Segerstedt & Olofsson 2010, Gosling et al., 2012). ETO-projects are described as having high levels of customisation and typically managed on a project basis (Gosling et al., 2012). Construction has generally an early Order penetration point (OPP).
- The choice of production process depends on process and product features. Construction is mainly based on two types of processes: small batch process and job process (Krajewski et al., 2007).

These characteristics are often seen as peculiarities of the industry and prevent the attainment of flows as efficient as in manufacturing (Koskela, 1992). The high levels of alignment and repetition within these supply chains have led to highly productive and fast operating strategic coalitions of firms (Kirche et al., 2005; Kim, 2006). The construction industry on the contrary, knows two typical problems resulting from high levels of fragmentation and low levels of repetition: lack of control and decreasing performance. The main contractor, the principal construction organisation that manages a construction project, executes only a small part of the product by its own personnel and its own production facilities (Dubois & Gadde, 2000).

2.2 SCM in Construction

SCM is a new way of thinking about management and processes, in order to coordinate supply chains more efficiently, by managing the associated relationships to deliver customer value, through innovation and continuous improvement (Christopher, 2005; Pryke, 2009; Blanchard, 2010; Fulford & Standing, 2014). A supply chain is described as a network of interconnected – through upstream and downstream linkages – organisations that are involved in the different processes and activities that produce value in the form of products/services to the ultimate consumer (Harland, 1996; Dainty et al., 2001; Christopher, 2005). The main objective of SCM is to enhance mutual competitive advantage through improved relationships, integrated processes and increased customer focus (Pryke, 2009). Businesses no longer compete as a sole entity, but rather in a ‘supply chain versus supply chain’ manner (Lambert & Cooper, 2000; King & Pitt, 2009).

Despite the critical role of a client in enabling supply chain integration, parties on the supply side – the lower tiers of the construction supply chain – are believed to be able to develop into more integrated production systems, independently from the demand (Vrijhoef & De Ridder, 2005; Segerstedt & Olofsson, 2010). Main contractors are acknowledged to have a central position in the management of supply chains (Pryke, 2009; Broft et al., 2016) – it is believed that main contractors have more influence on the organisation of the project and on the performance and quality of the work of its suppliers (Latham, 1994) – offering great potential in the effective integration of their supply chains. Implementation of SCM by main contractors, however, is relatively slow as SCM is often seen as a project-specific approach rather than a central strategy such as in industries like aerospace and car manufacturing (Green et al., 2005). Many applications have been limited to the management of construction materials and long-term arrangements with suppliers (Vrijhoef, 2011).

2.3 A Lean Perspective to SCM in Construction

The role of the supply system (or supply chain, network, stream, etc.) – comprising the purchasing activities of the assemblers and the supply activities of the component manufacturers (Lamming, 1996) – received attention from the outset of the discussion on Lean Production. Lean Production is the more generic and less culturally specific label for the Toyota Production System (TPS) – a de-contextualisation of a new dominant paradigm that is displacing mass production in search for methods to compress time and increase flow (Samuel et al., 2015). The logic of lean production describes value-adding processes unencumbered by waste, where lean is a means of waste identification in operations so that it can be eliminated for greater efficiency – to ensure that value flows swiftly and smoothly to the customer (Schniederjans et al., 2010; Samuel et al., 2015).

Lean challenges to fundamentally rethink value from the customer. This includes the identification of the ‘entire’ value stream (Womack & Jones, 2003). The value stream is

the set of all the specific actions required to bring a specific product/service through the critical management tasks of any business. Lean thinking must go beyond the firm to look at the whole: the entire set of activities entailed in creating and producing a specific product. Flow is created in order to accomplish tasks continuously from raw material to finished good rather than departmentalised, in batches (Womack & Jones, 2003).

The project-focus within the 'project-based production system' known in construction, supporting fragmentation and the believed uniqueness of each project, seems to overrule this product-focus and the advantages of flow, necessary to improve customer value. In Lean SCM, the entire flow from raw materials to consumer is considered as an integrated whole (Lamming, 1996). Interfaces between the different companies of the supply chain are thus seen as artificial – as a result of the economic arrangement of assets governed by many other factors rather than as natural transformation stages in the development (or addition of value) (Lamming, 1996). The combination of lean applied to the management of supply chains can generate outstanding business performance. It involves the application of all the lean principles within a SCM context (Schniederjans et al., 2010). Some authors refer to this combination as supply chain best practices (Blanchard, 2010), a lean supply chain (Wincel, 2004), or a way of harnessing value in the supply chain (Banfield, 1999). Lean SCM could be defined as “the use of a highly transparent, trusting and long-term relationship between the buyer and supplier to create a physically efficient supply chain through the reduction of waste in processes or responsiveness in product delivery” (Schniederjans et al., 2010). Value creation, that has become a function of the network of iterative and transient relationships between actors, is central.

This paper describes the advantages of the application of some important Lean principles to SCM in construction, through the use of a case study.

3 RESEARCH METHODOLOGY

A main contractor has initiated the integration of its supply chain and decided to form long-term agreements with twelve suppliers in its key supply categories (Holti et al., 2000). For reasons of capacity and limited working areas, the main contractor selected more than one supplier for finishing and tiling services, and the production of frames.

The study, conducted in the Netherlands, involves case study research (Yin, 2014) – case study research appears to be highly relevant to an industry that is project driven and made up of many different types of organisations, and comprises the following combination of data collection: Semi-structured interviews – where the emphasis is towards investigating a phenomenon within a context (Fellows & Liu, 2003), and detached observation. For this research an experiment was proposed, where the supply chain was challenged to adapt a product-focus within a project, rather than the usual project-focus generally known in construction. This means that tasks were continuously, and directly after each other, performed from foundation to the delivery of one completed product – flow of the product. The studied supply chain focuses on housing and the study was conducted on a project existing of 40 houses. Part of the project was constructed as Case I, the experiment, and the other part as Case II, the traditional situation – the activities of each supply chain actor are in flow (batch process). Due to chosen region, only nine suppliers were involved in the cases.

Data collection was largely based on primary data and gathered from semi-structured interviews with two key representatives – at management and project level – from each organisation involved. This approach is qualitative and investigates dependencies, barriers and points of improvement following from both cases. The study also uses detached

observation of the processes needed to produce one construction ‘product’ in two different ways, based on the activities of the workers on site. Through the use of Multi Moment Analysis (MMA) on site, the study examines the differences in lead times of all activities, and the amount of value-adding activities performed – value/waste ratios were calculated after classification (Womack & Jones, 2003).

The aim of the study is to investigate the effect value-stream thinking and flow, two important Lean principles, have on the collaboration within a supply chain and the SCM activities initiated by a main contractor. This way it provides readers with the necessary insights to take an important step towards the implementation of SCM in construction.

4 RESEARCH FINDINGS

It should be noted that the findings have limitations presented by the chosen research methodology, and concern only one supply chain and two cases within one project.

4.1 A Comparison of two Cases

The findings, resulting from the MMAs, give insight in the average duration, starting and finishing points of all activities performed on the construction 'product'. Table 1 gives a summarised and combined overview of these metrics per supply chain actor. It also shows the total number of employees needed to perform all discipline-dependent activities.

Table 1: A comparison of the two cases

Supply Chain Actor	Discipline	Activities Case I (Experiment)			Activities Case II (Traditional)			Number of employees involved	Value/waste ratio
		Lead time	Start	End	Lead time	Start	End		
T00	Main contracting	20 days	1	20	50 days	1	50	2	12/88
T01	Production of foundations	1 day	1	1	1 day	1	2	2	17/83
T02	Production of concrete	3 days	2	4	10 days	3	13	5	13/87
T03	Production of roofing	6 days	4	9	17 days	17	34	2	22/78
T04	Installation technology	17 days	1	17	48 days	1	48	5	34/66
T05	Production of frames	1 day	18	18	1 day	48	48	2	34/66
T06	Production of frames								
T07	Finishing	15 days	2	16	22 days	21	43	5	35/65
T08	Finishing								
T09	Tiling	7 days	12	18	8 days	36	44	4	15/85
T10	Tiling								
T11	Production of doors	1 day	18	18	1 day	48	49	2	39/61
T12	Contractor of storages	11 days	1	11	12 days	38	50	5	21/79

The biggest difference between the two cases lies in the average total lead time needed to construct one product, one house. The findings show a lead time of 20 days in Case I, the experiment, and 50 days in Case II, the traditional situation. A difference caused by the way individual tasks were performed – continuous flow of the product versus batch production of all the tasks per discipline, or in other words the amount of time a product needs to wait for its next value-added activity.

Additionally, the table shows the average value/waste ratio per discipline after all activities were classified. The total ratio between value-adding and waste activities is 29/71 (see Figure 1). The biggest types of waste can be appointed to motion of personnel (18%) and waiting times (8%) within the activities of different disciplines.

4.2 The Key Representatives' perspectives

The findings based on the semi-structured interviews reveal the different perspectives of key representatives (from every supply chain actor involved) about dependencies, barriers

and points of improvement (based on types of waste found) during the performance of both cases. An overview of the findings is shown in Table 2.

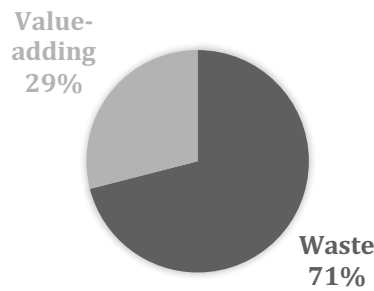


Figure 1: Total overview of value-added and waste activities.

Table 2: Overview of the dependencies, barriers and points of improvement.

Supply Chain Actor	Dependencies	Batch	Barriers	Biggest types of waste
T00		-	Currently no employees on site.	Over-processing, motion
T01	T00, T02, T04	20/week	Underload (transport), pile deviation, alternation of tasks	Motion, waiting
T02	T00, T01	5-7/week	Change in structure, safety, alternation of tasks, lower production on site	Motion, waiting
T03	T00, T02, T04	6/week	Limited day production, underload (transport)	Waiting, transportation
T04	T00, T01, T02, T07, T09, T12	Differs per discipline	Great dependency, many different disciplines/tasks performed on product	Over-processing, motion
T05	T07	6/week	Risk of wrong fit with current system	Motion, transportation
T06				
T07	T05	Differs per discipline	Limited day production, many different disciplines/tasks performed on product	Motion, measurement
T08				
T09	T04, T07	5/week	Limited day production, last-minute changes in client options in relation to production	Motion, measurement
T10				
T11	T00	5/day	Limited day production, alternation of time tables	Motion, transportation
T12	T00, T01, T04	10/day	Limited day production	Over-processing, waiting

During Case I, T01 proposed to help T02 with the installation of floors in order to decrease T02's activities to one day of production. Despite the fact that this task does not actually belong to its core business, its employees felt keen to think about who else to support in the future. T04, having specialised workers for every installation discipline, was challenged to overthink its task combinations. Interviewee T05 replies: "Collaboration between disciplines and people leads to many solutions – going for the same goal makes me willing to give". His employees found out about their dependency on the paint activities in the house. T03 has experienced that Case I invites workers to look beyond their own scope. The different answers show that site-workers discover unknown dependencies and feel more concerned than during Case II. Case II limits the scope of work to the employees' usual activities.

Interviewee T02, describes the construction method as the main challenge. His usual business challenge is to build as many structures as possible – mass production. Continuous flow asks for a different construction system, where his team activities and his transportation need to be adjusted. T03, also a production company, expects the traditional method, following Case II, to be more convenient for his type of company. T07 feels challenged in timing. Interviewee T09 describes this as “a puzzle and possibly a future

barrier between projects to shift personnel and get to full day productions”, whereas T04 sees this as challenges that could be overcome. According to some, mass production and batch thinking have more advantages than the continuous flow of a product – the interviews were held before insight of the results was provided.

5 CONCLUSIONS

The research findings outline important information about all the processes needed to produce one construction 'product'. The biggest difference is found in the delivery time, or in other words lead time, of this product – 20 days versus 50 days in the traditional process – and relates to the flow within the activities of all individual organisations versus the continuous flow of activities on the product. Where the value/waste ratio within these activities remain rather the same – the two biggest types of waste can be appointed to motion of personnel and waiting times within the activities – a lot of extra waste can be defined as 'waiting' time of the product between the activities of all parties.

This research provides the supply chain with information on how to improve its processes – both as individual organisations and as a supply chain – and eliminate waste. Additionally, it shows differing dependence in the two cases between the activities needed to produce a construction 'product' and deliver it to the customer. In case of continuous flow (Case I), supply chain actors become a lot more dependent on each other and therefore, tend to support each other by helping and/or taking over activities outside their usual scope, beyond the boundaries of their organisation. Moreover, it creates a learning loop of correct implementation of all discoveries onto the next product.

This paper gives an example and the results of the combined application of lean principles to SCM, where a supply chain based on long-term collaboration, is trying to integrate their activities. This way, it provides readers with the necessary insights to take an important step in implementing SCM in construction.

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3D CONCRETE PRINTING IN THE SERVICE OF LEAN CONSTRUCTION

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Abstract: with the current conventional construction practices, the application of lean thinking is deemed challenging. Yet the introduction of 3D printing to the construction industry seems to bolster the lean philosophy goals. The literature, however, has not yet sufficiently addressed the correlation between 3D concrete printing and lean construction. Thus, this research aims at uncovering the complementary relationship between the two. The study is based on mapping the value stream of the construction process of a residential house using data extracted from an actual project. Value stream mapping is conducted for both methods of construction, the conventional method and 3D concrete printing. Comparing the value stream maps revealed a 60% reduction in the production lead time. Further analysis unveiled reduction in construction cost, especially labour cost, minimization of different types of waste as well as improvement of quality. Such achievements satisfy the essential goals of a lean process including higher quality, lower cost, and shorter lead time.

Keywords: Lean construction, 3D concrete printing, traditional construction, value stream mapping

1 INTRODUCTION

Since its introduction into the construction industry, the lean ideal, which consists of giving customers what they want “instantly” and without waste (Liker 2004), seemed to be very far from realization. Approaching such a goal could be made possible by adopting various lean tools and principles in construction. Minimizing various types of waste including waiting, defective work, unnecessary movements or transport, and others (Liker 2004) can reduce construction cost and duration. Other lean tools such as Jidoka (i.e. stopping the work to fix quality problems), standardization of tasks, and use of visual control (Liker 2004) can improve work quality and, thus, increase value.

Nevertheless, traditional methods used in building a house cannot fully satisfy a customer interested in a sophisticated architecture due to the increased complexity and augmented cost of building the corresponding formworks. Also, the completion time of a simple housing construction project would span around 6 months on average (Edge 2000). Thus, delivering maximum value to the customer in terms of fast construction and minimum waste remains difficult to fulfil using traditional construction methods. Yet a real breakthrough with respect to this occurred when 3D concrete printing technology was introduced to the construction industry.

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Contour crafting, a construction automation technique, was first introduced by Behrokh Khoshnevis in the mid 1990's (Bos 2016). It is an additive manufacturing technique based on layered fabrication that is applicable to the construction of large structures. To transform a 3D model to a built structure, this technology employs computer control to create smooth and accurate planar subsequent layers of extruded materials (Khoshnevis 2004). It produces smooth surface layers by delineating the extruded materials using vertical and horizontal trowels (Hwang and Khoshnevis 2005). It is worth mentioning that a wide research has been focused on the materials that could be considered for 3D printing. Such materials comprise a variety of possible constituents including concrete, bioplastic, construction waste, steel, gypsum, and others (Labonnote et al. 2016). Other studies investigate the requirements that the mix design should meet including extrudability, buildability, adhesiveness, and strength (Malaeb et al. 2015).

At a time when quality of work is low, labour efficiency is low, site accident rate is high, and construction control is complex, 3D concrete printing appears as a revolutionary technology in construction (Khoshnevis 2004). In fact, remarkable and promising contributions by the technology has been already proven in a study conducted on 3D buildings that were printed in China (Feng 2014): (1) it is (+10) × faster than traditional construction, (2) it has a low cost since a few construction workers are needed, no formworks are required, and structure optimization to save materials is possible, (3) it allows to easily print high-cost curved buildings and sophisticated architectures that are hard and, sometimes, impossible to build in other ways, and others. In actuality, 30%-60% of savings in construction waste, 50%-70% reduction in production time, and 50%-80% cut in labour cost could be recorded (Whirlwind Team 2016). Such achievements greatly support the three pillars of the lean ideal; time, cost, and value.

Moreover, 3D concrete printing has the potential to greatly contribute to achieving various lean principles in construction. Work by Rouhana et al (2014) highlighted some contributions of 3D concrete printing that relate to lean principles including quality at bay, waste, standardization and continuous improvement, and target costing. However, in spite of this strong correlation between 3D concrete printing and lean philosophy, no other similar research has yet been conducted. Such a correlation could be illustrated using value stream mapping. A value stream map (VSM) allows a visual representation of material and information flows throughout a production process (Rother and Shook 2003). It provides a "door-to-door" analogy which reveals how transitions occur among various processes (El Sakka et al. 2016).

Thus, the aim of this paper is to elaborately show how 3D concrete printing complements the lean philosophy. The study is based on drawing the VSM's of the construction process of a residential house using both methods, the traditional method and 3D concrete printing. Finally, the maps are studied and compared from a lean perspective, and the lean benefits of using 3D concrete printing are pinpointed.

2 METHODOLOGY

In order to attain the goal of this research, a definite methodology was followed. First, a literature review was conducted to explore the various contributions 3D concrete printing has helped realize in the construction industry. An actual building project was then used to collect data on production rates necessary for mapping the value streams. Based on this data, VSM's were drawn for the construction process of a residential house assuming similar phases of slab-on-grade construction for both methods. A value stream

subsumes all the value adding as well as non-value adding actions necessary to bring a product from concept to delivery (Lean Lexicon 2003).

A floor plan drawn using Autodesk Homestyler software, illustrated in **Error! Reference source not found.**-a below, is adopted throughout the study. The footprint is 100 m^2 ($10\text{ m} \times 10\text{ m}$) with a total walls length of 60 m, a wall thickness of 20 cm (Refer to Figure 1-b) , and a clear height of 3 m. It is divided into four square rooms ($5\text{ m} \times 5\text{ m}$) with one exterior and three interior $2\text{ m} \times 0.9\text{ m}$ doors and four $0.8\text{ m} \times 1.2\text{ m}$ windows.

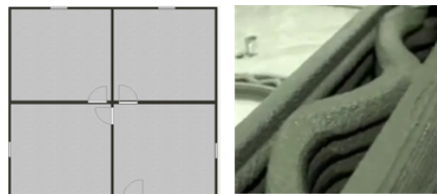


Figure 1. a- Floor Plan / b- Wall Section Layout (Hewitt 2010)

In the conventional method and for simplification purposes, all the walls, interior and exterior walls, are considered to be made of reinforced concrete. As for the 3D concrete printing technique, all the walls are post tensioned. For a sound comparison, in both types of construction, the roof is made of precast pre-slabs overlaid with 10 cm of concrete top slab.

For the traditional house construction, production values corresponding to different stages of construction are taken from an actual project. As for the 3D concrete printing technology, durations are computed based on an assumed nozzle speed of 15 cm/sec that matches the literature values. It should be noted that such a speed is contingent on many factors including the set up and the operation of the 3D printer.

For the conventional method, the unit of flow used for drawing the VSM is $5\text{ m} \times 3\text{ m}$ of surface area (i.e. equivalent to a wall) for the construction of vertical elements and $5\text{ m} \times 5\text{ m}$ of surface area (i.e. equivalent to a room's roof) for the construction of horizontal elements. For 3D concrete printing, selecting a single realistic unit of flow is more problematic since the building process does not have a cyclic nature. Thus, the unit of flow is considered only a function of surface area for now and is later clarified.

3 CONVENTIONAL CONSTRUCTION

Production rates needed for mapping the value streams are mainly taken from the case study project. The data is summarized in Table 1 below.

Table 1. Production Rates

Task	Rebar Installation	Formwork installation	Walls Concreting	Formwork Removal	Precast Installation	Slab Concreting
Production Rate	0.03 MANHR/ 1kg	1.4 MANHR/ m^2	2.5 MANHR/ m^3	0.35 MANHR/ m^2	0.12 MANHR/ m^2	1.75 MANHR/ m^3

The following calculations and assumptions are necessary for drawing the VSM.

- The total formwork area excluding doors and windows is

$$60 \times 3 - 4 \times 2 \times 0.9 - 4 \times 1.2 \times 0.8 = 169\text{ m}^2$$

- The quantity of vertical and horizontal reinforcement is computed based on the minimum requirements for concrete walls rebar. The minimum requirement is #4 steel bar with a maximum separation of 4 inches (American PolySteel, 2005). In this study, a total number of 66 vertical bars distributed along the perimeter and 3 horizontal bars along each wall are installed. The unit weight of a #4 steel bar is 0.996 kg/m. Thus, the total weight of reinforcement is approximately $0.996 \text{ kg/m} \times (66 \times 3 \text{ m} + 3 \times 60 \text{ m}) = 377 \text{ kg}$.

The total number of hours needed to install all the bars is $377 \text{ kg} \times 0.03 \text{ MANHR/kg} = 11.3 \text{ MANHR}$.

The equivalent production rate would then be $11.3 \text{ MANHR} \div 169 \text{ m}^2 = 0.067 \text{ MANHR/m}^2$.

- The production rate for concrete in MANHR/m^2 is

$$2.5 \text{ MANHR/m}^3 \times 0.2 \text{ m} = 0.5 \text{ MANHR/m}^2$$
- It is assumed that there are 1 steel fixer and 1 labourer for rebar installation, 2 carpenters and 2 labourers for formwork installation, 4 labourers for concreting, 1 carpenter and 1 labourer for formwork removal, and 1 skilled and 2 unskilled labourers for precast slabs installation. Accordingly, each rate is divided by its corresponding number of workers to be used in cycle time calculation.
- Vertical formworks are removed after 1 day after installation and roof installation starts after all the vertical elements are finished. The available working time is 8 hours per day, and construction proceeds continuously without any disruptions due to unforeseen or any other conditions.
- In a manufacturing process, lead time corresponding to inventory between different stages is determined by dividing the inventory quantity by the customer demand per day. In this study, the time for which inventory is waiting without any processing is more a function of the production rate of the subsequent process because the authors have assumed minimal overproduction between the stations. Hence, the inventory between stations is kept to a minimum.

The VSM for the conventional construction process of the house is displayed in Figure 2.

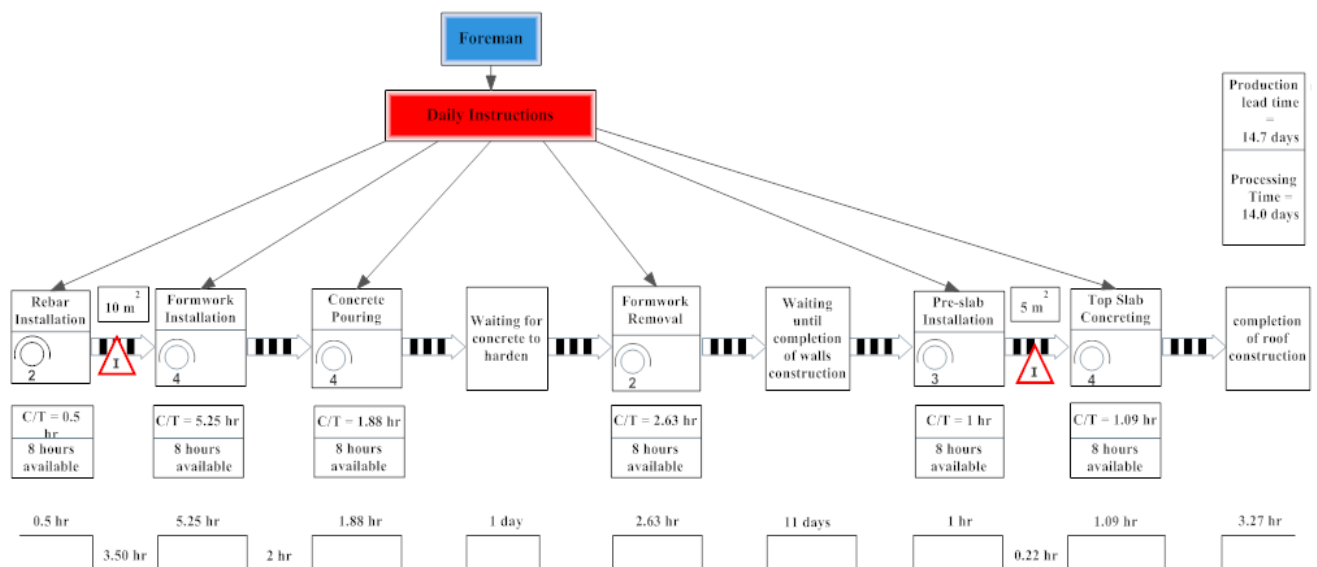


Figure 2. VSM for Conventional Construction

4 3D CONCRETE PRINTING

With a speed of 15 cm/sec, the printer takes 6.67 mins to deposit concrete layers along the whole perimeter of 60 m. Each layer is considered to have a depth of 5 cm and a filament width of 5 cm. The printer is directed not to deposit concrete at the locations of doors and windows.

Based on this information, the production rate of concrete printing is
 $(6.67 \text{ mins}) / (60 \text{ m} \times 0.05 \text{ m}) = 2.22 \text{ mins per } 1 \text{ m}^2 \text{ of vertical surface area}$

The printing process is divided into multiple stages as doors and windows impose modifying the commands fed into the printer. The first stage consists of printing concrete layers up to the bottom of the windows, a total surface area of $1.2 \text{ m} \times 60 \text{ m} = 72 \text{ m}^2$. Note that the widths of the doors were not subtracted from the total perimeter since the printer has to cross over them anyway. In the second stage, layers are printed up to the top of the windows which is designed to be aligned with the top of the doors in this study. This corresponds to a total area of $0.8 \text{ m} \times 60 \text{ m} = 48 \text{ m}^2$. This is followed by the installation of 8 precast lintels above windows and doors, a stage for which about 30 mins are allocated. The third stage comprises completing the printing process of the walls. This is equivalent to an area of $1 \text{ m} \times 60 \text{ m} = 60 \text{ m}^2$.

The concrete is left for three days to harden before post-tensioning is done. Tendons are to be placed every 6 m along the perimeter of the house. Thus, a total of 11 ducts are installed at equally spaced intervals of 6m. Half an hour is allocated for installing and tensioning tendons in each duct and, thus, a total of $11 \times 0.5 = 5.5 \text{ hr}$ are required for completion. This duration is converted to mins/m^2 to be used in the VSM as follows:

$$(5.5 \text{ hr} \times 60 \text{ mins/hr}) / (3 \text{ m} \times 60 \text{ m}) = 1.83 \text{ mins}/\text{m}^2$$

Post tensioning the tendons is followed by grouting the space left in the hole in order to establish a bond between the duct and the printed concrete. This could be easily done using the printer and can be completed within a few minutes. Yet a production rate of 5 mins/duct is used and is converted as follows:

$$(5 \text{ mins/duct} \times 11 \text{ ducts}) / (180 \text{ m}^2) = 0.306 \text{ mins}/\text{m}^2$$

Note that the unit of flow for these two stages is the tributary area corresponding to each duct, an area of $6 \text{ m} \times 3 \text{ m} = 18 \text{ m}^2$. Laying concrete over pre-slabs consists of printing $2 \times (10 \text{ m} \div 0.05 \text{ m}) = 400$ filaments that are 10 m long. These are equivalent to a total length of 4000 m of which printing necessitates $(4000 \text{ m} \div 0.15 \text{ m/sec}) \div (3600 \text{ sec/hr}) = 7.41 \text{ hr}$. Thus, the relevant production rate is $(7.41 \text{ hr} \times 60 \text{ mins/hr}) \div 100 \text{ m}^2 = 4.44 \text{ mins}/\text{m}^2$.

The VSM for the construction process using 3D printing is represented in Figure 3.

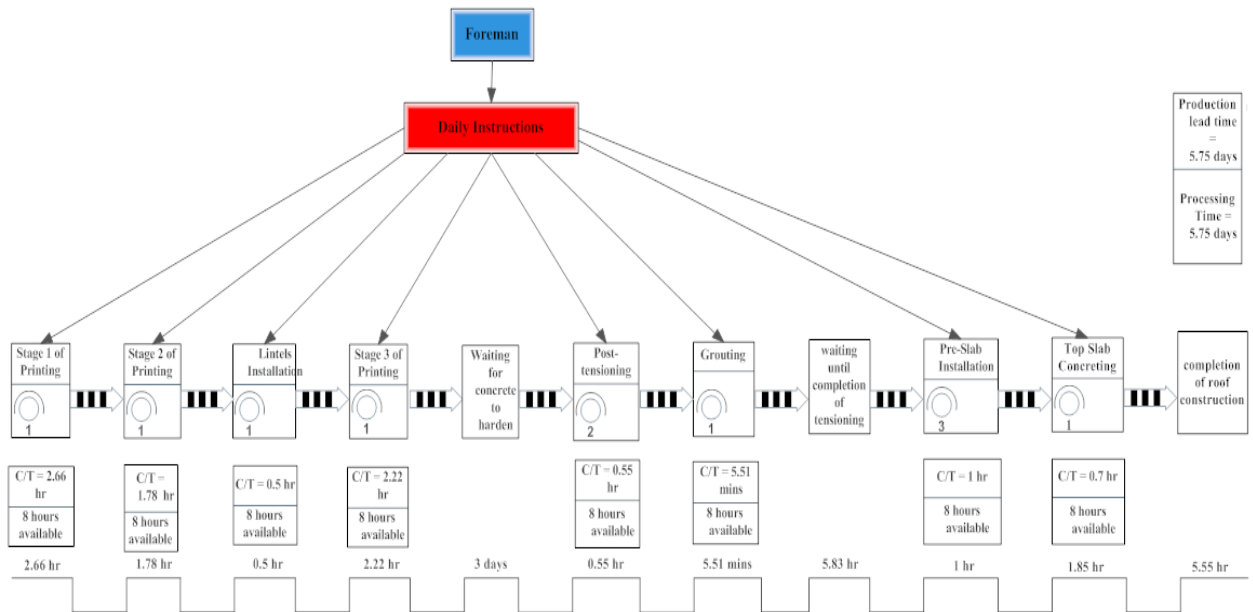


Figure 3. VSM for 3D concrete printing

5 COMPARISON AND LEAN ANALYSIS

The major lean enhancements that 3D concrete printing brings about are discussed in the following subsections.

5.1 Lead Time

The most noticeable improvement 3D concrete printing helps achieve relates to the delivery time of the house. It also occurs that such an improvement is deemed an essential goal in a lean environment (Liker 2004). Building the house using the conventional method takes around 15 days while 3D concrete printing requires only 6 days. Note that the latter duration can be further reduced if another reinforcement technique is to be used. Recall that 3 out of 6 days were allocated to allow concrete to harden before post-tensioning is done. Thus, a 60% reduction in the total construction duration is realized. This signifies a much faster response to the customer's needs.

5.2 Waste

Production lead time in the conventional method is greater than the actual processing time with approximately one-day difference. Note that this difference for such value stream maps depends on the selected unit of flow which in turn affects the quantity of inventory between subsequent processes. This unit was chosen, however, to be as close as possible to real life scenarios. Assuming similar conditions, this difference is eliminated in the 3D concrete printing technique resulting in a more lean process since inventory is classified as a major type of waste from a lean perspective.

Moreover, the conventional method of construction necessitates considerable movement of employees to transport materials and parts especially forms and the large number of steel bars in addition to all the necessary accessories. This transport of materials is considered waste and is greatly minimized/eliminated in the form-free construction, 3D concrete printing.

Finally, 3D concrete printing eradicates another form of waste which consists of producing and, consequently, correcting defective parts. This is clarified in the following subsection.

5.3 Jidoka and Quality

It is good to first note that many concrete problems that usually occur in form construction such as honeycombing, airholes, sand streaks, segregation or others are avoided since no formwork is used. This results in producing much less defective work from the first place. One advantage of using 3D concrete printing resides in the fact that problems that might occur during concrete pouring are made visible. Such defects are usually hidden by forms and are only exposed after stripping the forms. Repair and rework are then needed. In 3D concrete printing, any defect that occurs while extruding concrete filaments is easily spotted and, thus, can be directly treated before another layer is deposited. In fact, it is mandatory to stop and fix the problem because one defective layer at the bottom of a wall disrupts the pattern of all the subsequent layers. This fulfils the purpose of Jidoka which consists of never allowing a defect to pass to the next station (Liker 2004).

Therefore, 3D concrete printing enhances the quality of the final product as it imposes in-station quality control and facilitates error proofing. A better quality increases the product value in the eyes of the customer.

5.4 Cost

One advantage when it comes to 3D concrete printing is cost related. In fact, a Chinese company built ten houses in one day with a construction cost of approximately 4500\$ per house (Feng 2014). Many factors accompanying 3D concrete printing lead to a lower construction cost. To start with, 3D concrete printing necessitates much less labourers than conventional construction. For instance, one operator of the printer can replace all the labourers needed for shuttering and concrete works, a total of 8 workers in this study. Also, some materials as well as activities are not needed in 3D concrete printing; forms along with all their accessories are not used, vibrating concrete is not done, and some finishing operations are not needed. Not to forget that the construction duration is much shorter for 3D concrete printing. This results in a major cut down on overhead expenses in addition to labour and equipment costs. Finally, construction using 3D concrete printing requires less supervision as fewer labourers are involved in the process leading to an even lower cost. Nevertheless, it should be noted that the cost of 3D concrete printers is currently high. Thus, detailed studies will be later conducted to address return on investment analyses for 3D concrete printing.

6 CONCLUSION

A wide research aims at integrating the lean philosophy into the construction industry. The construction industry might seem very far from perfection from a lean perspective. Reducing cost and time is usually very challenging when it comes to construction. Quality improvement is easier but is mostly realized at the expense of cost and time. Yet introducing 3D printing to construction may tip the scales. It greatly serves the lean goals including time, cost, and quality. Production lead time could be reduced by up to 60% and even more if the process is better designed and optimized. Cost could be greatly reduced as less labourers, materials, and equipment are needed, less overhead expenses are spent, and less supervision is required. Finally, quality is improved due to a proactive

rather than a reactive environment for treating defects. Moreover, the fact that construction using 3D concrete printing is much more automated than conventional construction implies less uncertainty in the system. Fluctuations in the construction process and human errors are set to a minimum. Hence, quality is significantly ameliorated. Therefore, 3D concrete printing brings a lot of value to the customer and, hence, helps approaching the lean ideal.

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LEAN OPPORTUNITY ASSESSMENT OF CONTRACTORS' SUPPLY CHAIN IN SOUTH AFRICA

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Abstract: Although lean construction is now widely known and practiced by contractors in the developed world, contractors in developing countries such as South Africa are either unaware of it or just beginning its implementation. However, the application of lean construction practices is reported to occur with a gap between training/teaching and the actual reality of a company. To bridge this gap, a lean opportunity assessment (LOA) is usually used as a start. This paper is about LOA that was conducted among five contractors in the Free State province of South Africa. The aim of the multiple case study research design was to perform the LOA so that areas in which lean practices are in need of enhancement can be established and motivated. The study adopted an LOA protocol from the "lean supply chain and logistics management" book by Paul Myerson and then conduct further interviews to obtain more views on the LOA variables. The variables include internal communication, visualisation and workplace organisation, operative flexibility, continuous improvement, mistake proofing, quick changeover, quality of inbound and outbound materials, supply chain, balanced flow of work, total productive maintenance (TPM), pulling tasks on site, and standardized work. The data suggest that the five contractors have to address weak continuous improvement, physical construction activities, mistake proofing, and performance measurement practices in their companies.

Keywords: Assessment, Contractors, Construction, Lean, Supply Chain

1 INTRODUCTION

The application of supply chain management (SCM) concepts in construction appears to be marginal (Emuze & Smallwood, 2013a). The relative paucity of research work on SCM is existing side-by-side with the proliferation of horizontal contracting mode where almost all construction projects are undertaken and delivered by multiple parties with divergent interest (Shakantu, Tookey, Muya, & Bowen, 2007). The lack of empirical work is existing side-by-side with poor project delivery performance in construction. The principal problem of the research that is reported in this paper is 'the wrong management of supply chains may have contributed (or currently contributing)

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to sub-optimal delivery performance of projects in South Africa'. The reasoning behind the postulated problem is that SCM is now a confirmed practice in the country due to the nature of the industry (Benton & McHenry, 2010; Khalfan, McDermott, & Cooper, 2004). However, there appears to be performance problems in supply chain processes (Fontanini & Picchi, 2004; Emuze & Smallwood, 2013b).

To solve this widespread problem, some associated studies are underway in a South African research unit. This particular survey forms one of such studies, and it is aimed at assessing lean opportunities in South African construction, especially the supply chain aspect. In production environments, the best point to start a lean journey is to perform a Lean opportunity assessment (LOA) so that potentials for improvements in each company can be identified for benchmarking against best practices. The LOA addresses key performance areas in which contractors can make recovery. The LOA constitute a 'situation analysis' to each company regarding organization performance. It is important to state that LOA assessment is not done to generalize the causes and effects of a problem. Rather, it is done to know the status quo regarding lean implementation intentions of a single company. The deployment of LOA is common because of what is termed 'lean failure', which happens when lean initiatives fail in a company (Doolen & Hacker, 2005). Myerson (2012) contends that the main reason for Lean failure is lack of proper organizational and work culture to support radical changes in a lean journey. Through the use of problem-based learning, case studies and general train-do method, the implementation of lean have advanced in recent years, especially in developed and emerging economies. Despite the recorded progress, some authors have reported that there is a gap between the 'train' and the 'do' (practice). This gap between general lean training and how to implement the process is why doing an LOA is important (Myerson, 2012). The LOA is done to help a company to identify the potential for improvement by analysing various aspects/work processes from a lean perspective.

Within the lean construction research community, the assessment of lean readiness of either an entire industry (Abdul & Roza, 2006) or a particular company has been done to identify areas of improvement (Etges, Saurin & Bulhoes). In the case of a particular company, value stream mapping (VSM) provides leeway of highlighting weak areas to be addressed by the work team. Evidence from past Value Stream Mapping (VSM) based IGLC papers (Arbulu & Tommelein, 2002; Björnfot, Bildsten, Erikshammar, Haller, & Simonsson, 2011; Fontanini & Picchi, 2004) imply that when a visual map of value stream is created, people in a company would agree on how value and waste are produced in their processes.

2 METHODOLOGY

This research was conducted to establish how contractors in South Africa can begin to consider and adopt lean construction practices. To realize the intent of the study, a multiple case study research design was used based on its suitability for addressing the 'how' questions in research (Thomas, 2015; Yin, 2013). The study was conducted with construction contractors operating in the central region of South Africa. The selection of the companies was based on purposive sampling techniques (Ritchie, Lewis, & Elam, 2003). Out of the eleven contractors that were approached, only nine agreed to participate in the study. However, the screening of the completed survey questionnaire reduced accurate responses to five companies. Two techniques were used for the

collection of primary data from the companies – survey questionnaire and follow-up semi-structured interviews. The field work started with the survey questionnaire that was compiled from the LOA template provided in Myerson (2012). From page 237 to 248 in Myerson (2012), a reader can discern what is relevant regarding the assessment of a company in need of lean adoption. Apart from Myerson (2012), other LOA templates can be used for similar business self-assessment/evaluation. In brief, the template in Myerson (2012) was modified to suit construction contractors instead of manufacturers. The close ended questions in the template are on a scale of 1 to 5 and each category have a minimum of four variables (questions) and a maximum of eight variables (questions). The variables in each category range from 4 to 7. The questionnaire produced from the adaptation is freely available from the lead author of this paper. The analysis is after that rated against best practices (see Table 2 for illustration). The template in Myerson (2012) highlights areas to be evaluated regarding internal communication, visual systems and workplace organisation, operator flexibility, continuous improvement, mistake proofing, quick changeover, quality, supply chain, balanced production, total productive maintenance, pull system, standard work, engineering, performance measurement, and customer communication.

From these areas, 15 areas were revised and used for the contractor LOA survey in South Africa as shown in Table 1. With the use of two field workers who co-author this paper as evaluators, users of the questionnaire rated their performance in each category. The results of the rating are compared to Lean best practices to see where opportunities for improvement exist in their companies (please see Table 2 for illustration). The protocol for the administration of the LOA form was followed by:

- Notifying the key people in the contracting companies before the actual data collection.
- Obtaining the organogram of the contractors to identify functional managers for each category of the LOA to be completed.
- Sending the LOA, at least, a week ahead of the evaluation.
- Explaining the rationale behind the LOA evaluation.

After the collection of the self-administered questionnaire data and its descriptive analysis as described in Myerson (2012), additional interviews were conducted with the contractors who are hereafter labelled C1, C2, C3, C4 and C5. The five interviews were recorded and transcribed verbatim (Gugiu & Rodriguez-Campos, 2007; Longhurst, 2009; Yin, 2013). After transcription, the resultant information was analysed using content analysis method (Krippendorff, 2012). The resulting information from the analysed data were validated using follow-up discussions, which serve as a way to double check perceptions recorded in the field work.

3 RESULTS AND DISCUSSION

3.1. Opinions from LOA survey

As mentioned in the methodology section, organizations wanting to begin a lean transformation often ask, “Where do we start?” (Myerson, 2012). Even companies in the middle of a Lean transformation strategy must also determine the status of their progress to know the opportunities for enhancing the policy. The LOA is used to tackle such questions by assessing and measuring the potential for improvement and lean implementation success in a company. Depending on the size of a company, LOA is

done between 5 to 30 days and it usually involves management and operational staffs. In this study, functional management and operational teams of the contracting companies were involved and the entire duration of the exercise did not exceed a month. It stretches to a month because of the need to visit the contractors located in different cities multiple times in 2016. The LOA itself is made up of 15 categories and a total of 80 questions. To compute the percentage of each group based on the responses that were recorded and evaluated, percentages for individual category was assessed by dividing the total score in category by the maximum possible score. For instance, the maximum possible score in a category with four questions is 20 because the points range from 0-5. Based on this procedure, Table 1 was produced from the LOA.

Table 1: Lean opportunity summary for five South African contractors

Lean Practices	Score (%)					Practice Average (%)	Rank
	C1	C2	C3	C4	C5		
Construction supply chain	63	80	100	83	100	85	1
Client communication	75	70	85	90	80	80	2
Visualization & workplace layout	60	67	57	80	97	72	3
Internal communication	74	60	89	69	43	67	4
Quality of movement of materials	48	48	72	68	92	66	5
Balanced flow of work	60	60	75	60	60	63	6
Quick activity changeover	60	48	56	60	80	61	7
Worker/operator/driver flexibility	44	64	48	68	68	58	8
Pulling tasks	72	60	48	68	0	50	9
Total productive maintenance	51	60	83	49	0	49	10
Standardized work	40	68	60	64	0	46	11
Continuous improvement	32	56	32	68	0	38	12
Physical construction activities	20	63	57	33	0	35	13
Mistake proofing	64	0	56	48	0	34	14
Performance measurement	0	52	20	40	0	22	15
Company Average	51	57	62	63	41		

It is notable that construction supply chain, client communication, visualization and workplace layout, internal communication, and quality of movement of materials constitute categories in which the contractors perceive that they are performing well. It is also notable that C1 record '0' score for performance measurement, C2 record '0' score for mistake proofing, and C3 record '0' score for pulling tasks, TPM, standardized work, continuous improvement, physical construction activities, mistake proofing and performance measurement. The LOA is further interpreted with the metrics provided in Myerson (2012) as shown in Table 2. The aggregated (average) percentage score of contractors shows that C3 and C4 can be likened to be using integrated supply chain as opposed to lean focus companies given the fact that lean as a strategy is lacking in the companies. Also, C1, C2, and C5 that are likened to be making Lean progress on this metric scale are only implementing work and management practices that resonate with tools and principles found in Lean.

Table 2: Company characteristic of the surveyed contractors

Category (%)	Explanation	C1	C2	C3	C4	C5
0-20	Traditional supply chain and logistics					
21-40	Getting started with lean					
41-60	Lean progress	x	x			x
61-80	Lean focus/integrated supply chain			x	x	
81-90	Lean continuous improvement culture					
≥91	World class lean supply chain					

Adapted from Myerson (2012: 247)

3.2. Perceptions from follow-up interviews

Given that the five contractors rated themselves high on the management of their construction supply chain, the follow-up interviews were used to better understand their views on the characteristics and influence of a supply chain as well as the nature of supply chain on practice. As a start, the contractors expressed different views about the importance of managing supply chain in the industry. In their opinion, managing the supply chain involves understanding the breakdown and traceability of products and services, organizations, logistics, people, activities, information and resources that transform raw materials into a finished product that fits for its purpose. The proper integration of business functions that ensures that there is cohesiveness and high performance was also mentioned. These views were not at variance with the description of the supply chain in the literature. In fact, C2 (contractor 2) characterized supply chain as directing all material to the construction site where the object is assembled from incoming materials.

However, the contractors differ on how the characteristics of supply chain influence project delivery. One contractor stated that the features of a supply chain affect the effectiveness of supply information across a site, from management to workers so as to make sure that everyone understands their role. The contractor noted that *“On a building project, design consultants are first tier suppliers, working for the client, and the contractor has a supply chain of subcontractors and specialist suppliers.”* Another contractor said that *“there must be roles played in every tier and the characteristics of supply chain will be performed by each as best as their roles require them. All material needed for assembling a certain structure in a construction site will be delivered on time to speed up the assembling of a structure on a construction site.”* These responses show that the contractor knows what it means to work with subcontractors and suppliers in an environment where projects are delivered by multiple parties (Emuze, 2013; Emuze & Smallwood, 2013a).

As a result of these views, the interviewers asked the contractors to describe their individual supply chain in practice. The contractors indicate various ways in which supply chain is practiced in their organization. For example, C1 says, *“Supply chain at our company is agile where communication is much easier and the young employees at the company can adapt to the constant change in the channel of communication. Although to a great or complex projects, responsibility and performance cascades down the supply chain to a plethora of suppliers sometimes unknown to management at the*

top of the chain". In addition, C2 says, "our system can be described as healthy and flexible because as we have been able to adapt to changes whilst still managing to maintain good communication and relationship within the various structures in and out of the company" whereas C3 perceive that in the companies, the supply chain works well because channels in procuring items are followed before an activity can take place.

When asked "how are construction events organized on site to enhance productivity", C1 notes that the key to SCM is to provide a strategy that aligns it with the project program, which shows the schedule of works to be completed. He further stated that the strategy starts at the design stage, scoping the work into packages straight to site so that each work package can be directed to the required working space on site. C2 also states that activities will be organized strategically starting from the design stage where work is divided into packages and then these activities will be sent to respective areas on site where they are required. C3-C5 concur with this idea as they report that activities are organized on site to enhance productivity by the use of plant and equipment schedule, labour's schedule, material schedule and making sure that all works are finished with specified time frame.

In particular, the contractors use their relationship with suppliers to buttress their points regarding supply chain practice. For instance, C1 says that "The suppliers know each of their roles to play in every given project and deliver quality products." The interviewed contractors note that their reported good relationship with suppliers is responsible for their ability to deliver quality projects. C3 said, "If I were to rate our relationship with our suppliers will give it nine stars simply because when we place an order they will make it a point that they deliver specified material and on time." The good relationship between contractors and their suppliers should however be viewed with caution as most of them perceive that the level of professionalism keeps suppliers on their toes and this help to reassures the punctual process needed in each project." While C2 states that, "The good faith between us assures us that punctuality and quality is a standard norm in the multiple projects we engage in. This impacts our projects substantially because we are then also able to deliver on our deadlines", C3 opine that, "... our suppliers help us a lot in terms of time because they never fail to deliver on time and having material needed on site delivered on time results in high productivity."

The positive review of construction SCM by the five contractors that are not exposed core Lean principles and tools suggest that their use of Lean would only enhance and not harm their projects.

4 CONCLUSIONS

The LOA delivers crucial outputs, which include 'as-is' analysis, current-state VSM, future state VSM, and recommended improvement opportunities. For instance, Figure 1 shows where value is being delivered and where wastes may be hindering efficiency within the five contractors that were evaluated in this study. While the LOA is a first step that helps to identify, and plan for improvements, a VSM provides a road map for the journey.

As an illustration, Figure 1 gives insight into waste elimination opportunities in the work processes of the five South African contractors. The figure shows the weaknesses and strengths of the contractors regarding the need to embrace mistake proofing, ensure workflow in their physical construction activities, promote continuous improvement, standardize their work, and think about using total productive maintenance where

necessary. The embrace of the both LOA and VSM concepts would however depend on evidence to be produced through the development of current-state and future-state VSM for the contractors in 2017. It is expected that the VSM would show various connections between activities, information and material flow that can impact upon both value adding activities and wastes in the companies. The overall purpose of working with the same contractors in 2017 is to establish priorities for improvement efforts based on the LOA, encourage a common language about construction processes and create a basis for an implementation plan regarding Lean transformation.

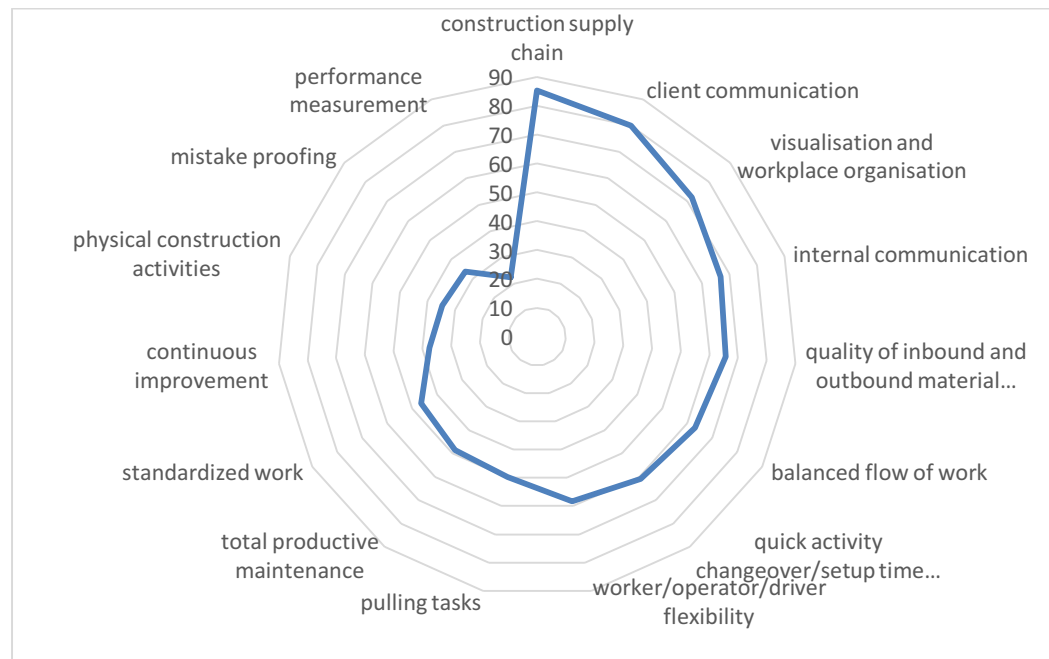


Figure 1: Lean opportunity summary graph for five South African contractors

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SUPPLY CHAIN DESIGN FOR MODULAR CONSTRUCTION PROJECTS

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Abstract: The construction sector is currently undergoing a shift from stick-built construction techniques to modular building systems. If construction supply chains are to support this transformation, they need to be modified and strengthened using an adapted logistics system. The aim of this study is to establish a mathematical model for the logistics of modular construction covering the three common tiers of operations: manufacturing, storage and construction. Previous studies have indicated that construction site delays constitute the largest cause of schedule deviations. Using the model outlined in this paper we seek to determine how factory manufacturing and inventory management should be adapted to variations in demand on the construction site. We propose a Mixed Integer Linear Programming model that captures construction scenarios with demands for modular products that are either foreseeable or abruptly disrupted. The use of the model is illustrated through a case study of bathroom pods for a building project. The model outputs include supply chain configurations that reduce total costs across a range of scenarios. The model could serve as a decision support tool for modular construction logistics.

Keywords: Logistics, modular construction, inventory, supply chain, mixed integer programming

1 INTRODUCTION

Building materials in modular construction projects are initially transported to manufacturing facilities where they are transformed into modular products (Rogers and Bottaci 1997). This process is absent in traditional construction projects (Lawson et al. 2014). Furthermore, these modular products are often large in size. Thus for construction sites with limited storage space, warehouses are needed to temporarily stock products (Azhar et al. 2013; Li et al. 2014). In these contexts, the structure of the construction supply chain is altered, because it now possesses the characteristic of both construction and manufacturing.

The logistics of modular construction also includes aspects that distinguish it from generic supply chains (De La Torre, 1994). For example, modular products such as bathroom and kitchen pods often are tailor-made and project-specific. Hence, they normally cannot be procured from other manufacturers when the production fails to meet the demand. Also, the quantity of modular products produced should match the demand from the construction sites, and consequently, the inventory will reach zero when a project ends. Furthermore, additional assembly processes and costs are required after the products are delivered to final customers (construction sites). Therefore, previous studies on

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integrated supply chains can only partially inform a new logistic model for modular construction as additional features have to be considered.

A key issue in a three-tier modular construction logistics - including a manufacturing factory, a storage facility, and construction sites - is understanding how to integrate the various elements of the supply chain seamlessly. The aim of this research is to develop a mathematical model to specify optimal configurations for the logistics of modular construction, and determine the best manufacturing rate, schedule and initial inventory level for multi-products needed on multi-construction sites under various demand profiles, so that the demand can be fulfilled at the lowest cost. Under this circumstance, the logistic system can remain competitive by operating at the lowest cost with minimal waste, in alignment with the goal of lean construction.

BACKGROUND

Supply chain integration

Supply chains are commonly modelled as dynamic systems involving multiple parties (Akkermans et al. 1999). Chandra and Fisher (1994) pointed out that in supply chain design, the activities in different tiers should be considered simultaneously to achieve high efficiency. Coelho and Laporte (2014) also suggested that decisions in production, shipment and inventory should be modelled in a single problem statement. Under this context, a single model and its solutions can serve as the foundation for tactical decision making in complex supply chain design (Adulyasak et al. 2014).

A recent review of research on integrated supply chain design by Díaz-Madroñero et al. (2015) found that a common assumption adopted by previous researchers is that the customers' demand must be satisfied at all time. Another finding in this review paper is that most of the integrated supply chain design problems studied were modelled using mixed integer linear programming (MILP), and the total operational cost of the supply chain was always set as the objective function in the model.

As with previous studies, the design of a multi-tier supply chain in modular construction can also be modelled by MILP. However, it should reflect its features that set it apart from conventional construction and generic logistics operations.

Fluctuation in the demand for modular construction products

In modern construction projects, many factors can cause schedule deviations. Gündüz et al. (2013) listed 83 distinct factors causing delays in building projects. Of these-over 90% are traced to activities within construction sites. When delays occur, progress lags behind the planned schedule and the demand for materials on sites becomes lower, which in turn would make an impact on the upstream logistics (Sweis et al. 2008). Since delays in construction schedules are almost inevitable (Sambasivan and Soon 2007), and changes in the demand often have a severe impact on the upstream logistics, their cause-effect relationship deserves special attention (Assaf and Al-Hejji 2006).

Although certain demand variations are foreseeable, some may happen unexpectedly. Illustrating these demand fluctuations in a mathematical model and identifying the optimal solution which can effectively mitigate the extra cost are problems that have to be addressed when building a logistic system for modular construction.

METHODOLOGY

Assumptions

The assumptions used in the model to represent logistics operations in modular construction projects are outlined. The factories are assumed to be able to manufacture several types of modular products simultaneously. Manufactured items are transported to warehouses, given component sizes and inventory holding restrictions. Additional costs are incurred when production rates are boosted.

Since most modular products are tailor-made with exact numbers being produced based on specific design requirements, product inventories are expected to be exhausted by the end of the project. On the demand side, modular products are transported from the warehouse to construction sites according to the daily demand for each product at each location on a just-in-time basis. It is noted that demands at each site must be met.

The model anticipates that delays may occur during construction. The case study presented later in this paper focuses on the lags triggered by foreseeable causes such as weather or abrupt disruptions.

The model

The objective of the model is to minimise the overall operational cost of the supply chain, which includes the costs of production, transportation, inventory and assembly. As such, the model seeks to determine optimal daily production rates and initial inventory amounts that can deliver the lowest overall operational cost. The following notation is used:

Indices

t	Working days; $t \in T, T = \{1, 2, \dots, NMD\}$
i	Construction sites; $i \in I, I$ is the set of sites
j	Product types; $j \in J, J$ is the set of product types

Parameters

NMD	Total period of construction in days
D_{tij}	Demand of product j at site i on day t
AC_j	Assembly cost of product j
SF_i	The fix cost at the construction site i per day
Vol_j	Volume of product j in m^3
WC	Inventory cost per m^3 per day
$WCAP$	Maximum warehouse capacity in m^3
MRM_j	Maximum manufacturing rate of product j per day
MF	The fix overhead for factory to operate per day
MV_j	Basal unitary (variable) cost for manufacturing one product j
ADJ_j	Adjustment factor for the unitary cost of product j , when production rates are boosted
LPW	Distance between factory and warehouse in km
LWS_i	Distance between warehouse and site i in km
TC	Transportation cost per truck per km
NL_j	Quantity of product j can be loaded onto a single truck

Decision variables

MR_{tj}	Manufacturing rate of product j per day at factory on day t
W_{tj}	Quantity of inventory of product j in warehouse on day t
$W_{t=0,j}$	Quantity of initial inventory of product j in warehouse

Objective function:

$$\text{Minimize: } TOC = FPC + VPC + IC + TCA + SCA \quad (1)$$

$$FPC = MF \cdot NMD + MF \cdot \text{Max} \left(\frac{W_{0j}}{MRM_j/2} \right) \quad (1.1)$$

$$VPC = \sum_{t \in T} \sum_{j \in J} MR_{tj} \cdot MV_j \cdot \left[1 + ADJ_j \cdot \left(\frac{MR_{tj}}{MRM_j} \right) \right] + \sum_{j \in J} W_{0j} \cdot MV_j \cdot \left[1 + ADJ_j \cdot \frac{1}{2} \right] \quad (1.2)$$

$$IC = \sum_{t=0}^{NMD} \sum_{j \in J} W_{tj} \cdot Vol_j \cdot WC \quad (1.3)$$

$$TCA = \sum_{t \in T} \sum_{j \in J} \frac{MR_{tj}}{NL_j} \cdot TC \cdot LPW + \sum_{t \in T} \sum_{i \in I} \sum_{j \in J} \frac{D_{tij}}{NL_j} \cdot TC \cdot LWS_i + \sum_{j \in J} \frac{W_{0j}}{NL_j} \cdot TC \cdot LPW \quad (1.4)$$

$$SCA = \sum_{i \in I} SF_i \cdot NMD + \sum_{j \in J} \sum_{t \in T} \sum_{i \in I} D_{tij} \cdot AC_j \quad (1.5)$$

The objective is to minimise the total operational cost (TOC) in Equation (1), which is composed by various costs. Equations (1.1) and (1.2) calculate the fixed and variable production costs for producing all types of products, respectively. The cost for manufacturing the initial inventory is also considered in the second terms of the respective equations. Note that the initial inventory is assumed to be produced at the half maximum production rate. Equation (1.3) calculates the inventory cost at the warehouse. Equation (1.4) calculates the transportation cost for moving products from the factory to the warehouse, from the warehouse to all the construction sites, and for moving the initial inventory from the factory to the warehouse, in the three terms, respectively. Equation (1.5) calculates the site fix cost and the assembly cost for assembling all types of products on all sites.

Subject to:

$$0 \leq MR_{tj} \leq MRM_j \quad \forall t \in T, \forall j \in J \quad (2)$$

$$\sum_{j \in J} W_{tj} \cdot Vol_j \leq WCAP \quad \forall t \in 0 \text{ to } NMD \quad (3)$$

$$\sum_{t \in T} MR_{tj} + W_{0j} = \sum_{t \in T} \sum_{i \in I} D_{tij} \quad \forall j \in J \quad (4)$$

$$W_{tj} = W_{t-1,j} + MR_{tj} - \sum_{i \in I} D_{tij} \quad \forall t \in T, \forall j \in J \quad (5)$$

$$W_{t-1,j} + MR_{tj} \geq \sum_{i \in I} D_{tij} \quad \forall t \in T, \forall j \in J \quad (6)$$

Constraint (2) states that the manufacturing rate of each type of product is within a pre-defined range. Constraint (3) ensures that the inventory volume sum for all products is smaller than the warehouse capacity. Constraint (4) makes sure that the production of modular products follows the demand on the sites. Constraint (5) represents the balance of inventory. Constraint (6) stands for the non-negativity of inventory.

Case study: bathroom pods a modular building project

The model has been tested on a case study involving delivery of bathroom pods to a new hospital project in Scotland. The case study implements a three-tier logistic structure in which two types of bathroom pods are manufactured, temporarily stored, and assembled on the three construction sites. The project duration was 2 years, and comprised assembly of bathroom pods for 344 single rooms.

RESULTS

Using a bathroom pod case study, this section presents a model which determines the most favourable production scheme and initial inventory level needed to serve multi-construction sites under two demand profiles, namely demand affected by foreseeable and abrupt disruptions. To deal with these demand profiles, two versions of the model instance have been developed using MILP and the models were implemented in IBM ILOG CPLEX Studio (version 12.6).

Dealing with foreseeable disruptions

According to previous studies (Assaf and Al-Hejji 2006; Gündüz et al. 2013; Nadu 2014), the most commonly recognised type of foreseeable disruption is inclement weather. Nowadays weather forecasts are quite accurate and easy to obtain. In addition, meteorological information such as the probability of precipitation and wind conditions can be readily transformed into variations in the demand level for building materials using mathematical equations. (Li et al. 2013; Jung et al. 2016).

For demonstration purpose, 20 scenarios of how the assembly of modular components will proceed over a 4-day period (June 24-27, 2016 in London area) with their probability of occurrence are derived from the daily weather forecast data for rain and wind conditions. Table 1 shows part of the 20 scenarios for the two module types studied, i.e. type-A and type-B bathroom pod. Here we assume that 8 type-A pods and 6 type-B pods are assembled in each of the three construction sites. In total, 24 type-A and 18 type-B bathroom pods are assembled.

Table 1: Foreseeable disrupted scenarios.

Date	June 24		June 25		June 26		June 27		Total		Prob.
	A	B	A	B	A	B	A	B	A	B	
Scenario 1	4	3	3	2	1	1	0	0	8	6	28.18%
Scenario 2	4	3	3	1	1	2	0	0	8	6	15.17%
:	:	:	:	:	:	:	:	:	:	:	:
Scenario 20	3	2	2	1	3	2	0	1	8	6	0.05%

The outputs of the model are shown in Table 2. The model initially calculates the expected demand of both pod types per day (see row 3). Then it generates the most favourable initial inventory level (row 5 – June 23) and daily production rate for the whole duration (row 4, June 24-27). Note that the costs for manufacturing and transportation of the initial inventory have been considered. In addition, the model reveals the variation of daily inventory (row 5, June 24-27).

Table 2: Output for the foreseeable disruption scenarios

Date	June 23		June 24		June 25		June 26		June 27	
	A	B	A	B	A	B	A	B	A	B
Expected demand	--	--	11	8	8	5	5	5	0	0
Production rate	--	--	6	4	7	4	5	4	0	0
Inventory level	6	6	1	2	0	1	0	0	0	0

Dealing with abrupt disruptions

An alternative model formulation was developed to address abrupt changes in the demand on sites. Here abrupt disruptions refer to unexpected events, which have negative consequences on the original construction schedule.

To demonstrate an abrupt disruption, we assumed a scenario in which a strong wind appears unexpectedly on day 2 of construction, and there is no sign of stopping over the next few days. The assembly rate drops to one half of its original value. The demand and the outputs of the model for the original scenario and the new scenario (disrupted) are shown in Table 3. Here we assume that originally 4 type-A and 4 type-B bathroom pods are assembled in each of the three construction sites per day. In total, 36 type-A and 36 type-B bathroom pods are assembled in three days (see row 4). The best initial inventory and production rate for the original scenario are also shown in rows 5 and 6, respectively.

The disrupted demand profile is shown in row 8 (day 2-5). Since the strong wind happens abruptly on day 2, the factory does not have enough changeover time to adopt a new production rate until day 3. The program thus sticks to the original production rate on day 2 and then calculates the optimal production rates for day 3 and beyond. The inventory level and production rate to generate the lowest total cost in the new scenario are given in rows 9 and 10 (day 3-5).

Table 3: Demand and output for the original and abrupt disrupted scenario

Day	0		1		2		3		4		5	
Original Scenario (no-delay)												
Pod type	A	B	A	B	A	B	A	B	A	B	A	B
Demand	--	--	12	12	12	12	12	12	--	--	--	--
Production rate	--	--	6	6	6	6	6	6	--	--	--	--
Inventory level	18	18	12	12	6	6	0	0	--	--	--	--
New Scenario (abrupt disrupted)												
Demand	--	--	12	12	6	6	6	6	6	6	6	6
Production rate	--	--	6	6	6	6	2	2	2	2	2	2
Inventory level	18	18	12	12	12	12	8	8	4	4	0	0

General discussion

This research proposed a model to output optimal logistics configurations specifically with modular construction in mind. The model incorporates several special features of modular construction. The modular products employed are generally made to order and designed exclusively to be used in a single project. This can lead to two main consequences. First, each type of module is manufactured in a quantity that matches exactly the need of the corresponding construction project, and the inventory should reach zero at the end of its assembly. Second, when the production of a module falls behind the demand, there is no way to source the module from the market. To solve this problem, this study takes the approach of building up an appropriate level of initial inventory. Here, an appropriate level means that the demand can be met under all possible scenarios, and the total cost is minimised. These characteristics distinguish our model from those developed to be used for general merchandise and traditional construction supply chains.

Furthermore, compared to the materials used for conventional construction projects, modular products are large in size. As a result, manufacturing factories and construction sites typically do not have enough space to store them. This issue is exacerbated when construction sites are located in urban settings. To solve this issue, this study adds a warehouse into the logistic system. Ideally, modular products are immediately transported from the factory to the warehouse once completed, and they are sent to the construction sites daily in response to the demand. Our model can also estimate the maximum level of inventory during the whole period of construction, providing useful information to determine the most suitable size for the warehouse.

We have developed two versions of the model instance to deal with two demand profiles. The first version is to address foreseeable demand variations in construction sites. In this study, the weather factor is used as an example. Weather is a widely accepted delay factor in construction and modern technology makes its prediction quite accurate. Our model can help a factory set up the best weekly production plan based on a weekly weather forecast. This can be a very practical application.

The second version of the model is to deal with abrupt demand variations on sites. Accidents inevitably happen, and a logistic system must be able to respond and find the best solution in the shortest time. Our model imitates the real situation, in which the production plan is not changed until the very next day after the disruption, due to insufficient changeover time in the factory. The model thus can be of great help to managers whose responsibility is to make decisions for production planning in a short time frame.

CONCLUSION

The three-tier logistics structure investigated in this research is absent in stick-built construction projects. The most favourable responses in the manufacturing factory and the storage facility following demand variations at construction sites have never been studied. The model established in this research, which finds the optimal configurations for the supply chain of modular construction, can serve as a basis for decision making.

Future work will add more features to the model, such as determining the number and location of warehouses and admitting uncertainty in transportation. The model can be tested with a larger variety of disruptions, and validated with more complete and detailed data from relevant construction projects.

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COUNTERFEIT, FRAUDULENT AND SUB-STANDARD MATERIALS: THE CASE OF STEEL IN NORWAY

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Abstract: The international construction industry is subject to several types of crime. Among the least researched is the exposure to counterfeited, fraudulent and sub-standard (CFS) materials. The study presented in this paper examines the presence of these materials in the Norwegian construction industry and the characteristics of the construction industry that render it vulnerable. A survey was sent out to different stakeholders within the industry, collecting experiences and knowledge about these types of materials. More than half of the respondents (9 of 17) stated that they pose a threat to the industry to a high or very high degree. To investigate the presence of these steel products, 3 semi-structured in-depth interviews were conducted with key actors. The data shows the occurrence of these materials in the industry. The interviewees all believed that CFS steel products exist in the Norwegian construction industry, and examples were given of the occurrence of it. The interviewees believed that the industry is vulnerable to this threat because it is easily accessible for temporary and dishonest actors, and it has a high degree of trust combined with a certain lack of controls. Further work can result in recommendations for possible countermeasures.

Keywords: materials, steel, construction industry safety, quality assurance, supply chain management

1 INTRODUCTION

Bertelsen and Koskela (2002) conceptualize production from three views: transformation, flow and value generation (TFV), with the crucial contribution from the theory being "its attention to modelling, designing, controlling and improving production from all these three points of view". Counterfeit, fraudulent or sub-standard (CFS) products threaten the whole production process, undermining all three elements alike. According to Howell (1999), some of the essential features of lean construction are to optimize the delivery process, maximizing performance for the customer at the project level, design of product and process, and the application of production control throughout the life of the product from design to delivery. Engebø et al. (2016) points out that counterfeit materials can threaten lean delivery of projects, and uses assorted steel products as an example. The essential features of counterfeit, sub-standard or fraudulent (CFS) steel products in

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Norway are though not fully explored. Equally, in the international research literature, little can be found concerning such products. Simultaneously, there are examples of both unethical and unlawful conduct in the Norwegian construction industry (Lohne et al., 2017). Therefore, this article will examine the presence of CFS steel products in the Norwegian construction industry. The research questions addressed are the following:

- 1) Do CFS steel products exist in the Norwegian construction industry?
- 2) Which key characteristics of the construction industry make it especially vulnerable to these materials?

Because steel products are under an extensive control regime, it is here defined that a breach with the CE marking (compulsory for steel construction products), implies that a product can be CFS. Because of that, the CE regime and the legislations around steel products are investigated in this article. The analysis is limited to load-bearing steel products.

2 METHODOLOGY

In order to investigate the research questions, a literature review related to steel, certificates and laws in the construction industry, a survey on CFS materials, and three semi-structured interviews were carried out. Additionally, a literature review on the characteristics of the construction industry was conducted.

After the literature review on characteristics – limited to research articles on the construction industry – a survey was conducted with different stakeholders in the industry. The survey questions were based on interviews previously done by the Construction Industry Institute (CII) (Minchin et al. 2014). The questions specifically targeted routines for quality control, and experiences with “fake materials”, which in this case was used to describe CFS materials. Although the survey did not specifically target steel, it provided valuable information about the phenomena in general. The survey was done as an online questionnaire, and was sent out to stakeholders in the industry in two rounds. In the first round, 33 possible respondents were contacted. In the second round, it was sent to 44 new possible respondents. In both rounds, the stakeholders who did not respond during the first week received a reminder. In total, 20 respondents answered the survey.

Three semi-structured interviews with senior professionals within the Norwegian industry (producer, purchaser and non-governmental certification parties) were carried out to supplement the findings in the survey. A common interview guide was developed and sent to the interviewees before the interviews. In addition to the questions listed in the interview guide, follow up questions were asked and other subjects were discussed when initiated by the interviewees, just as suggested by Yin (2013). The interviews were conducted at the offices of the interviewees, and the conversations were taped using a voice recorder application. Afterwards, the interviewees were allowed to read through the respective transcripts and comment any misunderstandings. Because of the nature of the topic researched, the interviewees have been anonymised in this article.

3 THEORETICAL FRAMEWORK

3.1 Counterfeit, fraudulent and sub-standard materials (CFS)

The following sub-chapter investigates some laws and regulations relevant to construction materials. It is essential to investigate this because of the definition of CFS materials previously given. Koskela (1992) investigates the 11 important principles for flow process

design and improvement. One of these principles is reducing variability, something that is highly related to material quality.

Actors within the Norwegian construction industry are bound to follow the “Regulation on the documentation of construction products” (In Norwegian: Forskrift om dokumentasjon av byggevarer, hereafter called DOK) (Norwegian Building Authority undated³) DOK includes regulations and rules about the documentation of products for use in the construction industry. DOK states that “CE-marking applies to those construction products where there exists a harmonised standard, or where the producer has chosen to have made a European technical assessment of the product.” (Norwegian Building Authority, undated¹). For manufactured steel constructions, the standard NS-EN 1090 is the harmonised standard that applies (Norwegian Steel Association, undated³) NS-EN 1090 consists of three parts, with two of them being relevant for steel products. Part one outlines the requirements for the conformity assessment, and part two provides the technical requirements for steel products.

A declaration of performance is obligatory for products covered by a harmonised standard (Norwegian Building Authority, 2016b). A declaration of performance describes the characteristics and use of the product (Norwegian Building Authority, 2016b). Further, there are ten different requirements that should be stated. Six of them are obligatory: tolerances on dimensions and shape, weldability, fracture toughness, the characteristics of the material when exposed to fire, hazardous elements and durability. In addition, the load bearing capacity, fatigue strength, resistance to fire and deformation should be declared (Norwegian Building Authority, undated²) (Norwegian Steel Association, 2016).

In addition to the declaration of performance, a product that is produced according to a harmonised standard needs a declaration of conformity. This is a confirmation from the producer that the product is produced in compliance with the technical specification (Norwegian Building Authority, 2016b). The requirements for a declaration of conformity, according to the Norwegian Building Authority, include information about the name and address of the producer or his representative in the EEA, description of the product, regulations that the product satisfies, special conditions for the use of the product, name and address of appointed technical organ, and the name and position of the person that has the authorization to sign the declaration on behalf of the producer or his representative.

The municipality administration is responsible for issuing a certificate of completion before the building or construction can be used. In “Byggesaksforskriften (SAK10)”, The Norwegian Building Authority states that before the construction or building can be used, a certificate must be given. The municipality must issue the certificate within three weeks (Norwegian Building Authority, 2016a). If a building is proven to be using non CE-marked products, the municipality authorities could refuse to issue the certificate of completion until the material or component has been replaced (Norwegian Steel Association, undated¹)

3.2 Characteristics of the construction industry

Ballard and Howell (1998) draw similarities between the construction industry and other manufacturing industries. They especially talk about three characteristics of the construction industry; temporality, uniqueness and on-site production. These characteristics are also investigated by Vrijhoef and Koskela (2005). They look at three fundamental characteristics, which they call site-production, temporary production organisation and one-of-a-kind product. The characteristics in table 1 are a summary of the characteristics found in the literature review. They also include characteristics mentioned by Thomassen (2004) and Dubois and Gadde (2012).

Bosché F., Brilakis I., and Sacks R. (2017). “Structural template and formatting instructions for your LC³ full paper.” In: *Proc. Lean & Computing in Construction Congress (LC³)*, Vol. 1 (CIB W78), Heraklion, Greece, pp. xx-xx. DOI: xxx/xxx/xx. [example of style ‘x-citation’]

Table 1: Characteristics of the construction industry

Source	Characteristics
Dubois and Gadde (2012)	Focus on single project, local adjustment, utilization of standardised parts, competitive tendering, marked-based exchange, multiple roles
Thomassen (2004)	Fragmentation due to many small (and often subcontracting firms), separation of design and coordination from production, highly interdependent activities, poor communication and coordination, sector troubled by low quality, late delivery and overspending
Ballard and Howell (1998)	Temporality, uniqueness, on-site production

Although all of these characteristics seem applicable to the industry, three fundamental characteristics are standing out: temporality, uniqueness and on-site production. These will be emphasised on in this article.

To complement these characteristics, it is also useful to note one peculiarity of the Norwegian society itself. It tends to, in general, have a higher trust than other countries. The World Values Survey (2005-2008) has published data from different countries, including Norway, Germany, Spain and Turkey. Table 2 shows results from the question; “Generally speaking, would you say that most people can be trusted or that you need to be very careful in dealing with people?”. (World Values Survey, 2005-2009) As can be observed, Norway stands out as a very high-trusting society.

Table 2: Data from The World Values Survey wave 5: 2005-2009 Question V23

	Norway (N=1,025)	Germany (N=2,064)	Spain (N=1,200)	Turkey (N=1,346)
Most people can be trusted	73.7 %	33.8 %	19.8 %	4.8 %
Need to be very careful	25.7 %	57.9 %	78.9 %	94.6 %

Lichtig (2006) discusses the “five big ideas” of lean project delivery. One of these is to increase relatedness among all project participants, which involves that participants must develop relationship between each other based on trust. The risk of CSF materials must be seen as a threat to a trusting relationship between actors.

4 RESULTS

4.1 Do counterfeit, fraudulent and sub-standard (CFS) steel products exist in the Norwegian construction industry?

Not much research on the occurrence of CFS materials in the Norwegian construction industry has been identified. The 2016 survey did, however, revealed such occurrence or perceived occurrence. As can be seen in figure 1, 53,0 % of the respondents (9 out of the 17 that responded to the question) believed that fake materials are a threat to the construction industry to a high or very high degree.

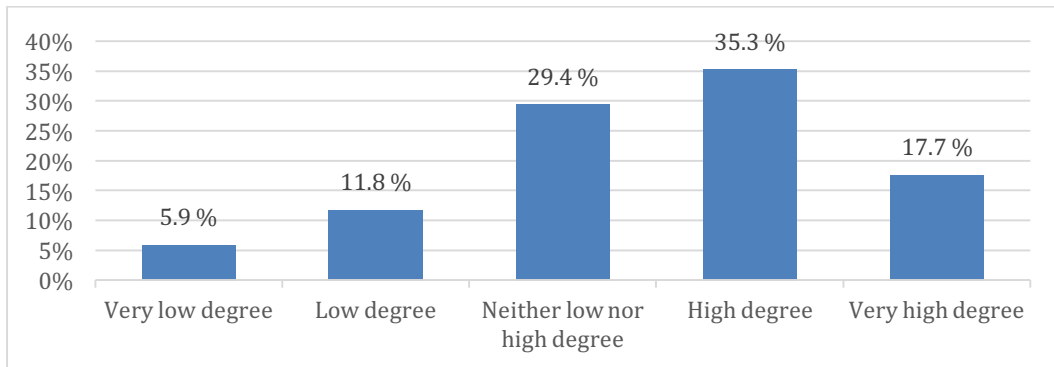


Figure 1 Q4: To what degree do you believe that fake materials are a threat to the construction industry?

Question nine was about the occurrence of such materials in the industry. Out of 17 responding, four people or 23,5 % answered yes to the question, as seen in figure 2.

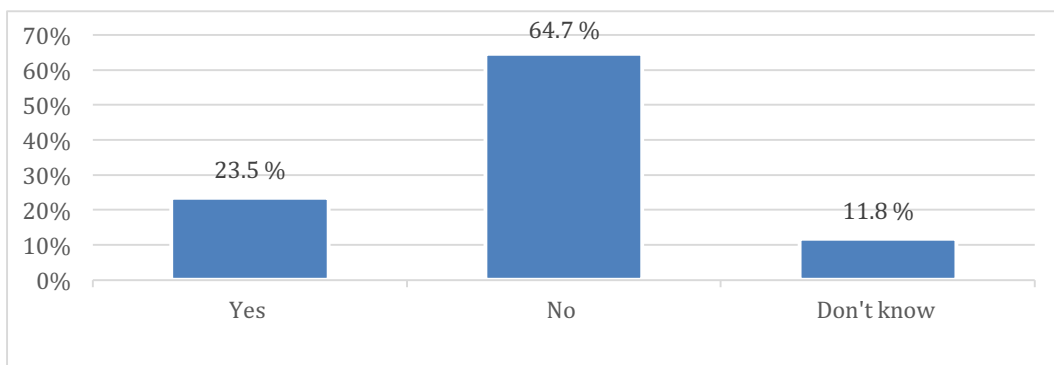


Figure 2 Q9: Have you heard (from what you consider to be credible sources) that someone was exposed to fake materials on a project you did not work on?

To uncover what kind of control functions the respondents of the survey used, they were asked about their quality control of materials. The responds indicated that although some had control procedures at reception, others had “as good as none”. The answers did not state the extensiveness of the control procedures, or whether it included inspections or just document control.

One of the question addressed whether the respondents perceived that the problem with “fake materials” was increasing or decreasing. Out of the eight, three believed that the problem was increasing, three believed that it was neither increasing nor decreasing and the final two did not know. None of the respondents believed that the problem was decreasing. In the semi-structured interviews, the interviewees were asked about the occurrence of fake materials. One of the respondents had experience with sub-standard steel products delivered to them: *“I have one case where we (...) received a steel product that (...) we later received information (about) from The Norwegian Building Authority that the certificates that were attached to the item most likely were fake or were not correct.”*

A foreign producer had delivered steel to their wholesaler, and it turned out afterwards that the producer delivering the goods was not approved for issuing the certificates. The steel was already in place in a building, and was a part of a load bearing system. The problem got to be known by the producer because they were contacted by authorities. *“We got to localise where (the steel) was, what kind of loads it was exposed to and et*

cetera, and then nothing more became of the matter after we sent over the documentation and what we had (...)”

The other interviewees did not suspect any CFS steel products on projects they had worked on. All of the interviewees had, however, heard of other projects with CFS steel materials. While one had heard about a problematic delivery, the two other had heard about specific cases with sub-standard steel. The interviewees that had heard about sub-standard steel in other problems had heard of sub-standard items:

“I know of a project in (name of place in Norway) somewhere where there was delivered steel from a foreign steel supplier (...), one steel quality was described, and it was delivered with a different steel quality.(...) There was described a higher steel quality than what was delivered.”

“I haven’t been in touch with materials where fake steel products were in a project (...), what I have heard from others is that materials that have been imported from China among other things have not had the carbon equivalent that is declared in the material, meaning that it was incorrectly alloyed. (...) And that is very serious.”

All the interviewees believed there was some risk of fake steel products existing in the Norwegian construction industry: *“Yes, I think it does (exist), but I don’t think it is... I think it’s the exception more than the rule (...) So luckily, and we should be happy about, I don’t think it’s a big problem, but (it is true) that it exists and that there are serious consequences if something happens”*.

4.2 Which key characteristics of the construction industry make it especially vulnerable to these materials?

The interviewees were asked directly which characteristics they thought made the industry vulnerable to these materials. One of the issues discussed was the accessibility of the industry:

“(...) very little is required to start a company in the construction industry. You can just buy yourself a pickup truck and a hammer and you’re started, right. So it’s an industry that has been familiar with a lot of ”cowboy-business”.

The trust in the industry was also emphasised. One of the respondents pointed at the combination of trust and a certain lack of control:

“Maybe we’re not naïve, but we (...) trust the papers that arrive. And when we never do a third party assessment or a third party control, it is, what can you say, you can’t say a bad characteristic, but an absent requirement in the construction industry. So we could wish that there be more control.”

The certain lack of control was also discussed by another respondent:

“I think the possibility for being caught (by the municipality or the authorities) is disappearingly low. And it is like with everything else: If you’re not controlled, it’s easy to cut a corner or drive too fast. So I think it’s important that the authorities do a lot more controls.”

“If no one asks those questions, we will never uncover anything. Then everyone think that everything is in order. You have the papers. You have the product. It is welded up and assembled. And everyone is happy.”

5 DISCUSSION

The findings provide evidence for the existence of CFS steel materials in Norwegian construction projects. When asked about whether they thought that fake steel products exist in Norwegian construction sites, the respondents answered that they did think so,

but they were not sure about how wide-spread it is. Although these responses could imply that the problem is not widespread, the interviewees underlined the graveness of the potential problem, and the importance of it being mitigated. The survey supports the idea that the problem is increasing.

The data presents two main characteristics that allow for the entrance of CFS materials. The first is the industry being easily accessible to temporary and dishonest actors. It is easy to establish a company and join the industry, which is quite unique compared to other industries such as offshore or aviation. This characteristic can be linked to two of the fundamental characteristics of the construction industry; the uniqueness of the product and the temporality of the projects. The temporary and dishonest actors can move between projects, close down business and start up again, and move over large distances and projects.

The second characteristic is the high degree of trust combined with a certain lack of coordinated control measures within the industry. The findings indicate that both the industry and the government have a high degree of trust in the certificates issued. It is not common to do material-testing on deliveries, instead a document control is preferred. The high degree of trust and lack of control can be linked to one of the central characteristics of the construction industry; on-site production.

6 CONCLUSION

From the interviews and the survey, there seems to be evidence for the existence of CFS steel products in the Norwegian construction industry. The survey also revealed that the respondents believe that the problems with “fake materials” are increasing. From the literature, three fundamental characteristics of the industry were mentioned. These were uniqueness, temporality and on-site production. According to the findings, it can be deduced that there are two important characteristics of the industry that render it vulnerable, the industry being accessible to temporary and dishonest actors, and a high degree of trust combined with a certain lack of control. These can in turn be linked to the three fundamental characteristics of the industry. Further work including more interviews with stakeholders in the industry can result in recommendations for countermeasures against the use of these materials. It would also be interesting to see if the same problems exist with other steel products and materials.

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OPTIMIZATION ON SUPPLY-CONSTRAINED MODULE ASSEMBLY PROCESS

Jing Liu¹, and Ming Lu²

Abstract: As off-shore prefabrication continues to gain momentum, supply chain management becomes increasingly complex for industrial modular construction projects and delays commonly occur to prefabricated modules. In order to make efficient utilization of limited module assembly resources (e.g., crews and bays) and reduce the waiting waste of materials on the module yard, a systematic optimization approach is desired to derive an optimal module assembly plan in coping with the dynamic supply chain and limited resource availability. By synthesizing information from the logistics management system, contract documents, and resources availability, a constraint programming based optimization algorithm is proposed. A case project abstracted from a real project is presented to demonstrate the feasibility and effectiveness of the proposed optimization approach. The information on module assembly start time, duration, and expected delivery time is generated to guide operations on the module yard. The minimum of total waiting time of materials on the module yard is derived for decision-making support. In conclusion, the proposed methodology seamlessly integrates principles of lean construction and constraints of resource scheduling into a constraint programming optimization formulation. This research potentially lends effective decision support to both crew work planning and materials logistical planning, ultimately leading to improvement on both construction productivity and logistical efficiency.

Keywords: Supply chain management, project scheduling, waiting waste reduction.

1 INTRODUCTION

To improve the construction industry performance, Ballard and Howell (1998) advocated the concept of lean construction, which is intended to turn the operation of construction industry into lean production while factoring in the unique characteristics of each construction process. Prefabrication and modularization is one typical case of lean construction. Over the past decade, mega processing projects have increasingly turned to pre-assembled modular construction in lieu of the conventional "stick build" construction. In Northern Alberta, Canada, the modular approach is generally adopted for executing mega oil sands projects, due to the benefits of reduction in construction cost and duration, along with improvement in quality and safety (Wu and Lu 2013).

The modular method separates the entire facility into multiple modular units in order to improve labor productivity and minimize on-site construction duration (Choi and Song 2014). For the modular construction method, each module, which is a basic building block, goes through off-site fabrication, transportation, and on-site installation. The balance among the three processes needs to be delicately maintained in order to

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minimize the waste of material, time and effort (Koskela et al, 2002). The concept of supply chain management (SCM), which was originated in manufacturing, aims to better satisfy the needs of end-customers and benefit all members in the chain (Walsh et al. 2004). However, due to productivity variability and unpredictable site demand, effective supply chain management is difficult to achieve in the construction industry compared to the manufacturing industry (Dubois and Gadde 2002; Tommelein et al. 2003). For the construction industry, instead of adopting a just-in-time (JIT) delivery method, the contractor tends to deliver the materials or pre-fabricated modules at the earliest time in order to mitigate the risk of late delivery (Tommelein et al. 2003). It would give rise to undesired wastes such as inventory waste, overproduction waste and waiting waste (Ohno, 1988).

Due to low labor cost and convenient sourcing of raw material (e.g. steel), the engineering design and fabrication of modules are usually undertaken by overseas vendors in East Asia, such as South Korea, China (Choi and Song 2014). The sizes of off-shore manufactured modules generally fit into sea containers and satisfy road traffic regulations for shipping from the manufacturers in East Asia to oil sands projects in Alberta. Part of these off-shore manufactured sub-modules will be transported to the local module yard for further assembling into larger modules based on design specifications. Other small modules are transported to the site directly for installation. A module yard is a designated open space used to assemble and store modules. Module yards are typically divided into different work areas which are called as assembly bays. Each bay is usually occupied by only one module. The entire process of overseas industrial module fabrication is shown in Figure 1.

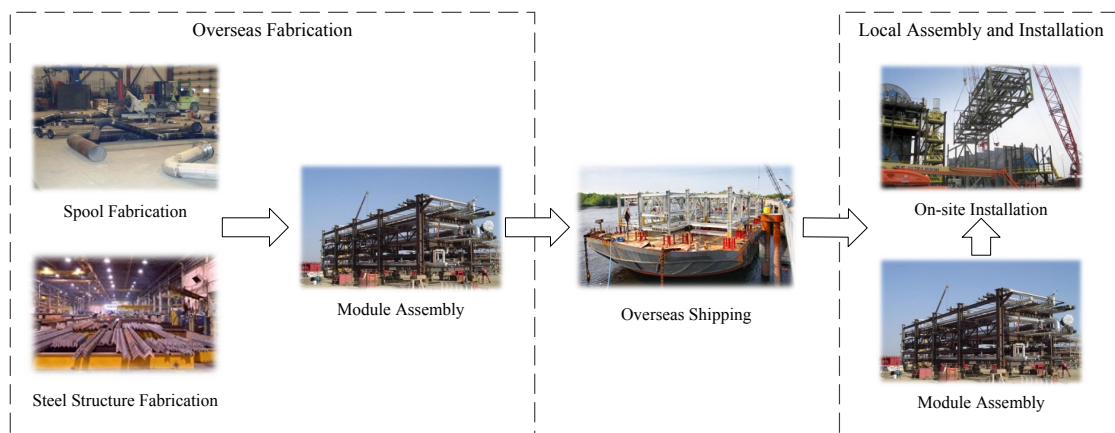


Figure 1: Overseas industrial module fabrication process

The overseas shipping process includes multiple stages of marine shipping, inland waterway shipping, and overland shipping. There are lots of uncertainties over the shipping process such as variable marine environment, the availability of transportation vehicle and local road regulations. The aforementioned supply chain management problems present risks to modular construction. Even if the module supply is planned based on on-site demands, unexpected interruptions to module fabrication and shipment can easily disrupt the original plan. In this circumstance, decisions should be made in order to mitigate the wastes potentially caused by the disrupted module supply, and in the meanwhile, the module assembly plan must meet on-site demands as closely as practically feasible. The unreliable supply of modules and the temporary nature of the module yard configuration make it difficult for project managers to update plans in a fast

and effective manner. Furthermore, decisions resulting from subjective experience often turn out to be less efficient and non-optimal. For example, Liu and Lu (2016) demonstrated "improvised" schedule strategies based on common sense to mitigate material delay would actually increase the crews' idling time and lead to further project delay. Thus, a computer-aided optimization system is needed to derive and adjust the assembly plan in the module yard, aiming to mitigate the modules' waiting time on a module assembly yard. The revised module assembly plan is made according to the most updated shipping information of manufactured sub-modules.

In this paper, a constraint programming based optimization approach is presented to optimally plan assembly sequences in the module yard by using the supply information extracted from the logistics management system, the pre-set field erection deadlines extracted from construction contract and information of limited resources available in the module assembly yard. The aim is to minimize the total module-waiting-time on the module yard while ensuring on-time delivery of required modules to the downstream value-adding conversion activities in the field. This paper is organized as follows. In the following section, the constraint programming based optimization framework is presented to show the established model in terms of how to structure, formulate and solve the identified problem. Next, an illustrative case study is conducted to demonstrate the effectiveness of the proposed framework in scheduling the sequences of consolidating large modules by considering space and crew limits at the module assembly yard, and the arrival time and waiting time of each small module on the module yard. At the end, the conclusion is given to summarize the research.

2 CONSTRAINT PROGRAMMING BASED OPTIMIZATION FRAMEWORK

In the module yard, due to the limited availability of module assembly bays and the other installation constraints, some of these small modules, which are not to be assembled within 24 hours after their arrival, are stored in a laydown area. Thus, it will cause additional storing cost and handling cost without adding any value. Therefore, the total waiting time of all small modules is set as the objective function in order to evaluate the effectiveness of a module assembling plan. The smaller the waiting time is, the more effective is the module assembling plan. The waiting time of a small module is defined as the difference between the finish time of assembling the large module (when the small module becomes one part) and the arrival time of the small module.

The proposed constraint programming based optimization framework for module assembly is presented in Figure 2. There are four elements in this framework: data sources, extracted information, optimization engine and outputs for decision-support. To optimize the module assembly plan, three data sources are investigated for identifying constraints. They are 1) the logistics management database for overseas module supply information; 2) construction contract documents for on-site demand information, and 3) module yard crew information for the availability of labor resources. The mathematical modeling process for the three constraints will be explained in detail later.

After identifying the three constraints, they are entered into the optimization engine in search of the optimum solution resulting in the smallest waiting time averaged over all small modules. There are two outputs of the optimization engine. One output is the optimal assembly plan with the start time and finish time of consolidated large modules. The other one is the total waiting time for each small module, which provides a basis for calculating the additional logistics management cost (e.g., storage cost).

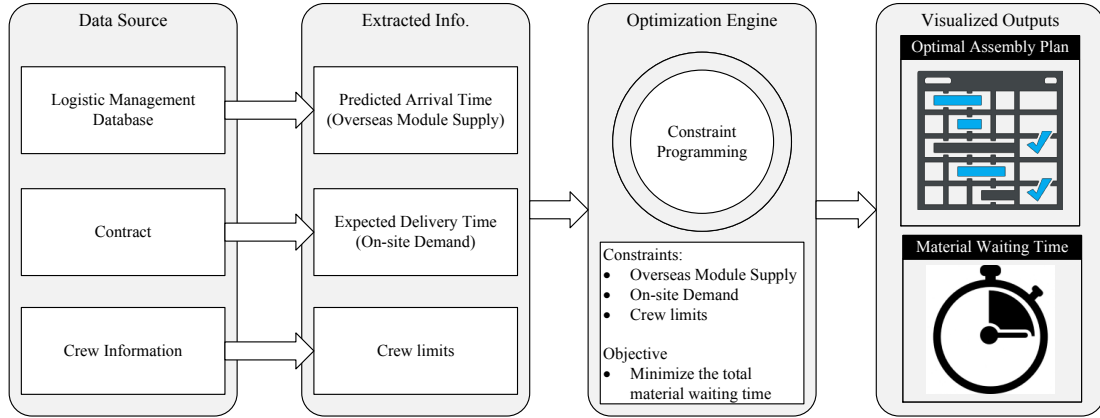


Figure 2: Industrial module construction process

2.1 Formulation of the Mathematical Model

Considering a module yard, there are n large modules to be assembled using m off-shore fabricated small modules. There are R resources (i.e., crews and bays) available in the module yard. Each large module j is composed by k small modules. As described above, the objective function, which is to minimize the total waiting time of all small modules, can be expressed as Eq. (1).

$$\min \left(\sum_{j=1}^n \sum_{i=1}^k (SF_j - T_{i,j,arrive}) \right) \quad (1)$$

where, SF_j is the scheduled finish time of the large module j ; $T_{i,j,arrive}$ is the arrival time of the small module i , which is one part of the large module j .

Furthermore, the arrival time $T_{i,j,arrive}$ of small module i puts one hard constraint on the start time SS_j for assembling the large module j , namely, the large module j cannot be started before all required k small modules have arrived at the module yard. The start-time constraint is expressed as Eq. (2).

$$SS_j \geq \max(T_{i,j,arrive}); \quad i = 1, \dots, k; \quad j = 1, \dots, n \quad (2)$$

On the other hand, the expected delivery time $T_{j,deliver}$ of large module j limits its finish time SF_j , which equals to the summation of the scheduled start time SS_j and the duration D_j . It means the large module j has to be finished before the expected delivery time. The constraint is shown in Eq. (3)

$$SF_j = SS_j + D_j \leq T_{j,deliver}, \quad j = 1, \dots, n \quad (3)$$

The crew limit R puts another hard constraint on the number of crews that can be employed in any period. Thus, the resource constraint can be expressed as Eq. (4)

$$\sum_{j \in Mod_t} R_j \leq R, \quad t = 1, \dots, D \quad (4)$$

where R_j is the required crew amount for assembling large module j ; Mod_t is the set of large modules which are already started but not finished or ready to be started at time t ; D is the total duration for assembling the n large modules. Note all the time related

variables except for duration variables (i.e., activity duration D_j and total assembling duration D) refer to time points with the start time being zero.

The mathematical model, which is shown as the Eq.(1), Eq.(2), Eq.(3) and Eq.(4), can be readily solved by constraint programming. Constraint programming is a hybrid method integrating multiple techniques in operations research (OR), artificial intelligence (AI) and graph theory (Rossi et al. 2006). It is much effective for solving complicated scheduling problems (Bockmayr and Hooker 2003). For example, Liu and Wang (2012) employed constraint programming to enhance the computation efficiency for scheduling linear construction projects with multi-skilled crews. Menesi et al. (2013) demonstrated the capability of constraint programming to handle the time-cost trade-off problem for large-scale projects involving thousands of activities. It is worth mentioning that IBM ILOG CPLEX Optimization Studio V12.6 (2016) provides a powerful toolkit for performing constraint programming and optimization, which has been utilized as the computational platform in construction scheduling research (Menesi et al. 2013; Siu et al. 2015). Hence, in this study, it was used as the computing tool to solve the constraint programming formulation and search for the optimum solution to the defined problem.

3 CASE STUDY

In this section, a case project is used to illustrate the effectiveness of the proposed methodology. The data and information for this case were prepared based on a modular construction project in Alberta, Canada. Assume 10 large modules in total are to be assembled. Three assembly bays and three crews are allocated to assemble the 10 large modules. For each large module, it is composed by 4 small sub-modules. 40 small modules are manufactured off-shore. And then each small module is packed in a sea container for overseas shipping. Due to unreliable supply process and limited assembly bay resources, the large module is only scheduled to start with assembly after all required 4 containers arrive at the module yard. Table 1 lists the required container IDs for each large module.

Table 1: Required container ID for each large module

Module ID	M1	M2	M3	M4
Required Container ID	1 6 8 15	5 16 22 26	19 24 30 32	3 9 11 17
Module ID	M5	M6	M7	M8
Required Container ID	7 10 13 14	2 4 12 18	21 27 34 39	20 28 35 40
Module ID	M9	M10		
Required Container ID	23 33 36 38	25 29 31 37		

Typically, the layout of assembly bays in a module yard changes over time as the type of modules being fabricated changes, and thus some preparation work is needed before starting to assemble one module such as changing the layout and installing structural blocks to support modules. Thanks to the logistics management system, the expected arrival time of each small module is available, the preparing work can be

finished before small modules arrive at the module yard. Thus, in the case study, it is ignored. The assembly of one large module can be scheduled on the same day with the arrival time of the last required container. In this section, different scenarios with different arrival times of small modules are assumed to simulate the effectiveness of the proposed optimization approach in coping with the uncertainties in the module supply chain, while minimizing the wastes in terms of "idling" materials as per the lean principle. The arrival times for each scenario is shown in Table 2. Scenario 2 can be treated as an update of Scenario 1: some containers are delayed due to unexpected disruptions.

Table 2: Arrival time of each small module in different scenarios

Container ID	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Scenario 1	0	2	3	4	5	5	6	7	7	7	7	8	9	9	9
Scenario 2	0	2	3	4	5	5	6	9	9	9	9	8	9	9	9
Container ID	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Scenario 1	9	10	11	11	12	12	13	14	14	14	15	15	16	16	16
Scenario 2	9	13	11	11	12	12	13	14	14	14	15	15	20	20	20
Container ID	31	32	33	34	35	36	37	38	39	40					
Scenario 1	17	17	18	18	19	19	19	20	20	21					
Scenario 2	17	17	20	20	19	19	19	20	20	21					

The expected delivery time for each large module is extracted from the contract document and listed in Table 3. The duration needed for assembling each large module is shown in Table 3 as well. Preparation tasks need to be done prior to loading the finished module onto a truck, such as fixing lugs for lifting and lashing for fixing the module on the truck. Thus, the module is required to be finished one day before the expected delivery time. For example, module M1 is expected to be delivered on Day 15, so it must be finished by Day 14.

With all the available information, the proposed optimization approach was readily applied to schedule the assembly sequence of the 10 large modules in search of the shortest total waiting time of all small modules subject to available resources, which include two crews and two assembly bays. In the meantime, the start time for assembling one large module should be no earlier than the last arrival time of the required containers, and the finish time should be one day before the expected delivery time. The optimized start time and finish time of each module for different scenarios are listed in Table 3. The total waiting time for all small modules is 298 days and 311 days for Scenario 1 and Scenario 2. The total waiting time increases due to the delay of some containers, which delays the start time for assembling the corresponding large modules, thus increasing the idling time of arrived small modules in the module yard. The proposed method can provide the plan with the least total waiting time. The related storage cost can also be derived for supporting the decision-making process.

For an actual project, the developed optimization algorithm can be run multiple times over the project duration in order to mitigate the potential increase of module waiting

wastes given the most recent module supply information. Under the fast-changing logistical conditions, the proposed methodology can provide effective assistance for project managers to make and update module assembly plans, aimed to reduce the waiting waste of materials.

Table 3: Detailed schedule information for each large module

Module ID	Assembly Duration (day)	Expected Delivery Time	Scenario 1		Scenario 2	
			Scheduled Start Time	Scheduled Finish Time	Scheduled Start Time	Scheduled Start Time
M1	5	15	9	14	9	14
M2	3	20	15	18	15	18
M3	4	25	17	21	20	24
M4	3	18	10	13	13	16
M5	2	13	9	11	9	11
M6	3	16	11	14	11	14
M7	5	31	20	25	24	29
M8	4	29	24	28	24	28
M9	4	26	21	25	20	24
M10	5	28	19	24	20	25

4 CONCLUSIONS

To improve construction efficiency, prefabrication and modularization are implemented for most industrial construction projects. However, with more and more modules prefabricated overseas, the supply chain of the industrial modular construction becomes increasingly complicated and uncertain. Module supply delay is commonly encountered in the module pre-fabrication and shipping processes, which would disrupt the ensuing module assembly plans. Module yard assembly, which is actually part of the material flowing process, precedes the final installation on site, represents the value-adding conversion activity according to the lean concept. Therefore, the total module-waiting-time on the module yard needs to be well planned and controlled such that all the "Mura" (i.e., uncertainty/inconsistency) along the flowing process prior to the module assembly yard are accommodated. In the meanwhile, the "Muda" (i.e., waiting time) at the yard is best controlled in order to feed materials to the execution of value-adding conversion activities in field erection.

In this paper, an optimization framework for implementing constraint programming is proposed to mitigate the increase on total waiting time of materials caused by uncertain module supply processes. The framework consists of (1) data sources, including contract documents, logistics management system and crew hiring documents; (2) extracted information including contractual deadline, time-dependent module supply patterns and resources availability; (3) constraint programming based optimization

engine; and (4) analytical outputs in terms of the detailed schedule of each large module and the total waiting time of small modules. Information and data were extracted from a real modular construction project in order to build a case study for demonstration and validation of the proposed framework. The resulting schedule for assembling 10 large modules is presented. The least total waiting time for small modules is derived providing a basis for calculating the corresponding storage cost. In conclusion, the proposed methodology can assist practitioners in (1) interpretation of material supply data and project scheduling data in an integrative fashion and (2) generation of the best crew job plan resulting in the least material waiting time incurred at the module assembly yard.

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VALUE STREAM MAPPING: CASE STUDY IN COLUMNS CONCRETING

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Abstract: Based on the principles of lean thinking, originated from the automobile industry, which seek to eliminate waste, practice continuous improvement and add value to the product from the perspective of the customer, some adaptations have been made to apply the philosophy of lean production in construction. Thus, this paper aims to propose improvements in the concrete placing process using Value Stream Mapping. Therefore, the research strategy adopted was the exploratory case study. The results suggest that the columns concreting process lead time could be potentially reduced from five hours and nineteen minutes to two hours and four minutes.

Keywords: Lean construction, continuous flow, value stream mapping.

1 INTRODUCTION

Architecture, Engineering and Construction (AEC) industry is a scenario that is more complex than other industries (Koskela, 1992). Problems related to productivity, job safety, labour shortages and the lack of working conditions are commonly observed in such sector. Such context has motivated several researches that seek to solve problems faced in the context.

The five basic principles of lean thinking highlighted by Womack and Jones (1998) are: Specify value from the standpoint of the end customer; Identify value flow, Flow, Pull, and Perfection. Picchi (2003) further emphasises that the experience of other industrial sectors shows that the simplicity of the flow principle, using the Value Stream Mapping (VSM), is an important way to provide a systemic view.

Several studies have applied VSM to improve construction processes. More recently, Rosenbaum et al. (2014) applied VSM as a green-lean approach in the construction of a hospital to improve its environmental and production performance during the structural concrete work stage.

Shou et al. (2016) conducted a systematic literature review aiming to identify critical success factors in the VSM implementation across five sectors: manufacturing, healthcare, construction, product development, and service. A total of 97 journal papers were identified by the authors between 1999 and 2015. Results showed that the majority, 72 papers, are related to VSM implementation in the manufacturing industry, and only

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eight papers are related to VSM implementation in the construction industry. However of those eight papers, only one (Yu et al., 2009) seeks to standardize the variety of production by reducing waste in construction processes.

This paper aims to apply the VSM methodology to improve the concrete placing process in a Brazilian construction site. The mobile pump is a concrete placing method commonly practiced in Brazil. In this concrete placing method, the placing rate is dependent on the pumping rate, the continuity of concrete supply, and the capacity of the placing gang (Lu and Anson, 2004).

In this sense, this paper seeks to answer the following question: “How to improve the stream of materials and information in the process of concreting columns?”

2 LITERATURE REVIEW

2.1 Principles of lean thinking related to concreting process

The new production philosophy proposed by Koskela (1992) considers production as a stream of material and/or information from raw material to final product. In this flow, there are conversion activities and flow activities, which represent value adding and non-value adding activities distributed throughout the flow.

The main idea of this production philosophy is to reduce or eliminate flow activities and increase the efficiency of conversion activities. From this analysis, Koskela (1992) proposed eleven principles to improve the design of production systems: Reduce the share of non-value-adding activities; Increase output value through systematic consideration of customer requirements; Reduce variability; Reduce the cycle time; Simplify by minimizing the number of steps, parts and linkages; Increase output flexibility; Increase process transparency; Focus control on the complete process; Build continuous improvement into the process; Balance flow improvement with conversion improvement; Benchmark.

Of the aforementioned principles, four of them deserve special attention in the concreting process: reduction of non-value-adding activities, reduction of process cycle time, increase of process transparency (transparent work environment are susceptible to observation) and continuous improvement (effort to reduce wastes and increase value in process management should be conducted continuously with the participation of the responsible team).

2.2 Wastes

In order to keep production in a continuous flow, Ohno (1988) proposed seven types of wastes that compromise the value stream: transportation, inventory, motion, waiting, over-processing, over-production and defects.

Those required to understand this research are: overproduction (producing a given product in quantities greater than those needed to satisfy demand), waiting (idle time of material, machine, information or equipment), defects (components or products that do not meet the specification), available inventory (early production leads to the generation of stocks that are stagnant at different points in the value chain), unnecessary movement (exit of employees from their work environment in search of materials, tools, work instructions and/or help). Moreover, Koskela (2004) proposed the eighth type of waste: making-do (or improvisation) refers to a situation where a task is started without all its standard input has ceased.

2.3 Value Stream Mapping

Value stream mapping is a qualitative tool that describes in detail how the productive unit should operate to create a stream. Originally, VSM was conceived as a lean production management technique, which consists of the elaboration of maps that represent the value stream of a specific product family (Rother and Shook, 1999). Therefore, VSM is a tool to fight waste and reduce lead time, communication, business planning and that manages the process of change.

The material flow is the movement of material inside the construction site and the information flow tells each process what to manufacture or what to do next. Some specific VSM concepts that were used in this research are presented in Table 1.

Table 1: VSM Concepts.

Concept	Meaning
Push system	Production system in which each process tries to produce the maximum quantity of possible units (demand forecast).
Pull system	Production system in which each process produces only what the next one requires (actual demand).
Cycle time	Frequency with which a part or product is completed by a process.
Value adding time	Time of the work elements that actually transform the product in such a way that the customer is willing to pay.
Lead time	Time required for a product to move through all stages of a process, from start to finish.
Kaizen events	A concentrated effort to solve production problems and improve the value flow.

Source: Adapted from Rother e Shook (1999).

3 RESEARCH METHOD

An exploratory case study was adopted as the research strategy. Case study is appropriate to answer “why” and “how” questions, and also when the researcher has little or no possibility of controlling the events, or even when general circumstances of the phenomenon to be studied are contemporary, in a context of real situation (YIN, 2001).

Construct validity was addressed through the data triangulation from multiple sources of evidence: direct observation, interviews and documents. External validity is related to analytical generalizations, in which the researcher seeks to generalize a particular set of results to a more comprehensive theory.

VSM implementation stages are: (i) selection of a family of products, (ii) map the current state (collection of information at the construction site), (iii) map the future state (state to be achieved) and (iv) preparation of a work and implementation plan that describes how to achieve the future state. In both current and future states, icons are used to represent material and information flows. The data collected in the current state

mapping were value-adding time, cycle time, and lead-time. The future state map was later reviewed by the company's construction planning director.

4 RESULTS AND DISCUSSIONS

4.1 Case study

The selected company is a medium-sized real estate developer in Natal/Brazil. The project under study was a 27-storey residential tower. It was mapped the stage of columns concreting of the second level below ground. It is worth mention that the concrete work should already be running on the tenth floor according to the project planning. The project delay was due to legal problems related to the project's neighbourhood, which started during the foundation stage.

Given the evidences obtained that indicate cycle times, inventories generated throughout the work execution, number of workers involved in each process and, according to the discussion about respective causes, it was possible to draw the current state map of the columns concreting work (Figure 1).

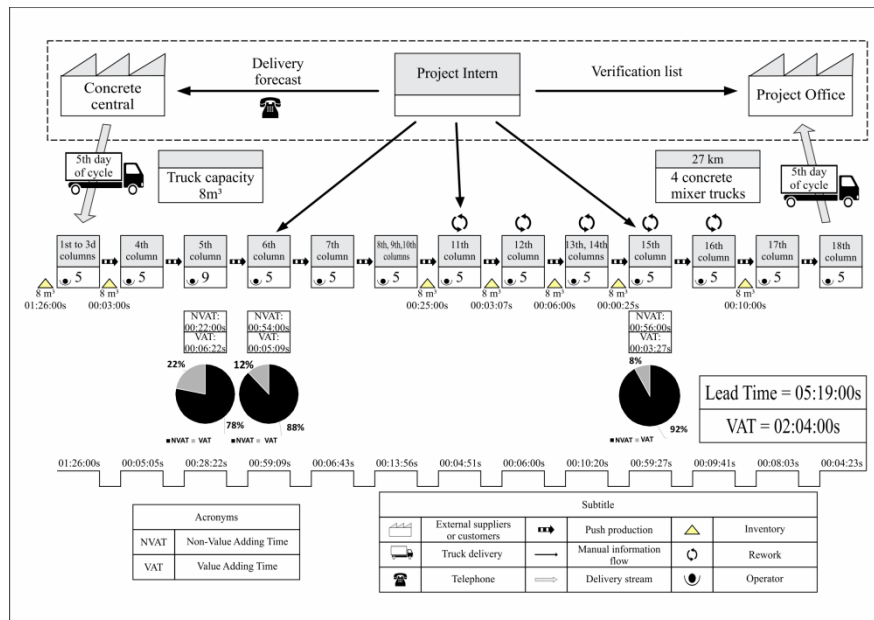


Figure 1: Current state map.

As established by the weekly planning, the columns concreting work should start at 7:00 a.m. The pumping machine arrived at the construction site after a 15-minute delay. The concrete mixer truck arrived at the site only at 7:50 a.m. due to bad traffic conditions. Each concrete mixer truck was fully charged, carrying 8m³ of concrete.

A further 26 minute-delay occurred due to improper positioning of a backhoe in the construction site that prevented the concrete mixer truck from parking inside the site. This indicates non-compliance with restrictions that should be eliminated in advance to ensure flow continuity with subsequent activities. Consequently, the concreting work began at 8:26 a.m.

During the concreting pouring process, some interruptions occurred due to the truck's arm size. The truck's arm was too small to reach the columns formworks far from the truck (Figure 2.a). Such problem happened due to the lack of a site layout design, by

means of which it would be possible to specify the exact arm’s length and hose necessary for the concreting of all the pavement columns, without interruptions, improvisations or excess in the number of workers (Figure 2.b) to complete the work.

The insufficient size of the hose for concreting the more distant formworks resulted in improvisations that led to a considerable increase in cycle times. Figure 2.b shows improvisation where a wooden board was used without success to prevent the concrete from being thrown out of a column formwork. Thus, the concrete placing activity was performed by workers.

After the concreting of 15 columns (the amount possible with the initial arm and hose), a 30-minute interruption occurred. Five workers installed an extension in the hose consisting of a metal tube of difficult handling due to the high weight and the high material rigidity. Such interruption reduced the workers production rate, making the work slower and configuring an activity that clearly does not add value to the product.

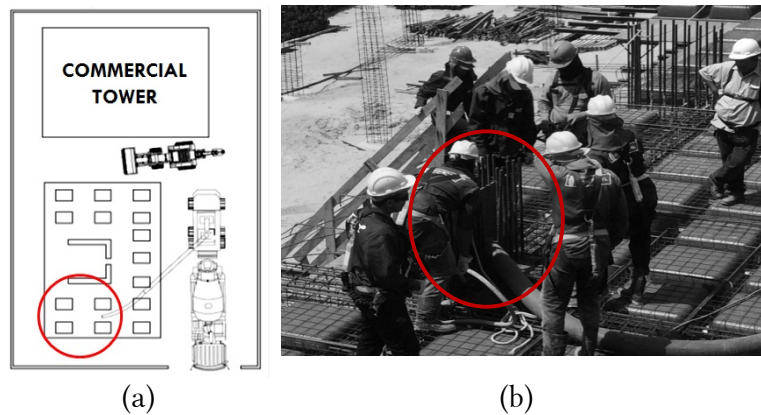


Figure 2: Construction site layout (a) and making-do in concrete placing process.

During the concreting of the fifth column, the connection of the hose to the arm of the pumping machine broke, resulting in another interruption that lasted twenty-two minutes to repair the equipment and involved nine employees including the site manager and an intern.

Another interruption commonly observed was due to the waiting for the following batch of concrete. An intern performed the release order of the following batch of concrete from the concrete plant by the time the previous batch of concrete arrived in the construction site. Nevertheless, the transportation time of batches varied significantly between 26 and 50 minutes, generating great waiting times during the work.

The intern also documented (in his own way, since there is no standard document for this type of control) the arrival and departure times of concrete mixer trucks, as well as the columns formwork filled with concrete.

It can be noticed that a push production system is adopted, since the request of batches of concrete is carried out through a demand forecast, which involves low reliability and can generate waste. In fact, the company requested four batches of 8m³ of concrete, and only three batches were sufficient to concrete the eighteen columns. That is, a full batch of the four batches requested was unnecessary for the work in process. Therefore, without prior planning, the project team decided to concrete others structural elements such as some columns of the commercial tower that is part of the project and part of the curtain wall foundations.

Another identified waste was the excess of workers involved in the work execution. Two workers were still handling the concreting hose, while two others were handling the vibrator and another one was operating the truck arm.

In view of the current state conditions, a series of improvements are proposed to eliminate the identified wastes, making the flow continuous, eliminating interruptions, reducing cycle times and the percentage of non-value adding activities and, ultimately reducing lead time. The future state map is presented in Figure 3.

The first suggested improvement refers to the change of the push production system into a pull production system, so that the subsequent processes trigger the execution of previous processes, based on the actual batch demand of concrete, avoiding the occurrence of overproduction.

It is suggested to use spreadsheets with the actual volumes required for each formwork to be filled with concrete (data obtained through the structural design itself). It is also suggested that the site manager review the data collected by the intern.

Another fundamental improvement consists in the elaboration of a detailed site layout design, through which it is possible to extract accurate information, such as distances and available space for the movement of people, materials, machinery and equipment. The use of this information should make it possible to know the required lengths of both the pumping machine arm and the concreting hose to avoid wasting time by trying to push these tools to the most distant columns without success and to avoid improvisation as was observed in the current VSM.

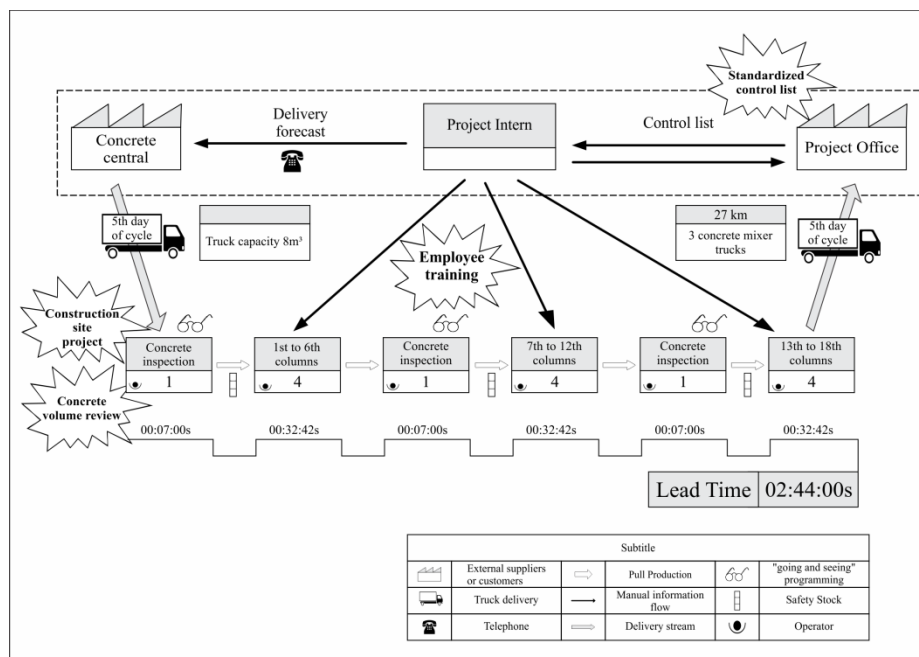


Figure 3: Future state map.

After the last work performed before the concreting, the organization of the construction site must be carried out, so that all the restrictions regarding moving space are solved, so that, without waiting-related wastes, machines used for the concreting work can be placed in the workplace and start the work.

After the arrival of each batch of concrete at the construction site, it is suggested that, in parallel to the collection of a sample of concrete for carrying out standards tests, a

trained professional goes to gemba (“go and see” principle) and check the hose connection to ensure that decoupling accidents do not occur during the concreting execution.

A kaizen can be applied by a technical training and collaboration developed with the workers in order to make them more proactive and work collaboratively. This should enable a reduction from five to four workers involved in the concreting process, in which two workers should handle the hose, another one should handle the vibrator and the fourth worker should control the pump arm movement.

Another kaizen consists of the elaboration of a standardized control list. This list would include: (i) arrival and departure times of the concrete batches; (ii) start and finish dates of concrete work activities and (iii) information indicating which columns formwork was filled by each batch of concrete. The standardization of such control tool should provide greater processes transparency, in order to make information clearer and more comprehensible, regardless of the worker involved in the concrete filling process. The document should always be forwarded to the office and planning teams to support the preparation of plans.

As previously mentioned, the concrete transportation time from the concrete plant to the construction site was highly variable and can hardly be controlled, since it represents an external factor with a high degree of uncertainty. However, the VSM aims to delineate the ideal state for execution of a given work. Therefore, the estimated times in the future state map for such transportation are equal to the lowest observed time, during the mapping of the current state. In order to avoid flow interruptions, a “safety stock” could be used to minimize the effects of eventual delays by the concrete supplier. Safety stock represents goods held at any point (raw materials, work in process, or finished goods) to prevent downstream customers from being starved by upstream process capability issues (Lean Enterprise Institute, 2011).

This safety stock will be guaranteed by means of a ready-mixed concrete truck, with a volume of 8m³ of concrete that will accompany the previous trucks in the concreting process, allowing a continuous supply of concrete after the discharge of the previous truck. This could potentially eliminate interruptions due to truck delays or due to failures in previous processes.

Finally, it is noted that lead time could be reduced by approximately 50%, from 5 hours and 19 minutes in the current state, to 2 hours and 44 minutes in the future state, proving the achievement of the established goal for this work.

5 CONCLUSIONS

The use of VSM in the columns concreting process allowed the identification of six types of waste: waiting, handling, inventory, overproduction, rework and making-do. The improvements opportunities showed in the future state map would eliminate or reduce the interruptions observed in the process flow, making it continuous, and reducing the cycle times and the lead-time of the columns concreting work.

One limitation of this study is that the authors did not include the works that precede the concrete placing process, which could explain the delay in the project schedule and propose improvements that may support future planning and execution. An additional future study would be to elaborate and test an implementation plan for the future state map developed in this paper.

6 ACKNOWLEDGMENTS

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VALUE STREAM MAPPING - A CASE STUDY OF COLD-FORMED STEEL HOUSE FRAMING FOR OFFSITE MANUFACTURING SUPPLY CHAIN

Rehan Masood¹, Vicente Gonzalez², and James B.P. Lim³

Abstract: Offsite manufacturing (OSM) has the potential to help reduce the housing shortfall by increasing the supply of housing stock. The poor performance of the construction supply chain is the main reason for the low uptake of OSM. OSM supply chain characteristics such as configuration, information flow and material flow are different for OSM technologies. Furthermore, there are inefficiencies in the supply chain causing waste, which also varies with OSM technology. A case study of the OSM supply chain for structural framing for cold-formed steel (CFS) houses is mapped and assessed using value stream mapping (VSM). From the VSM it is possible to understand current performance and determine opportunities for improvement. Such information can help foster further adoption of OSM of CFS in housing.

Keywords: Offsite manufacturing, Supply chain management, Value stream mapping, Housing, Cold-formed steel framing

1 INTRODUCTION

The poor performance of housing industry (London & Siva, 2011), has resulted in a shortfall of the housing building stock globally, with New Zealand not being an exception (Bassett & Malpass, 2015). Offsite manufacturing (OSM) (otherwise known as prefabrication) has the potential to enhance production for housing with cost effective solutions, from prefabricated components to complete building (Goulding et al. 2015).

However, OSM has shown slow adoption globally (MHC, 2011) as well as in New Zealand (Scofield et al. 2009). The poor performance of OSM supply chain management (SCM) is one of the reasons for its low uptake in the housing industry (Pan et al. 2012). Also, application of SCM concepts is a large challenge for key stakeholders (Goulding et al. 2015) due to its dependency on technological development (Edum-Fotwe et al. 2001). CFS as emerging OSM technology, however, does have the main potential to reduce the lead time of house building supply chain (SC) (Donyavi et al., 2009). There is difference in configurations, information flow, material flow and problems of SCM.

This is a preliminary study on the performance of OSM SCM that focusses on CFS house framing using value stream mapping (i.e. following the design-to-order strategy). The key processes are mapped and also the identification of waste types in the value stream. This study can lead to an improved performance of the CFS house framing SCM.

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2 LITERATURE REVIEW

The concept of SCM is not well utilized in both practice and research, even though it has the potential to improve the speed and quality of house building projects (London & Siva, 2011), specifically for industrial house building projects (using OSM technologies) (Gann, 1996). OSM SCM addresses the off-site concepts in the construction SC (Mostafa et al. 2014) demonstrating the transfer of activities from site to SC (Vrijhoef & Koskela, 2000). The OSM approach creates a space for application of lean supply with similarities driven by manufacturing to construction but demands more integrated processes (Fearne & Fowler, 2006). Adoption of lean production principles also improves the performance of SCM (Flores et al. 2009), but it is more challenging in the context of the construction industry (Höök & Stehn, 2008). A triangulation improvement strategy based on OSM, SCM and lean for house building projects is gaining attention by construction community (Pero et al. 2015), however, focus on CFS OSM technology is still limited (Boyd et al. 2012).

To evaluate the OSM SCM and lean, VSM is a potential lean thinking tool for performance measurement and mapping. A value stream comprised of all the activities which are value-adding, non-value adding or necessary but not always adding value (Rother & Shook, 2003). VSM helps to identify the flow, value, and perfection (Womack & Jones, 2010). In empirical studies (Arbulu et al. 2003; Fontanini & Picchi, 2004), the current state maps processes and agents, and identifies wastes (non-value adding activities) and relevant problems in processes and interfaces, focusing on a single product SC. For the future, solutions and strategies are proposed that can improve overall performance.

3 RESEARCH METHOD

A case study approach is adopted (Yin, 2013) that focusses on the OSM SC of six CFS houses of different sizes, but follows the same SC. The steps followed in this study follow the guidelines from valid sources (Dolcemascolo, 2006; Rother & Shook, 2003; Womack & Jones, 2010), to apply VSM. Most critical step is selection of product family i.e. structural framing of CFS houses. Data collection was done through project and company documentation. Also, interviews with five employees (with designations as commercial manager, business development manager, sales manager, design manager, factory manager and foreman) involved in the marketing, design, and manufacturing, having experience from 5 to 15 years in the CFS housing industry.

The lead time was considered as a key performance indicator (Yu et al. 2009) for single components (i.e. CFS framing) in the house building SC. Lead time helps to understand the complete SC from order to delivery of a particular project (Arbulu et al. 2003), and comprises factors such as process time and queue time, refer to Table 1.

Units of analysis for processes in design and manufacturing were area/time and length/time respectively. Initially, ERP documentation for process flow was reviewed. Interviews were conducted with key personnel of the company. The current state map shows key processes, interfaces; stakeholders (or agents) were identified. The time for each process and queue time at the interface were also determined. Key observations developed on reasons for non-value adding process time and queue or wait time in the value stream which leads the investigation to some wastes causing long lead time. A future state map was proposed addressing the peculiarities of identified wastes which has the potential to improve the OSM SC with reduced lead time, which also impacts the overall lead time of the house building stock.

Table 1: Process Indicator

Name	Acronym	Unit	Description
Process time	PT	Hours	Value adding time
Queue time	QT	Hours	Non-value adding time
Lead time	LT	Days	Time from order to delivery

4 CASE STUDY DEVELOPMENT

The selection of product family has described i.e. CFS structural framing for housing. The selection of the product is a critical step towards VSM in the context of construction SCM, as performed in empirical studies (Arbulu et al. 2003; Fontanini & Picchi, 2004). Selection of a critical product/material of building is necessary which has a pivotal influence on the performance of the overall process and SCM (Rosenbaum et al. 2013; Yu et al. 2009).

In New Zealand, the construction industry has an overall contribution of 52% in gross fixed price formation; 26% covers housing (MBIE, 2013). Detached houses with one or two floors are common, covering 75% building consents per year (MacPherson, 2016). The average size of a dwelling in NZ is 149 square meters (QV, 2011). Preliminary data of six houses has been considered with dwelling sizes ranging from 88m² to 200m², and an average size of 139m².

For VSM, there is a need to select a product or product family following criteria based on high volume by revenue, high volume by units produced, high defect rates, highest customer return rate, and visit the most processes (Dolcemascolo, 2006). A particular house is made up of several building components but structural framing is more critical because more than 90% of building components (services, cladding, and all finishing) in house building follows the structural framing, so that, it can affect the construction of house building in term of time, quality and cost.

In New Zealand, structural framing is manufactured by different OSM technologies such as timber and CFS. According to National Association of Steel-framed Housing (NASH), the market share of CFS housing is increasing and expected to achieve 10% in coming years (Davies, 2009). CFS is very well utilized in OSM which creates promising affordable technology but with low uptake by housing industry stakeholder, which is a common scenario in the construction industry for new construction technologies (Donyavi et al., 2009). CFS framing (i.e. roof trusses and wall panels) are one of the most common approaches in New Zealand (PrefabNZ, 2016). This study focused on the design and manufacturing of CFS framing for housing as it has the potential to create value in SC by reducing the overall lead time of housing. The firm selected for this research is a leading in CFS OSM technology covering both designing and manufacturing domains. The company has a well-established business setup in New Zealand (around 50 employees with an estimated 5 million dollars of revenue per year) and clients around the globe using their technologies for design and manufacturing.

5 VALUE STREAM ANALYSIS

A highly or macro level value stream map was developed (Figure 1), identifying the SC configuration with key firms (agents), processes and workflow. Linkage with both end

arrows shows two-way communication. In this preliminary research, only VSM for one design and manufacturing firm was developed focusing only on the analysis of the current and future state.

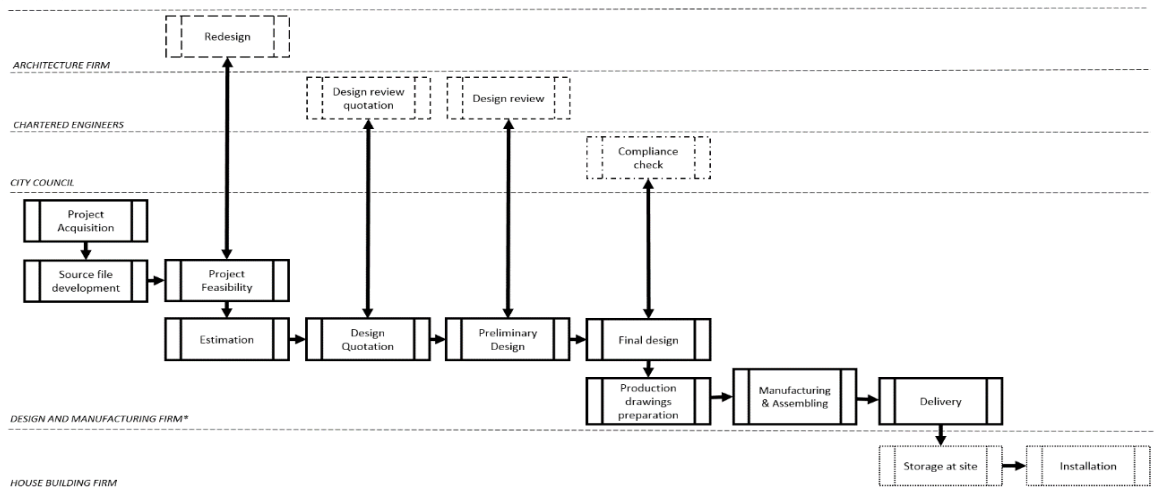


Figure 1: Value Stream Macro Mapping - Current state

For simplification, time of external processes is taken as queue time for internal processes as the scope is limited to design and manufacturing firm. For example, the design of structural framing is not finalized until approval from the council is obtained, with respect to code compliance; for the company, it is a non-value adding step and causes queue time. There are ten processes involved in the value stream of CFS framing from order to delivery. Each box represents a process and is considered to add value in the value stream; triangles represent the wait/queue time.

5.1 Value stream map - Current state

Figure 2 shows the VSM of the SC of CFS structural framing in the context of the company with ten processes.

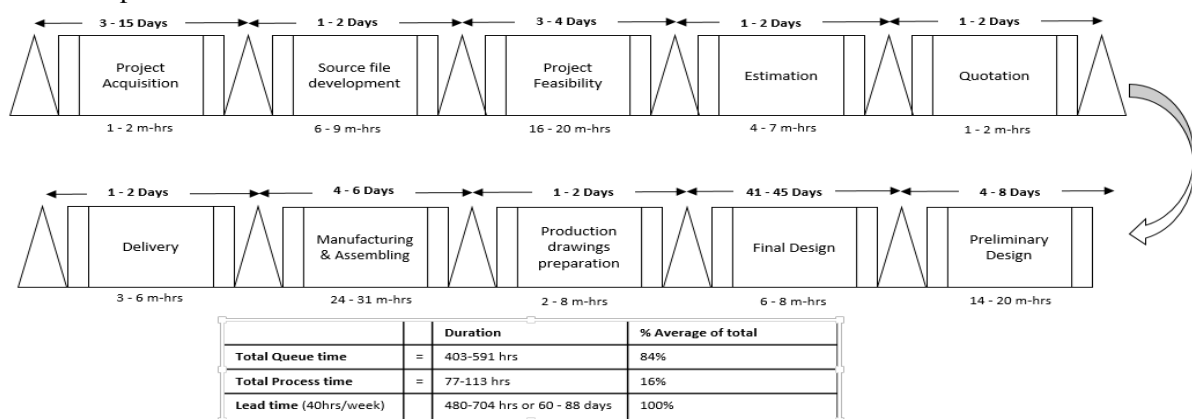


Figure 2: Value Stream Mapping - Current state

The total time taken by each process ranges from between 77 and 113 hours (10 and 14 days) i.e. 16% Queue times ranges between 403 and 591 hours (50 and 74 days) i.e. 84% of the whole system time. The lead time of CFS framing from order to delivery (i.e. process times and queue time) is 60 to 88 days, assuming eight man hours per day. Information flow (i.e., design information) is visible in the first eight steps in the SC, but the material flow is seen only in the last two processes. Communication within design and manufacturing follows ERP system of the firm. Table 02 shows wastes, mainly drive

through site observations, identify a number of possible wastes defined by Locher (2011), see Table 02;

Table 02: Common waste in OSM supply chain

Waste	Description
Over production	CFS OSM technology is comparatively new, so clients take on average two weeks to place the order. The client needs 1-2 visits to the factory to understand this technology. Energy spent on this process is considered to be overproduction because it is not adding value.
Transportation	The transportation waste is observed in information flow when the client provides hard copy, and furthermore, the process of code check is done manually by the council. The effort is needed to manoeuvre the framing panel for congested space in a factory, or the site is not ready for installation.
Inappropriate processing	The architectural drawing is developed in CAD as a source file, which takes 1-2 days depending on the complexity of the design. Later on, in project feasibility stage, the constructability of design is checked which takes 3-4 days. For example, there is a limitation of floors, span length, and openings' areas. Both of these processes are inappropriate which are non-value adding to the SC.
Defects	Defects are associated with the waste of time and resources, generated from wrong design (compliance issues); errors in the production file; manufacturing machine malfunction; a poor quality control system; unskilled operators, assemblers, and installers.
Unnecessary inventory	OSM needs economies of scale (mass production) but the production depends on the capacity of industrialized organization and projects at hand. Raw material is normally stocked for 4-6 months, which depends on the availability in both local and overseas markets. Current research shows that on average two house building framings per month are constructed. Low demand of framing and variation in profiles leads to unnecessary inventory.
Waiting	Waiting times is the key waste in the SC. The client takes time in making decisions at different stages in SC, such as providing architectural drawings, resolving constructability issues with architect, approval for manufacturing. The quotations generated are normally valid for one month. The council takes around 1-2 months to approve the design for housing projects.
Unnecessary movement	Poor factory layout causes unnecessary movement of workers during setting up, manufacturing, assembling and stacking which impact the productivity.
Underutilized people	This refers to the potential of employees is not fully utilized. Third party review is not needed if the design engineer at the organization is a chartered engineer, which will reduce time in quotation and preliminary design processes. There is a need of four workers during manufacturing and assembling process.

5.2 Value stream map - Future state

Womack and Jones (2010) proposed that a future state could demonstrate waste elimination with the application of lean principles. The improvement should take place in quality, productivity and lead times (Rother & Shook, 2003). This proposed research aims to reduce the lead time of CFS framing for housing projects (see Figure 3). The future state proposes two processes to be eliminated i.e. source file development and project feasibility. Architectural drawing should be provided by the client in CAD format preferably in IFC format so that it can be opened to any structural design drawing format. The architect should consider the potential and limitation CFS OSM technology while designing the house for elimination of project feasibility process. The time of four processes (estimation, quotation, production drawing preparation, and delivery) cannot be reduced significantly because of the requirements of the processes. Use of building information modelling (BIM) technologies improves visualization, estimation and drawing generation. The time for four processes also queue time can be reduced significantly (project acquisition through selection of bespoke design; preliminary design by avoiding third party involvement, final design by efficiently address the compliance issues, manufacturing and assembling by enhancing productivity of workers).

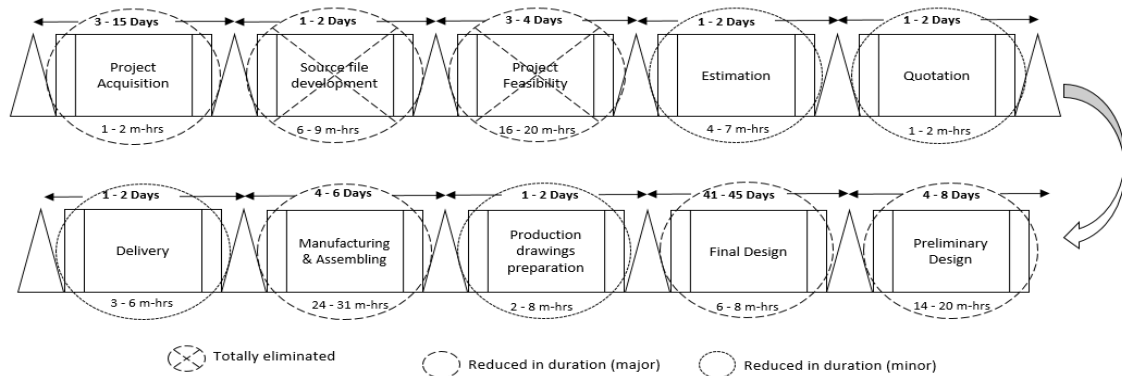


Figure 3: Value Stream Mapping - Future state

Industrialized firms should take measures to housing market the potential and benefits of OSM, which helps to increase the adoption and increase the trust level of client on OSM. Although, there is less provision for design modifications (i.e. flexibility), which encourages the standardization, but limits the innovation as the bespoke design modification takes less time. Code compliance can be performed through BIM, which can help to reduce checking time at the council. Productivity during manufacturing and assembling of CFS framing can be increased through simulation by using BIM, as the scenario can be different in terms of factory layout and worker behaviour. It is needed to explore more BIM potentials integrated with lean construction to efficiently manage CFS OSM SC through solving problems. It is estimated that by using the propose strategies mentioned above, the lead time can be reduced to 10-15 days if the queue time and process time is reduced or eliminated, which helps in enhancing supply of housing stock.

6 CONCLUSION

This research has presented a preliminary diagnosis of OSM SC in for CFS structural framing of housing projects. Understanding the SC helps members for decision making regarding adoption of OSM technologies which leads to construction innovation and enhancing business portfolio. Addressing the inefficiencies in context of CFS OSM SCM enhance the supply of house building and increase affordability along with high quality. This study focused on private housing, and SC configuration is different for social or relief housing constructed through OSM. This study canvas the prevailing practices and problems in CFS OSM SCM which helps in enhancing the adoption of OSM technologies in construction. Limitation of performance measurement frameworks (such as balanced scorecard and SCOR) for SCM of house building projects highlights the need of dynamic framework based on well-developed performance indicators. This study shows the potential of VSM as a performance measurement and lean improvement tool for the OSM SC for CFS. The waste in different OSM technologies SC also varies regarding nature and impact. This study reported eight common wastes in value stream of CFS OSM SC which will be further investigated to understand the impact on overall performance. The future stage suggests that the lead time of SC can be reduced if the recommended strategies are implemented. This study provides grounds to explore the lean approach for improvement in the SC of housing with BIM, keeping the OSM technology perspective, which is changing the dynamics of the construction industry on a global scale. A further research focuses on the development of a BIM-lean integrated theoretical and methodological framework to improve OSM SCM in CFS housing industry.

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PREFABRICATION OF SINGLE-FAMILY TIMBER HOUSES – PROBLEM AREAS AND WASTES

Djordje Popovic¹, Tobias Schauerte², and Jimmy Johansson³

Abstract: Industrialization of house building has shifted the activities traditionally done at building site to the off-site assembly. The design, manufacturing processes and on-site assembly in industrialized house building are defined and documented to form a process platform, but these must be evaluated and improved to constantly develop better and more efficient practice. Lean production and philosophy are still not well understood concepts at the shop floor and wasteful activities that decrease production efficiency are often overseen. Current waste categorizations and descriptions seem not to be addressing problem areas and occurrence of waste in prefabrication of single family timber houses. The research aim is to define problem areas that occur during the prefabrication of wall modules, associate them to eight types of waste and identify key problem areas for possible development and improvement. The study was based on secondary data from five case studies that primarily focused on identifying and proposing possibilities for development of productivity. Four problem areas were identified and the future improvement efforts for the prefabrication of single family houses can be placed on developing the processes of the assembly system problem area. The possible future study can aim at quantifying these problem areas.

Keywords: Waste categorization, off-site production, wall modules.

1 INTRODUCTION

Industrialization of house building is a process that shifts the activities traditionally done at building site to the off-site production (Lidelöw et al 2015). Off-site production has been claimed by various authors to increase the quality of buildings, decrease costs, and increase the efficiency and control of processes (e.g., Apleberger et al 2007). The design, off-site production, and on-site assembly in industrialized house building are defined and documented to form a process platform (Lessing 2015), but these must be evaluated and improved to constantly develop better and more efficient practice. To set the foundation for improvements, the identification of the current state of value adding and non-value adding activities has shown to be a good starting point (Rother and Shook 2003).

Prior work related to waste in off-site production of industrialized house building is already present in the literature (e.g., Sandberg and Bildsten 2011; Barker and Naim 2004). The need to categorize waste in construction industry has already been identified and some contributions are made. Johansson and Meiling (2009) have compared traditional and industrialized construction in terms of waste of defects. Josephson and Saukkoriipi (2005) have classified waste that occurs in the construction industry supply chain into four

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categories: defects and controls, utilization of resources, health and safety, and system and structure. Gustafsson et al (2012) have followed the same categorization in a single case study and investigated waste that occurs during final on-site assembly of multi-storey buildings with timber structure. However, none of the abovementioned waste categorisations and descriptions seem to address problem areas and occurrence of waste in prefabrication of single family timber houses. Therefore, the research aim is to define problem areas that occur during the prefabrication of wall modules, associate them to eight types of waste and identify the key problem area for possible development and improvement. Off-site production is hereafter referred to as prefabrication.

2 LEAN PRODUCTION AND DIFFERENT KINDS OF WASTE

Lean has its origin from the Toyota Production System, aiming at utilizing a company's resources in the most efficient way possible, while delivering a product of the right quality, that customer needs and is willing to pay for. Lean production thus focusses on producing e.g. a product by optimizing resources in a smart manner (Olhager 2013). Two major parts of the Lean production concept are value and waste (Pavnaskar et al 2003). Value is what the customer is willing to pay for (Olhager 2013), whilst waste is considered being all activities that do not create value. Aiming at shortening the lead time from order to delivery, the optimization of resources according to Lean production can be accomplished by eliminating as much waste in production as possible (Liker et al 2009). Ohno (1988), a former Toyota executive, formulated seven different types of waste and Womack and Jones (2010) added another one, as described below. These are the wastes of:

1. Overproduction: by producing more than ordered, the production acts according to push principles instead of pull. Unnecessary costs for inventory and transportation occur. Overproduction is often considered as the worst type of waste, since it causes other wastes (Segerstedt 2008).
2. Waiting: as production stands still, no value is created. According to Lumsden (2006), certain products wait up to 90 % of their time through production.
3. Conveyance: transportation of work-in-process to intermediate storage or between production stages does not add any value to the product (Liker et al 2009). It is impossible to eliminate but should be reduced as much as possible.
4. Over-processing: refining products more than necessary, i.e. as demanded by the customer (Lumsden 2006), but as well ineffective refining due to bad choice of tools and/or machinery or bad product design (Liker et al 2009). Therefore, in this study this type of waste will be referred to as inappropriate processing (Bicheno and Holweg 2008).
5. Excess inventory: too many work-in-process articles and storages can cause e.g. longer lead times, damaged products, or transportation delays. Yet, it could even hide problems related to production planning (Segerstedt 2008).
6. Unnecessary motions: it is related to both human and layout factors. The operations have to be performed in an ergonomic way in an optimal layout. (Bicheno and Holweg 2008). Basically, all kind of transportation is waste as it never creates value but only prolongs lead times (Liker et al 2009).
7. Defects: producing products that cause adjustments, reparations, need to be reworked in any way or even scrapped and replaced (Liker et al 2009).

8. Unused employee creativity or expertise: managers not listening to their employees will lose time, ideas, competence, improvements and miss chances to learn (Womack and Jones 2010).

As value stream mapping identifies all activities in order to produce the final product, the above-mentioned types of waste will be part of that (Schauerte et al 2015). According to the Toyota Production System, all types of waste should be eliminated, or at least reduced as much as possible, to improve production efficiency (Liker 2004).

3 CASE COMPANIES

In this study, five companies have been investigated. These are referred to as cases a, b, c, d, and e. All of them act on the same market, are direct competitors producing wooden single family-houses and are located in the province of Småland in Southern Sweden. The industry at hand is highly competitive, as e.g. described by Schauerte et al (2014) and Schauerte and Lindblad (2015). As the authors of this study and the involved universities are cooperating with the case companies in various research projects, they will be handled as anonymous entities in this study. Elsewise, potential sensitive results could be used to create competitive advantage, which might burden the existing relationship between the authors and the companies.

4 METHOD

This study is based on secondary data from five case studies conducted during 2014-2016 (Andersson and Jönsson 2016; Tingström and Gunnarsson 2014; Björk and Andersson 2016; Ulriksson et al 2014; Popovic et al 2016). The aim of those studies was to identify and propose possibilities for productivity development in the pre-fabrication of wall modules, i.e., offsite production. The basic tool used as a starting point for all the studies was value stream mapping and data collection was based on observations of the production process for identification and mapping of that process. This was followed up by time studies of the different process steps and shorter interviews or discussions with operative staff, mostly during continuous observations of the production. Semi-structured interviews with production management staff were conducted to collect information about critical aspects in the production.

The data used in this study is of qualitative manner and collected from the material and the reports from the five case studies described above, with the specific aim of identifying problem areas and connecting them with waste that has occurred. The data was analysed using workshop technique (Williamson 2002). The participants of the workshop were four academic researchers and two middle managers from one of the case companies. The first goal of the workshop was to discuss and make a consensus on which types of wastes that are related to each observation. The second goal of the workshop was to categorize observations into problem areas to enable easier representation of findings.

5 FINDINGS AND DISCUSSION

As the primary data was collected with different research questions, the observations made in the case studies were described as problem instances in a qualitative manner. Some observations are common between the case studies but the majority is different or at best similar due to the uniqueness of production systems.

To fulfil the aim of this study, the authors have first categorized problem observations into four problem areas: material handling, internal logistics, assembly system, and work balancing. In the following section, the categorization of observations will be given together with the occurrence in case companies in parenthesis. The grouping of instances into problem areas and case companies is shown in Table 1. The authors define the problem areas as following:

- Material handling refers to the activities of moving materials, subassemblies, and tools from their storage to the point of assembly. Operators must walk long distances to fetch materials, components and/or subassemblies (all cases). A structure or replenishment of intermediate storage is not defined (a, b, and c). Here are also included issues of non-ergonomic activities that the operators perform during material handling (a). Working environment: issues caused due to the lack of systems that effectively collect dust and material and tool residuals.
- Internal logistics is related to the material flow between different process groups within the factory. Problem instances can be related to: available capacity of resources – trucks (a and b) planning of work orders for trucks (a and c), truck routes – factory layout (a, c, and e).
- Assembly system refers to problem instances that occur in, or are related to, assembly processes, equipment, control, and operators. Physical and cognitive levels of automation in the assembly processes are relatively low and non-optimal, although the design process is performed using ICT tools that can provide CAD/CAM data to the production (a, d, and e). Another problem instance relates to the usage of paper based drawings in the production, while there are already available digital information making prerequisite for a shift towards digital information carriers (Popovic and Winroth 2016) (a, d, and e). Some operations of the assembly process are non-ergonomic (d and e). Idle times of the assembly line are observed (c and d). Parallel support processes, that supply the assembly line with parts and components, produce more than needed (c), have long setup time (e), could be part of the assembly process instead (b and c) and have illogical positioning of machines (b and c). There is a lack of preventive maintenance (a and d) of machine resources. The assembly lines lack flexibility for special variants. This leads to double work on some parts, since there is no other way to realize certain design with an available assembly process (b, c, d, and e).
- In this paper, work balancing is referred to as unevenly distributed operations and tasks in assembly lines for wall modules (all cases) or unbalanced productivity between all departments to form a whole product (house), causing bottlenecks (a and d) and thus having unnecessary work-in-progress. Companies are either producing parts in batches for the intermediate storage or are ordering materials or subassemblies from suppliers in batches.

Table 1: Overview of the problem areas and their presence in the case companies in terms of number of problem observations.

Problem area	Case a	Case b	Case c	Case d	Case e
Material handling	4	2	2	1	1
Internal logistics	4	1	2	0	1
Assembly system	3	3	5	6	5
Work balancing	2	1	1	4	1

After the problem areas have been defined, the next goal of the workshop was to associate them to eight types of wastes. Problem observations on the other hand rarely related to only one type of waste. To give an overview and facilitate discussion, the occurrence in case studies was summed both per problem area and per type of waste (Table 2).

Table 2: Connection between problem areas and eight types of waste in case companies. Superscript is used to denote the number of waste observations per problem area if it is higher than one in a particular case.

	Over prod.	Wait.	Trans.	Inapp. proc.	Unn. inv.	Unn. mot.	Def.	Unus. h. p.	Σ
Material handling			a^3, b, c^2, d, e	a	a^2, b, c	a^3, b, c^2, d, e		b	22
Internal logistics		a^3, b, c^2	a^2, c, e	a, b, c, e	a^2	c, e			18
Assembly system		a, c^2, d^2	b, c	a^3, b^3, c^5, d^6, e^5	c	b, c, d	d	b, c	36
Work balancing		b, c, d^3, e		a, d^3	a	a, e			13
Σ	0	17	14	31	8	15	1	3	

By interpreting the numbers of waste observations in Table 2, it is possible to differentiate between types of waste and problem areas in terms of their significance for improvement. This is based solely on the assumption that eliminating waste can contribute to an improved resource efficiency (Liker et al 2009). Below, the types of waste, in terms of their significance, are shortly discussed in a descending order:

- The waste of inappropriate processing is present in the assembly system areas of all case companies and is, by the number of observations, the most significant waste identified. It points out that processes of assembly, parallel support and assembly control should be changed or improved. As it can be seen from the table above, processes of internal logistics and work balancing can be done differently to improve the prefabrication efficiency.

- The wastes of waiting, transporting, and unnecessary motions are the second significant group of wastes, present in almost all case companies and problem areas. With currently used resources, in all four problem areas, these three types of wastes are present in almost all case companies. The waste of waiting is mainly related to work balancing, while the waste of transporting and unnecessary motions is mainly related to the area of material handling.
- The waste of unnecessary inventory is less present, while the waste of overproduction has not been identified. This might be explained due to the fact that all companies operate by orders and the final products are always produced in right amounts.
- The wastes of defects and unused human potential were two less significant types of wastes. This can be dependent on how the primary data was collected and the research questions that were used. Since neither quality control nor human resources were the primary focus in the five case studies, the result in this study can be biased and not show the real significance of these two types of wastes. However, the waste of defects in prefabrication processes was comprehensively covered in the study of (Johnsson and Meiling 2009).

An interesting example of wastes that occur concurrently is identified in the problem area material handling. Since material handling is performed manually in most of the cases, the operators walk certain distances every time to fetch material from the intermediate storage, which is a repetitive waste of unnecessary motions. At the same time the trucks are used to replenish materials in the intermediate storage. Therefore, the waste of transporting is present. Hypothetically, having systems for automatic material handling instead of manual would eliminate these two types of waste or at least decrease their impact.

Of all the problem areas, assembly systems are related to the highest number of waste observations, counting all types of wastes in all the cases. That can be an indicator of a primary problem area of wall module assembly. The second significant problem area is material handling, followed by internal logistics and work balancing. This finding can contribute to facilitated prioritization during the process platform development (Lessing 2015).

What is important to notice is that both different types of wastes and problem areas are interrelated. The change/improvement made in one problem area can cause both positive or negative changes in other areas. Likewise, eliminating one type of waste can affect elimination as well generation of another type of waste. Therefore, in order to optimize and improve certain parts of the prefabrication process, a holistic view is needed (Barker and Naim 2004). The examples of related types of wastes are overproduction and unnecessary inventory and waste of transporting and unnecessary movements (Liker et al 2009). Depending on the work organisation, some operations done within the assembly process are, in other organisations, included in the parallel support processes for assembly. To describe the interrelations between assembly systems and work balancing problem areas with related wastes, an example is given: shifting an operation, that is the part of an assembly sequence, to be a parallel support for the assembly instead, can possibly reduce the wastes of waiting and unnecessary motions, while it can generate the waste of transporting, depending on the new physical location for this operation.

6 CONCLUSIONS

Following the aim of this study, four problem areas of wall module assembly were defined: material handling, internal logistics, assembly system, and work balancing. Although qualitative data was used, the findings to certain extent point out to what extent which wastes are present in the four problem areas. This, by relating to the number of waste observations that were made during the workshop. Considering observations from all case companies, the waste of inappropriate processing was the most significant one, notably in the assembly systems problem area. The wastes of waiting, transport and unnecessary motions were the second most significant ones. Furthermore, the problem area of assembly systems had the highest total number of waste observations. Therefore, the main conclusion is that future improvement efforts for the prefabrication of single family houses can be placed on developing the processes of the assembly system problem area.

Apart from the elimination of several types of wastes, improving one problem area can lead to changes in other problem areas as they are interrelated. Hence, a holistic approach should be used for the sake of avoiding sub-optimization. Therefore, the findings of this study can be a starting point for future work that aims at quantifying these problem areas.

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LEAN CONSTRUCTION IN SMALL-MEDIUM SIZED ENTERPRISES (SMES): AN EXPLORATION OF THE HIGHWAYS SUPPLY CHAIN

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Abstract: Lean Construction (LC) is under the spotlight to improve the overall performance of civil construction projects in England. A strategic target of public clients is to effectively extend the current LC efforts, which have been mainly led by large companies to date, across small-medium sized enterprises (SMEs). This paper presents a summary of the initial findings of a research effort aimed at understanding the current condition of and future directions for LC at the SMEs in England's highways supply chain.

The research comprises of 20 interviews with senior managers, of which the initial findings were summarized in this paper, and a comprehensive survey study with 110 responses across the highways supply chain. 31 points for the current condition and 40 action items for the future of LC in the highways SMEs were presented and discussed.

Keywords: Lean construction, SMEs, highways, civil, deployment, implementation

1 INTRODUCTION

Lean Construction (LC) has been under the spotlight to achieve a better value for investment and an improved performance in civil projects in England since the late 2000s (Drysdale 2013). Practical factors like soaring asset delivery and operations costs, Government's budget cuts and a general dissatisfaction with the services are the main causes of this attention.

In the highways sector specifically, LC has actively been championed by Highways England (HE), the main public client responsible for the delivery and operation of England's strategic highways network. HE promotes LC through engagement and contractual configurations with some large-sized main contractors (Tier 1s) and some specialised sub-contractors operating in key delivery areas like soil works, paving/surfacing or traffic management (large Tier 2s). Those large Tier 2s are almost on par with the Tier 1s in terms of their annual turnovers and employee numbers.

HE prefers to use prime contracting with the Tier 1s as its project delivery method. In that contractual configuration, a small number of Tier 1s form long-term partnerships with HE and the large Tier 2s for the delivery of a series of projects. HE commonly imposes a cap contract price, from which deviations in the form of price overruns or savings are shared between the Tier 1s and HE to supposedly incentivise the Tier 1s to make operational cost savings and to encourage the deployment of LC. Alongside this, HE is

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contractually imposing the use of some LC techniques like the Last Planner System or Visual Management in its contracts with the Tier 1s. Also, the Tier 1s and large Tier 2s are monitored by HE for their LC maturity. This active LC agenda led to the entrance of many consultants into the sector. Those consultants work collaboratively with the Tier 1s and large Tier 2s and offer LC trainings for the supply chain.

Despite constituting the largest group in the supply chain (Morton and Ross 2008), the engagement with small and medium sized enterprises (SMEs) for LC has been limited to date. In this equation, the SMEs have been chosen by the Tier 1s, often for short terms on the minimum price basis with fixed-priced contracts. Also, the SMEs have been rarely in direct contact with HE for their LC or other process improvement efforts, which are mostly shaped and directed by their Tier 1 clients. Due to the nature of work, the SMEs have to execute their on-site operations in short working windows to avoid extended traffic disruptions. Given this context, one of the strategic targets of HE is to effectively disseminate LC across the whole highways supply chain, primarily including the SMEs. This paper will present a summary of the initial findings of a comprehensive research project aimed at understanding the current condition of and future directions for LC in the SMEs in England's highways supply chain.

2 LITERATURE REVIEW

2.1 Lean Construction Deployment

LC deployments can be categorised into three levels with increasing degree of sophistication (Green and May 2005; Ogunbiyi et al. 2014); (1) process based LC deployment efforts to reduce waste, variability, information deficiencies and so on through some specific LC techniques, (2) arrangements to eliminate adversarial relations and to increase integration in the supply chain, and (3) a strategic change in the overall project governance towards the Integrated Project Delivery (IPD).

Most of the criticism for the current LC discussions is based on the assertion that they are way too much process and LC techniques focused, largely overlooking the macro factors like the industry's business and economic context, market dynamics and its overall governance (Green 1999; Barros Neto and Alves 2007; Alves et al. 2012). Therefore, while conducting a LC deployment research, beyond some specific LC techniques or mantras, it is necessary to take the overall industry and sector context, and project governance structure into account.

2.2 Lean Construction and SMEs

As for the LC deployments in smaller-sized construction companies, some of the general arguments have been that (1) SMEs are more prone to variations in the economy; therefore, they do not have spare resources to invest in innovation (Alves et al. 2009), (2) the common lack of trust between SMEs and their larger clients as a hindering factor for partnering for LC (Briscoe et al. 2001), (3) competent LC deployments should integrate SMEs into the process, reducing the transaction costs of all parties; not only large contractors' (Miller et al. 2002), (4) a general lack of belief that there are mutual benefits in supply chain integration practices and other business improvement initiatives like LC (Dainty et al. 2001), and (5) the need for large clients' active support in terms of know-how and resources to develop capabilities in innovative approaches in SMEs (Ferng and Price 2005).

The exploration of LC in SMEs is limited in construction. The issue has been mainly discussed from the innovation and supply chain integration perspectives. Beyond generic

remarks, the lack of sector-specific analyses (i.e. highways, rail, building, energy etc.) of LC in SMEs is even more salient, which presents one of the main justifications of this paper.

3 RESEARCH DESIGN

A mixed-research approach involving interviews and a comprehensive survey was used to explore two research questions:

1. What is the current LC condition in the SMEs in England’s highways supply chain?
2. What should be the way-forward to disseminate LC across the SMEs in England’s highways supply chain?

Following a literature review, 20 senior managers (4 from HE, 5 from the Tier 1s, 4 from the large Tier 2s, 7 from the SMEs) were interviewed face-to-face for circa 45 minutes between December 2015-May 2016. Companies with less than 50 million GB £ annual turnover were considered as SMEs. The interviewees were identified through HE and personal contacts.

After the literature review and analysis of the interviews, 31 points for the current LC condition in the SMEs and 40 actions for the way-forward were identified. To validate and rank the importance of the findings, the identified points and actions were turned into Likert-scale questions on a survey of 98 questions and distributed among managers across the supply chain. HE’s database was used to pinpoint the relevant managers, who are experienced in both the SMEs’ business context and the current LC efforts in the supply chain. Of the outgoing 289 surveys, 110 responses were collected between June – October 2016 with 38% response ratio. The research process can be seen in Figure 1. The analysis and write-up of the survey findings are currently underway. A summary of the interview findings outlining the current condition of and future directions for LC in the highways SMEs will be presented in the subsequent sections from the process, project delivery, training and project governance perspectives.

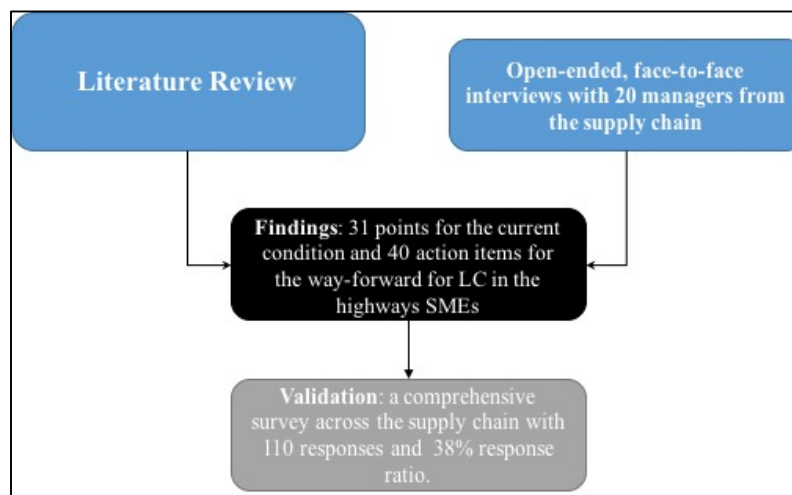


Figure 1: The research process

4 FINDINGS

4.1 Current Condition of LC in the SMEs

As for the current condition of LC in the highways SMEs (for the first research question), as shown in Table 1, the interview findings were classified into four groups; process, delivery, training and project governance.

Table 1: Current condition of LC in the SMEs

Process	Delivery	Training	Project Governance
Short-working windows on site hamper LC improvement efforts	LC deployment is not an important parameter for the SMEs to win future contracts	Current LC training mechanism just cover basic LC concepts	Focus of HE for LC has been mostly on the Tier 1s to date
Due to lack of a complete systems thinking, some improvements made by an SME can put extra workload or pressure on others	SMEs generally start working on short notice without much earlier preparation	SMEs generally do not have internal LC training mechanisms	Clients' drive is the main LC motivation for the SMEs
Application of some specific LC techniques has not been standardized enough	Conventional unit price or lump sum contracts do not incentivize the SMEs much for LC	External training mechanism run by consultants and the Tier 1s are the main formal training mean for LC for the SMEs	There should be a SME specific LC maturity evaluation framework Clients' specifications are too rigid for the SMEs to deploy innovation
Some Lean techniques have been applied fragmentarily	SMEs have a little say on the design at the moment.		
Due to lack of a complete systems thinking, some improvements made by an SME can put extra workload or pressure on others	Clients' commercial teams could present barriers before the SMEs		Business case for LC is essential for the cash-sensitive SMEs
Application of some specific LC techniques has not been standardized enough			LC has been rushed and pushed from the top without a deeper understanding
Some Lean techniques have been applied fragmentarily			Top-down imposition of LC is common
Although not labelled as "Lean", the SMEs have been already doing process improvement (innovation) in their daily activities.			Knowledge retention for LC is problematic
SMEs currently give support to the LC practices led by Tier 1s			There is no effectively working SME innovation groups for LC
Use of BIM as an enabler is very limited between the SMEs and their clients			Lack of real top management buy-in for LC
SMEs struggle sparing enough time and resources for LC			Strategic alliances and supply-chain integration are limited. Risk aversion is too high for LC Current allocation of funds and resources for LC in the supply chain is generally not enough Current LC knowledge is superficial and limited in the supply chain. Cooperation between the organizations for LC is not enough

4.2 Future Directions for LC in the SMEs

For the second research question, using the same classification groups, the future directions to disseminate LC further in the highways SMEs and across the supply chain were identified (see Table 2).

Table 2: Future directions for LC in the SMEs

Process	Delivery	Training	Project Governance
Lean techniques should be better extended to the operations phase.	Forming long term alliances with the Tier 1s for different projects	SME clients should provide more support for training and staff employment in the SMEs	SMEs would benefit from more direct contact with HE
There is a need to improve the use of BIM at the SMEs	Earlier engagement with the SMEs for projects	SMEs should develop their in-house training for LC.	There is a need for the SMEs to improve their current skills and expertise on LC
LC should be better extended to the design phase.	SMEs should have a say in the design stage	SMEs should better understand the terms like value, waste and flow.	SMEs should be shown the business case for LC
Increased standardization in the execution of specific LC techniques in the supply chain	Current lump-sum contracts should be replaced with more incentivizing contract structures	HE should take more initiative in disseminating LC learning and knowledge	Overall organizational support and commitment for LC should be increased in the supply chain
Value based prioritizing is necessary to implement some Lean techniques in short working windows	Aligning commercial teams with LC teams	More academic collaboration focusing on LC and the SMEs. LC related lessons learned, best practices, cases should be better captured, retained and communicated	There is a need for successful pilot LC projects in the SMEs
Bottom-up practices for LC should be given more importance	Longer term contracts involving the Tier 1s and SMEs		Increasing benchmarking efforts for LC against other sectors and countries.
Improving systems thinking to harmonize different LC efforts	Current tendering mechanism at the Tier 1s should better support innovation (LC)-share the risk and gain	Current LC training mechanism should be extended to cover more advanced topics and be continuous	Supporting the SMEs to form innovation driving and sharing work groups
		Going beyond the techniques, training the SMEs for the strategic deployment of LC	There is a need for the SMEs to change their work culture for LC for more information share
		Competencies and teachings of Lean consultants should be better monitored/ regulated.	A strategic long-term focus for LC should be developed at the SMEs
		Joint training mechanisms for the SMEs and Tier 1s led by HE. Raise the awareness on how different techniques are linked to each other and work as a complete system.	HE should get more SME managers on board at their lean dissemination events.
			HE should expand the capacity of its LC department.
			Tier 1s should embrace a supportive management style with the SMEs
			Extended modularization and standardization (off-site) in the design.
	Evaluation of objective third parties for LC are needed in the supply chain		
	Coordination and collaboration in the supply chain should be increased to make innovations		

5 DISCUSSION

The initial findings as to the current condition of LC mostly validated the literature; lack of resources for LC deployments in the SMEs, conventional project delivery systems not incentivizing LC or innovation, need for creating the business case for LC in the SMEs, fragmentation and short-term contractual relations, lack of support for and focus on the SMEs. However, there are also more sector specific parameters like short on-site working windows in the highways sector, and fragmented and unstandardized LC techniques (i.e. the Last Planner, Visual Management). Also, although not labelled as LC, the interviews highlighted that the SMEs do ad-hoc process improvement and innovation in their operations. It was identified that in the highways sector, where the deployment of LC is relatively new, the same concerns that were identified 20 years ago still exist.

For the future action points, there are responsibility items for all the supply chain actors (e.g. HE, the SMEs and large companies). The gist of the findings for the future is to engage with the SMEs directly, to support them with necessary resources and incentivizing project delivery mechanisms, and to devise a continuous training plan going beyond the basics and specifically targeting the SMEs. Also, demonstrating the business case for LC through pilot LC projects, and effectively capturing and disseminating the LC knowledge seem necessary. Training and project governance related findings come to the fore.

6 CONCLUSION

SMEs often constitute the largest group in construction supply chains. However, LC deployment discussions have rarely focused on SMEs to date with sector-level analyses being even scarcer. For an extended dissemination and deployment of LC across construction supply chains in different sectors, it is essential to gain a better understanding of the issue from the SMEs' point of view.

This paper summarized the initial findings of a research effort supported by HE and aimed at understanding the current condition of and future directions for LC at the SMEs in England's highways supply chain. After the analysis of the findings from the survey, which was prepared based on the interview findings outlined in this paper, a more complete understanding of LC in the SMEs will be achieved. Alongside validating the interview findings, the statistical analysis of the survey study will help rank the relevance of each current condition point (the first research question) and the importance of each future directions (the second research question) from different supply chain actors' perspectives (e.g. the SMEs, Tier 1s and large Tier 2s) for prioritization.

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DEVELOPMENT OF A MATERIALS MANAGEMENT STRATEGY TO ENABLE CONTINUOUS WORK FLOW ON-SITE

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Abstract: When project teams are pressured to limit internal or external Lean coaching due to budgetary concerns, Lean coaches may not have sufficient time to guide project teams in materials management to support milestones. Consequently, while organized project teams will make the time to develop a strategy for managing key materials that impact the critical path, disorganized project teams will more likely manage most materials on an ad-hoc basis. This lack of a materials management strategy then leads to unrealized profits and hidden wastes on projects. As a result, this research seeks to investigate how to develop a basic materials management framework to help project teams begin determining which bulky materials should be: (1) Using a pull system (e.g., through the use of Kanban cards or milk runs) to coordinate deliveries, (2) Kitted off-site vs. on-site, and (3) Organized into prefabricated assemblies. Specifically, this paper will identify various questions, calculations, and artefacts (e.g., equipment for handling and staging materials, signage used to make the materials management strategy transparent to all project participants) that contribute to establishing a comprehensive materials management strategy. In particular, space management emerges as an important tool to organize the flow of materials to match job-site installation rates.

Keywords: Materials Management, Space Management, Floor Plan Boards, Procurement, Prefabrication.

1 INTRODUCTION

Materials management is critical in helping project teams achieve continuous work flow on-site. By introducing pull-based systems, kitting, and prefabrication to organize material deliveries, project teams introduce standardization and repeatability into the design of their project's production system. This reduces the likelihood of work variation errors and allows workers a chance to gain learning curve benefits, thus yielding improvements in installation quality and productivity.

Discussions over the years have debated if prefabrication is "better" than on-site construction in one way or another and if it leads to higher quality or faster completion (e.g., Bekdik et al. 2016). Even though these are interesting arguments, the reality

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evidences that on-site work and prefabrication can yield mixed results due to a variety of factors that may or may not be within the control of project teams. In addition, project materials sit on a spectrum of off-site to on-site work processes, and a project's product design can limit the production strategies that materials vendors may need to use for the specified materials (Figure 1). For instance, if an architect developed a building's envelope to consist primarily of stick-built elements, building envelope trade partners that advocate for prefabrication will need to advocate for a re-design of the building envelope if they want to propose that the project consider using unitized assemblies instead within the building envelope. Furthermore, while vendors will use different production strategies (e.g., engineer-to-order, make-to-stock) for the materials that they supply to construction projects, they may also need to adjust those strategies due to a number of other factors, both internally- (e.g., the types of equipment owned by the company, current employee skill set) and externally-driven (e.g., relationships with their suppliers, services and products offered by their competitors).

Then, from the perspective of production system design, the spectrum of off-site to on-site work processes may require different work structuring approaches in terms of sequencing, work handoffs, decision-making, and coordination (Tsao et al. 2004). Due to these inherent differences in the respective production and delivery systems (e.g., Ballard and Howell 1998), a conflict may emerge in the production strategies for materials that need to be installed on projects.

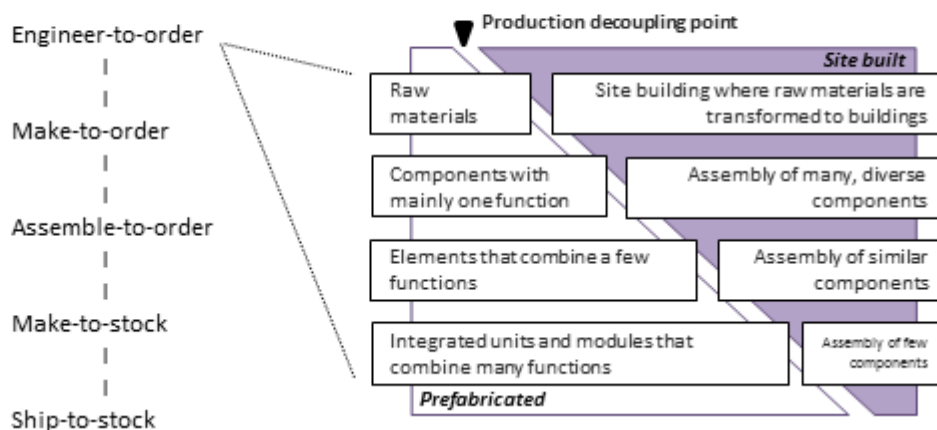


Figure 1: Spectrum of Off-Site to On-Site-Built Work Processes
(e.g. Lidelöw and Olofsson, 2016)

Planning for prefabrication means knowing in advance the size, arrival and use rates, and quality of goods. Then, a challenge that is often over-looked is the space the arriving prefabricated assemblies take up on the building site. Similarly, any activities needed to prepare or kit materials also need designated spaces and, at times, special tools and equipment. On-site activities may also compete for these same resources of space, tools, and equipment. Thus, there is a need for understanding production system design and planning when mixing prefabricated assemblies with on-site work, and this line of thinking has many predecessors such as Arbulu and Ballard (2004), Bekdik et al. (2016), and Pasquire et al. (2005).

The long-term aim of this research effort is to help project teams determine (within the spectrum of off-site fabrication to on-site installation) the best materials management strategy for major project elements. The goal of this paper is to begin identifying a framework, method, and tool set that will help project teams (both experienced and

inexperienced in LPS implementation) understand and manage the flow of incoming materials, its placement, its changing stages over time, and couple this to the work flow. Thus, this particular study aims at describing the basic building blocks for a materials management strategy that supports the spectrum of off-site to on-site work.

2 METHODOLOGY

We began this research effort by organizing various factors that are considered in the planning and purchasing of project materials into a spreadsheet to assist with data collection and analysis. Then, we distributed this spreadsheet to multiple project teams to get some initial feedback but we got a very limited response. As a result, we adjusted our methodology to test the spreadsheet with one project as the first case study and then refine it for testing on the next case study. This approach was not only easier to sustain, it reinforced the spirit of continuous improvement for developing, testing, and refining the framework for a materials management strategy.

Our first case study involved a hospital renovation project in the U.S. On this project, the construction manager / general contractor (CM/GC) not only self-performed some trade specialties but also managed the order and delivery of select materials for a few trade partners. This was necessary because this project involved renovating only one floor at a time within one of the hospital's buildings, and the hospital wanted to minimize disruption by the construction project to healthcare providers, patients, caregivers, and hospital operations in adjacent areas and floors.

As a result, before this research team got involved in the project, the CM/GC project team had already developed a comprehensive materials management strategy that was driven more by logistical challenges as opposed to budgetary concerns. The materials management strategy in place had used various lean techniques, including kitting, development of off-site assemblies, and pull-based material deliveries to limit job site clutter from excess materials and packaging. Because of these developments, the research team used this project as a case study for developing the initial framework for materials management planning. Then, using that same framework, we could help the project team determine how to best manage materials in the next phase of the project.

We began by asking the project team to identify the top ten bulkiest items that they coordinated for the project. Then, we developed the initial draft of the materials spreadsheet to clarify the various parameters that influenced the order, delivery, staging, and installation of these bulky items for the recently completed floor.

During data collection, several questions came back repeatedly: Is it better for the project team to purchase prefabricated assemblies from a third party or should the CM/GC organize a field factory to form separately-procured materials into sub-assemblies before final installation? Where should any staging of materials take place – on- or off-site? If off-site, how close should that off-site location be in relation to the project? What is the lot size in each delivery and how should materials be handled (on pallets, one piece, etc.)? From these questions combined with the knowledge gathered from earlier research in production system design, we started developing an understanding of the basic ingredients that are needed in a planning tool to support the development of a materials management strategy. Thus, our revised spreadsheet represents the first draft of such a planning tool that builds on developments in space scheduling, extending the work of Choo and Tommelein (1999), Frandson and Tommelein (2014), and Cheng and Kumar (2015).

The questions listed above also revealed the need for a daily check-in tool that makes transparent the status of materials delivery, staging, and installation on the job site. Thus, based on the lessons learned from our first case study and our experience on recent projects, we will also discuss a prototype method for materials management to help implement whatever materials management strategy is developed with the planning tool and prevent construction workers from spending much of their work time searching for and handling materials instead of doing value-adding work. This line of thinking aligns with Mossman (2007) who called for a new discipline within Lean Logistics.

Next, the following sections will describe in detail facets of the planning tool that have emerged from the revised spreadsheet as well as a prototype method for daily materials management that we seek to test in future research.

3 SPREADSHEET FOR MATERIALS MANAGEMENT PLANNING

Table 1 is an excerpt from the revised spreadsheet that we used on the hospital renovation project. It contains some headers that we used to analyze each bulky material, and we included one of the more challenging material components – vinyl wall protection – to illustrate how the spreadsheet helped the project team review the lessons learned from the recently completed floor and then revise their procurement, delivery, handling, staging, and installation processes for that same material on the current and future floors of the renovation project. For example, on the recently completed floor, the project team submitted kitting orders to an off-site materials storage facility to arrange and deliver to the job site kits of 4' x 10' sheets of wall protection consisting of varying colors. Then, carpenters would make at least two cuts on the job site to match the sizes needed within the patient rooms and corridors. For the current and future floors, the CM/GC decided to ask the wall protection fabricator to complete the first cut for all pieces. Then, carpenters would only need to complete the second cut on site.

4 PROTOTYPE METHOD FOR DAILY MATERIALS MANAGEMENT

The materials management spreadsheet examines two critical parameters in job site planning: the space occupied by a material and the time when this space is needed. These are issues that are addressed by space scheduling, and a BIM model can help simulate the occurrence of activities and the space they occupy over time (Frandsen and Tommelein 2014). Past research efforts have also worked on combining the BIM model with a schedule using automation (e.g., Cheng and Kumar 2015).

We intentionally make a distinction between storage and staging materials for the following reasons:

- **Storage** – On previous projects, we have heard lean coaches declare, “The most expensive statement on the job site is ‘Just put it over there for now.’” Materials not delivered just-in-time (JIT) may be stored on-site indefinitely and moved multiple times before installation.
- **Staging** – Staged materials do not need to be handled a second time before installation. Ideally, materials are delivered JIT, which can be better translated from Japanese as “at the right time.”

Table 1: Excerpt from the Materials Management Spreadsheet for a Sample Bulky Material (** indicates follow-up items for the project team)

Material Component	4' x 10' Wall Protection (WP) pieces
Color Variation	4 colors in Patient Room A; 4 colors in Patient Room B; 3 colors in corridors
Size Variation	12-14 sizes amongst the 4 colors in each patient room
# of Material Pieces Needed for each Unit	13 sheets (4' x 10') needed for Room Type A; 9 sheets (4' x 10') + 1 strip (6") needed for Room Type B
Number of Units	5 Room A and 15 Room B; # Corridors TBD
Total # Material Pieces Needed	100 sheets for patient rooms; ** TBD # of pieces for corridors
Procurement Rate and Delivery Condition to Off-Site Location	Once all WP has been released for fabrication, fabricator will deliver large crates containing mixed colors and sizes
Off-Site Location Material Processing	Unpack from large crates from fabricator; ** fill smaller shipping crates (no need to sort according to color)
Delivery Truck Condition and Rate to the Job Site (# pallets, carts, or crates per delivery)	Transport smaller shipping crates that contain up to 20 sheets each to job site; 3 trips for 100 sheets in patient rooms; ~3 trips for corridors
On-Site Location Material Processing	Unpack from smaller shipping crates at Loading Dock and sort according to height and color into 2 site-crates (4'H x 10'L x 1'W) before elevator; Bend to fit into elevator **How many within each site-crate and still fit within elevator?
Union Rules for Materials Management?	Carpenters needs to distribute WP because it is a finish material
Staging Condition	Keep 2 site-crates in the Equipment Storage Room; ** Sort WP according to color and size within the site-crates so carpenters can pull from the middle of the WP stack
Equipment needed for Installation	** 2nd site-crate and 4' x 8' plywood table with jig for carpenters to make second width cut in WP using razors
Space needed for Staging / Installation	** Project team to determine if Loading Dock has enough space to sort WP from shipping crates into site-crates; Wall spaces in patient rooms + corridors for installation
Labor needed for Staging / Installation	3 carpenters to transport + stage material on previous floor; Typically 2 carpenters to install each piece
Installation Rate	2 weeks for North side patient rooms; 2 weeks for South side patient rooms

Project teams should strive to avoid the storage step on-site because this will tie up critical work space. However, if storage is unavoidable, then it would be helpful to clarify where and when materials are “stored” vs. “staged.”

Space planning requires project teams to track not only installation activities that are normally accounted for in traditional project schedules, but also the space required during delivery, storage, and staging of the materials and equipment required to support final installation (Figure 2). Thus, the materials management spreadsheet is intentionally structured to help tease out the various parameters that should be considered during space planning to assist project teams with accounting for the various resources required during delivery, storage, staging, and installation while designing and organizing the project’s production system.

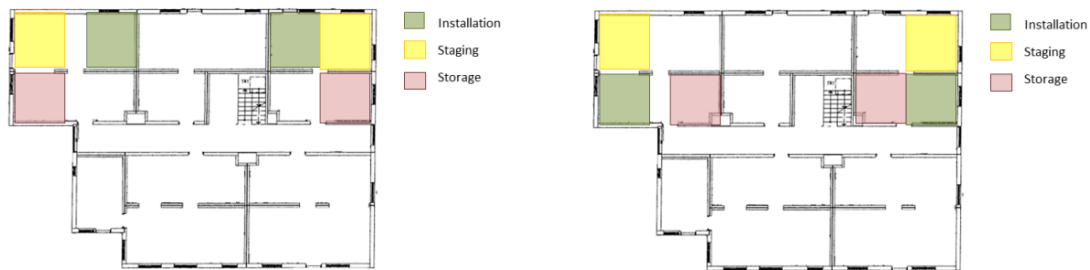


Figure 2: Mock-up of Space Planning for Storage, Staging, and Installation on Day 1 and Day 3

When a building site is small, there might not be enough room for staging materials near final installation locations. The project team would then have to store materials in another location and coordinate workers with equipment to move those materials from the storage location to the staging and installation locations. In these situations, the project team should evaluate whether this extra materials handling should be regarded as wasteful or necessary. If there are ways to organize the materials into prefabricated assemblies, then this extra materials handling can be considered primarily wasteful.

However, if the product design and site logistics prevent the ability of trade partners to form prefabricated assemblies, then this extra materials handling might be considered necessary but wasteful. Furthermore, the additional costs for handling, storage, and staging prefabricated assemblies may exceed the production gains from streamlined installation processes, so the project team may decide prefabrication is not worth the effort in such a situation. In the worst case, project teams with limited prefabrication experience may store / stage and re-store / re-stage the prefabricated assemblies around the job site several times because they occupy space required for other activities. Each re-handling represents a cost, and thus the gain with prefabrication diminishes with each re-handling of the assemblies.

To improve materials management visualization, project teams can use posted floor plans to track the storage, staging, and installation of materials and prefabricated assemblies throughout the job site. Then, by generating a series of floor plans that represent materials management over time, project teams can more easily integrate materials management discussion into on-site daily huddle meetings (Figure 2).

Ideally, as mentioned at the beginning of this section, project teams have resources available to enter the details of materials storage, staging, and installation within their projects’ 4D-BIM models. Then, project teams can easily generate the posted floor plans by printing out select views of their building models. On projects that do not have such resources, project teams could instead, for example, use one of the following approaches

to manually generate posted floor plans: (1) using permanent marker or black graphic chart tape on whiteboards (Figure 3), (2) printing floor plans on mounted foam board with whiteboard lamination, (3) placing printed floor plans under acrylic sheets on a table, or (4) attaching printed floor plans onto walls using adhesive material.



Figure 3: Floor Plan Boards used for Weekly Commitment Planning and Materials Management on an Office Renovation Project

These manual approaches enable meeting participants to discuss and quickly consider different strategies for materials management in real-time during on-site daily huddles. As a result, the posted floor plans have the potential to become a close representation of the actual status of key materials and prefabricated assemblies on the building site. If they get key foremen to regularly use this prototype method to collaborate on materials management, project teams will then become more capable of proactively managing the material flow and supply chain for the building site (Mossman 2007).

5 FUTURE RESEARCH AND CONCLUSIONS

The next research steps involve: (1) refining the spreadsheet for materials management planning through the analysis of additional materials, (2) identifying reasons why project teams should manage materials using kitting, prefabricated assemblies, or pull to coordinate deliveries, and (3) trying various manual approaches of posted floor plans to determine which are easier to manage in real-time.

Then, the next phase of research may involve: (4) examining how to set up guidelines on which materials to include in a materials management effort, (5) establishing project conditions that represent different levels of effectiveness in materials management, and (6) comparing the timing, frequency, and duration required of a 4D-BIM approach to materials management vs. a manual approach to attain these different levels of materials management effectiveness. Additional future research efforts may also involve: (7) testing IT tools that can assist with representing the actual status of key materials and prefabricated assemblies and (8) investigating how accurate of a representation of the actual status of key materials and prefabricated assemblies is needed for the different levels of materials management effectiveness.

As this research is in its infancy, limited conclusions include: (1) materials management efforts should first focus on bulky, difficult to manage items as identified by project teams, (2) a simpler approach for planning and staging materials improves the likelihood that project teams can become proactive in materials management, (3) multiple work sessions with project teams provides opportunities for critical parameters that should be considered in materials management to emerge, and (4) discussions with workers directly involved in materials management in earlier project phases are critical for clarifying lessons learned and getting feedback on ideas for future project phases.

Material elements go through different stages of transformation as they are fabricated from raw materials and handled off-site and then delivered, stored, staged, and installed on a building site. Thus, by testing the spreadsheet for materials management planning and the prototype method for daily materials management, this research is contributing to the development and refinement of tools that support the Transformation-Flow-Value Generation (TFV) theory of production (Koskela 2000).

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FLOW AND RESOURCE EFFICIENCY MEASUREMENT METHOD IN OFF-SITE PRODUCTION

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Abstract: Although the focus remains primarily on high resource efficiency, the significance of flow efficiency in construction is continuously increasing. Flow and resource efficiency describe two competing target viewpoints, which focus on reducing non-value adding activities and maximizing resource utilization, respectively. Recent research has shown that balancing both perspectives provides a viable solution. However, the exact measurement of flow and resource efficiency in construction remains unclear. Therefore, the aim of this work is to evaluate a possible flow and resource efficiency measurement method in the off-site production context of volumetric element construction, and assess the industrial relevance thereof. Work sampling has been used to collect data from a building project flowing through the off-site production system. The validity of the method has been checked statistically, through a focus-group workshop and with calculation figures from the case company. Work sampling allows flow and resource efficiency measurements in an off-site production system. The method delivers current status figures of companies, yielding a balance between flow and resource efficiency.

Keywords: House building, Industrialized construction, Performance measurement, Volumetric element, Work sampling.

1 INTRODUCTION

Traditionally, construction companies have tried to minimize production costs by maximizing their resource utilization, which represents a rational approach to using resources as efficiently as possible. However, to satisfy customers and stakeholders, factors (such as customer value, high delivery performance, short delivery times, or low tied-up capital) must be considered, which may contradict a strict resource efficiency focus. The flow efficiency approach focuses on the creation of a consistent flow from the customer order stage to the delivery stage. Companies, such as Toyota, have managed this by operating in accordance with the Lean philosophy (Liker 2004; Womack et al. 1990).

Industrialized construction companies try to improve their processes by working with platforms (Robertson and Ulrich 1998), where known technical solutions, manufacturing processes, cooperation agreements, and knowledge are preserved and repeated between projects. A successful platform addresses both resource and flow efficiency perspectives. If both approaches are essential, can they be combined in an off-site production context of industrialized construction? This work seeks to address that gap, by evaluating a possible flow and resource efficiency measurement method in the off-site production context of volumetric element construction, and assessing the industrial relevance thereof.

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2 THEORETICAL FRAMEWORK

2.1 Resource efficiency

Resource efficiency is the traditional form of efficiency and focuses on using resources in the best manner possible. This approach has formed the basis of industrial development in the previous two centuries and enabled a significant reduction in production costs. Resource efficiency or utilization rate measures the amount of resources we use in a certain time interval (Modig and Åhlström 2015). The utilization of process resources refers to the fraction of available time that the resources perform useful work (Slack et al. 2013). Furthermore, the utilization of a workstation may even refer to the fraction of time it is not idle for lack of parts. This includes the fraction of time the workstation is working on parts or has parts waiting and is unable to work on these parts, because of a machine failure, setup, or some other detractor (Hopp and Spearman 2008). Resource efficiency can be calculated as:

$$\text{Resource efficiency} = \frac{\text{Usage of resource}}{\text{Available time interval}} \quad (1)$$

The available time can be defined as the sum of the setup, maintenance, waiting, and processing times. The processing time will, in most cases, be the time the resource adds value (Koskela 1992) to a flow unit and can be considered the time required for transformation of the work (Modig and Åhlström 2015).

2.2 Flow efficiency

Production refers to the flow of material and/or information from the raw-material stage to the end-product stage. The production flow can be described by the cycle time, which refers to the time required for a piece of material to traverse the flow. The cycle time, flow time, or throughput time, is the average time from the release of a job at the beginning of the flow to arrival of the job at an inventory point at the end (Hopp and Spearman 2008). The cycle time may even refer to the frequency with which a process completes a part or product (Rother and Shook 2009). Therefore, the authors will use the throughput time to express the time required for a piece of material to traverse the flow. During this flow, the material is processed (converted), inspected, waiting or moving. Processing represents the conversion aspect of production; inspecting, moving, and waiting represent the flow aspect (Koskela 1992). Obtaining a single unit of flow is essential for flow efficient operations (Simu and Lidelöw 2014). The flow efficiency is defined as the sum of times a flow unit receives value from the resources divided by the throughput time (Jones and Womack 2002; Modig and Åhlström 2015), and in this work is defined as:

$$\text{Flow Efficiency} = \frac{\sum \text{Value-adding times}}{\text{Throughput time}} \quad (2)$$

2.3 Balancing resource and flow efficiency

Resource and flow efficiency both measure value transfer from the resources to the flow unit, albeit from different viewpoints. While the resource perspective focuses on maximizing the value added by the resources (high resource utilization), flow efficiency refers to the degree of value received from the flow unit perspective (Modig and Åhlström 2015). The resource perspective drives companies toward production cost minimization, whereas the flow perspective pushes companies toward a customer-value focus, short delivery times, and reduced inventory. These perspectives should either be combined

(Modig and Åhlström 2015) or balanced (Wernicke and Lidelöw 2016). This study is theoretically based in operations management. It is an operational principle, that process flow objectives should include interrelated parameters such as the throughput rate, throughput time, work-in-progress, and resource utilization (Slack et al. 2013).

3 RESEARCH DESIGN

3.1 The case

A single case study was performed with a medium-size construction contractor, producing multi-storey buildings using prefabricated volumetric elements delivered from the company's off-site production system. This system can roughly be described as four planar element production lines for floors, walls and ceilings, one volumetric element assembly line, three parallel final assembly lines (for completion of electricity, pipes, tiles, wall paints, wardrobes, bathroom, and kitchen interior), and a wrapping line. The production lines are divided into workstations. In this study, the flow unit consists of planar floor elements before and volumetric elements after the volumetric element assembly. The flow units move through all lines, in accordance with the "first in first out" principle. The resources of the study are the operators who process the flow units on the workstations, without being permanently linked to a workstation. These operators move between different workstations and are organized in different teams depending on the volume of work and the corresponding tasks (e.g., assembly, electricity, piping, and final inspection), respectively.

Lean has been influencing the company since 2006 and became the foundation of the company's philosophy in 2010. The company is a Lean-award winning organization and is known as a strong performer in that field. Flow-related questions have increased in recent years and many ideas and improvements have been tested, but a method for quantifying the complex effects on the production system remains elusive. Production proceedings and operator times spent in production are reported daily. The company's calculation system delivers estimated figures for operator work load planning on a project basis. However, resource or flow efficiency cannot be calculated from the available data.

3.2 Data collection method

The study was limited to a project consisting of two buildings with eight apartments each, prefabricated as 42 volumetric elements in the company's off-site production system. Data collection in this system was limited to the following observation zone: floor line (five workstations), volumetric element assembly line (four workstations), all three final assembly lines (44 workstations), and a safety stock between the floor and the assembly line. The following had to be accounted for during the design of the data collection method: (i) the size of the project and the observation zone and (ii) at a certain time during collection, all 42 flow units could be located inside the observation zone.

According to Freivalds and Niebel (2009), work sampling is effective for determining personnel utilization and production standards, yielding the same information as time studies, but requires less time and is considerably more cost-effective. Work sampling, a statistical technique for work studies, is based on the law of probability, where random objects are studied at fixed time intervals or fixed object sequences are studied at random time intervals (Almström and Kinnander 2011). For this study, the workstations and the safety stock were designated as the fixed objects, while the flow units and the operators were defined as random objects. Compared to time studies, data collection via work

sampling is based on momentary observations, without the intention of observing all the activities. The results are derived from several observations with the time interval as a steering parameter for the number of evaluable observations.

In this study, the time interval between the observations (~15 min) is considered random due to observer breaks, unsteady time for the observation cycles through the observation zone, and the difference between observation and production times. The observations (for 11 days between ca. 7:30 am and 4:00 pm) begin with the production start of the first flow unit and lasts until the last flow unit leaves the observation zone. Production occurs in three different shifts from 5:45 am to 1:00 am, with most operators working between 7 am and 4 pm. With more than 20 flow units in the observation zone, the number of observers is increased to ensure an observation cycle of ~15 min. On those days, the observation zone is divided among three observers, with the intention that they are all able to observe their allocated part within a measurement cycle time of 15 min. The results of the observations are either directly input into an Excel spreadsheet or first notated on paper spreadsheets, following the flow units, before transmission (by the observers) to the Excel spreadsheet.

Each observation yields a data notation consisting of the date, time, observer, flow unit number, workstation or stock, number of operators inside or around the flow unit, and an operator activity classification. The activities are simplified, i.e., all operators are considered busy with activities that are classified as follows: a) value-adding activities or processing tasks with direct value transfer from operators to a flow unit, b) supporting activities e.g., planning, material handling, cleaning, maintenance or setup, c) waiting including disturbance and personal time, and d) unclear for the observer. The classification is further used in table 2. The details provided are obtained from measuring the group, rather than individual workers.

3.3 Data analysis method

To enable data analysis supplementary to both the overall project and individual flow unit levels, all flow units are divided into six similarly designed flow unit types (table 1). The case study is analyzed using an Excel database. Equations 1 and 2 are modified for applicability to the case data, and are therefore based on time units, rather than discrete numbers. Jones and Womack (2002) employed the particular value-creating steps and related them to the total number of supply chain steps. Therefore, the flow efficiency is redefined as:

$$\text{Flow Efficiency} = \frac{\sum \text{Value-adding flow unit type observations}}{\sum \text{Flow unit type observations}} \% \quad (3)$$

The observed operator activity categories are used to describe resource utilization. All value-adding and supporting activities are labelled as utilization, whereas waiting and unclear activities are not and, hence, the resource efficiency is redefined as:

$$\text{Resource efficiency} = \frac{\sum \text{Value-adding} + \text{Supporting operator activities}}{\sum \text{Operator activities}} \% \quad (4)$$

4 EMPIRICAL FINDINGS

The empirical results obtained from the Excel database are used to calculate the flow and resource efficiency. Table 1 shows the observation data aggregated at the flow unit type level. Each flow unit observation contains a discrete number of operators ranging from

zero to seven. The observed activities per flow unit type and for the overall project are shown in table 2.

Table 1: Number of flow unit observations from a 15-min observation cycle.

Flow unit type	Kitchen & Bath type 1	Kitchen & Bath type 2	Two Bed-rooms	Stair-well	Living room	Living & Bed-room
Number in project	8	8	6	4	6	10
Number of observations	1069	1070	799	536	776	1310
Number of value-adding observations	501	512	249	119	147	369

Table 2: Number of categorized operator activities (see section 3.2).

Flow unit type	Kitchen & Bath type 1	Kitchen & Bath type 2	Two Bed-rooms	Stair-well	Living room	Living& Bed-room	Total project (No.)	Total project (%)
Value-adding	822	919	397	196	224	591	3149	64
Supporting	347	241	165	99	95	229	1176	24
Waiting	141	152	50	59	15	65	482	10
Unclear	25	57	13	11	12	7	125	2

5 ANALYSIS & DISCUSSION

Using the data from tables 1 and 2 and equations 3 and 4, flow and resource efficiency (see figure 1) can be calculated on the flow unit type level. This figure shows the number of observations (in terms of a percentage) with at least one operator that adds value to the flow unit type. For example, the living room accounts for 19% of the observations. This is realized by the operators who can be described by the resource efficiency, e.g., 94% of the operators perform value-adding or supporting activities when attendant to the living room. According to the operational principle, the process flow objectives should include interrelated parameters such as the throughput rate, throughput time, work-in-progress, and resource utilization (Slack et al. 2013). Therefore, the flow efficiency of a flow unit type is realized through a certain set, and use, of resources.

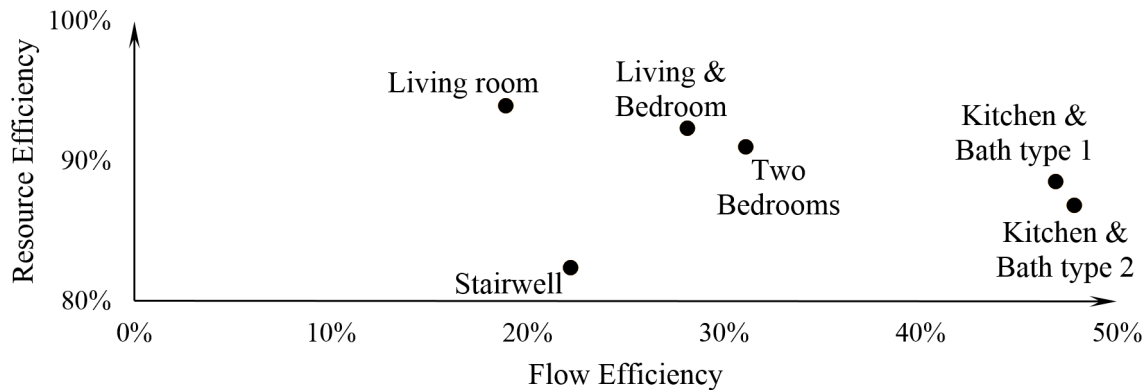


Figure 1: Flow and resource efficiency per flow unit type.

The combined visualization of flow and resource efficiency has been discussed by Modig and Åhlström (2015). They describe the difficulty organizations face in increasing their flow efficiency, while focusing mainly on high resource efficiency, and the possibility of simultaneously achieving high flow and resource efficiency. Furthermore, according to these authors, the potential for maximizing both types of efficiencies is affected by variations in the flow unit. Figure 1 shows that, except for the stairwell, the flow unit types with the highest flow efficiency (Kitchen & Bath) have relatively low resource efficiency. This may have resulted from the fact that this flow unit type (i.e., the stairwell) accounts for the lowest number of flow units and observations in the dataset. Therefore, the corresponding statistical uncertainty is higher than that associated with the other flow unit types. However, the figures enable discussion of the differences in the flow of the units through the off-site production system, effect of flow unit type variation on the involved resources, and potential operational strategies for managing both.

5.1 External validity

A workshop together with two production managers (one first line manager, one head of production management) from the case company has been completed to discuss the figures. The first line production manager pointed out that visualizing flow and resource efficiency in one diagram is quite challenging, because (i) on the one hand, meeting requests of meeting flow efficiency targets as short throughput time or takt and (ii) resource efficiency targets as minimizing operator times spent on the other hand. The fact that competitive targets occur represents the generalizable part of this study. Although the figures are case specific, the methodology can be applied to other cases.

5.2 Internal validity

The validity of using work sampling as a method is debatable (Kalsaas 2011). For example, the observers review only a part of the observation zone and the observations are accidental. In the present study, an observation interval of ~15 min yields 5560 single observation points, creating a consistent dataset that enables correlation between the discrete number of observations and the time units associated with throughput and activities. An average of 132 observations with a standard deviation of 6.4 per flow unit is obtained. The number of observations and its even deviation create a stable base for calculating the flow unit or flow unit type level. Owing to the targeted observation interval, the number of observers had to be increased to ensure a stable high-quality observation cycle, when the project accounted for more than half of the observation zone. However, the internal validity is negatively affected by the increasing number of observers. The first author of the article was the main observer and was always present at the case company

during the observations. Depending on the number of objects in the flow, additional observers were present at the final assembly lines. They were introduced by the main observer with prepared examples and a test notation run prior to the real observations. Between the observation cycles, the observers discussed the encountered scenarios and possible methods for notating hesitant observations. The number of unclear observations (table 2) is considered a quality indicator of the measurement method. A significant share could be interpreted as unsure observers or a method uncertainty, but the figure has been on a low level with ~2%.

To further validate the measurement method, the observed number of operators per flow unit type is compared with the estimated figures for operator work load, as determined via the company’s calculation system (figure 2). Both data series equals 100% each. The company’s calculation system classifies the work load in terms of the different flow unit types, whereas the data denoted as observed correspond to the total number of operator activities shown in table 2. The level of uncertainty of the estimated figures stems from equal distribution, among the flow unit types, of some of the tasks associated with the operator work load. In addition, some of the tasks were excluded and the production managers (head of production management) explained that the company’s calculation system is only sometimes updated with the current figures corresponding to the production activities. Nevertheless, the comparison indicates that the results of the measurement method and the estimated figures are correlated and enables an evaluation of the company’s calculation figures.

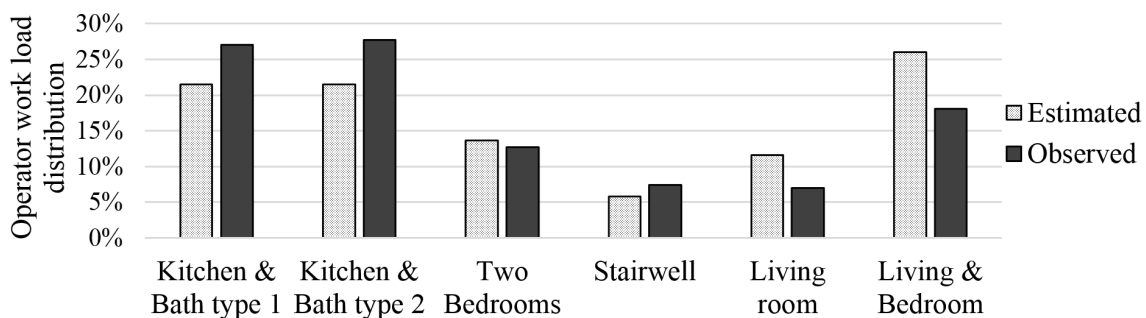


Figure 2: Comparison of estimated and observed operator work load.

6 CONCLUSION

Combined measurements of flow and resource efficiency are possible in the off-site production context of volumetric element construction, and work sampling can be used as a data collection method. The results indicate that discrete observations are correlated with the physical production flow for the chosen observation interval, but work sampling remains a time consuming method for the observation object considered. The question of balancing flow and resource efficiency is an important issue for the case company. Strategic targets of improving flow (expressed by takt or reduced throughput time) meet operational goals of using minimum resources (expressed as operator times spent).

7 FUTURE RESEARCH

The measurement method has the potential to help companies with their decision making process by showing the current status figures of how companies balance flow and resource efficiency. This method should be evaluated in different case companies and contexts, e.g.,

during on-site production. Moreover, the validity thereof could be determined via statistical methods that answer legitimate questions (such as required observation interval, demand for time interval stability, and the measurement method confidence interval).

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KEY PERFORMANCE INDICATOR FOR MANAGING CONSTRUCTION LOGISTICS PERFORMANCE

Fei Ying¹ and John Tookey²

Abstract: Construction logistics is an essential part of lean construction for both project management and cost aspects. The quantum of money that is embodied in the transportation of materials to site could be 39 to 58% of total logistics costs and between 4 to 10% of the product selling price for many firms (Coyle, Bardi et al. 2003). However, limited attention has been paid to this issue in the New Zealand construction industry. The purpose of this paper is to contribute to the knowledge about managing transportation costs by setting a Key Performance Indicator based on the number of vehicle movements to the construction site. A case study approach was adopted with on-site observations. Observations, including vehicle movements and material delivery patterns, were performed from the start of construction until "hand-over" to the building owner. Data analysis of vehicle movements suggested that construction transportation costs can be monitored and managed. The identified number of vehicle movements as a key performance indicator offers a significant step towards logistics performance management at the operational level in construction projects. It provides a basis for benchmarking that enables comparison, learning and improvement and thereby continuous enhancement of best practice.

Keywords: Lean construction, construction logistics, KPI, New Zealand.

1 INTRODUCTION

Lean construction has been adopted by the construction industry as a means of Supply Chain Management (Jorgensen and Emmitt 2009). The aim of lean construction is to work on continuous improvement, waste elimination, strong user focus, value of money, high quality management of projects and supply chains, and improved communications (OGC 2000). The construction industry is a project-based industry where each project is unique. This uniqueness has a direct influence over the implementation of lean construction. Furthermore, each project presents a logistical exercise customised to fit its operations. Since the industry does not elect where it conducts its productive activities, it therefore has to move where the work is. Construction logistics covering materials management and physical distribution is thus an essential part of lean construction. Considering that materials usually account for between 30 to over 50 percent of the cost of a building project (Fellows, Langford et al. 2002), transportation costs represent approximately 39 to 58 percent of the total logistics costs resulting in between 4 to 10 percent of the product selling price for many firms (Coyle, Bardi et al. 2003). The transportation costs of material hence represent a substantial percentage of the cost profile of the construction industry.

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Therefore, a small percentage cut in transportation costs could bring a sizable increase in profits.

Key performance indicators (KPIs) are widely used internationally to measure the performance of the construction industry (The KPI Working Group 2000). In New Zealand, a series of KPIs based on those developed in the United Kingdom (UK) have been measured over five years. Ten KPIs endorsed by the government address both project and company performance. These KPIs focus on construction cost, construction time, predictability of cost and time, defects, client satisfaction, safety, profitability and productivity (Constructing Excellence (NZ) Ltd 2008). Although the government intends to endorse a broad set of practical indicators, there is no KPI to address the performance of logistics costs and efficiency. Considering the sizable expenditure involved in transport related activities, it is therefore paradoxical that there is no appropriate KPI to measure logistics performance in the construction industry.

The aim of this paper is to propose that vehicle movements to the site can be used as KPI in monitoring and improving logistics performance. The focus is to measure transportation costs at both project and company level. To demonstrate the application of a proposed KPI, a case study of a commercial project in major New Zealand city is assessed. The findings of the project offer insights into the implementation of such an indicator to measure material transportation costs and monitor logistics performance.

2 PERFORMANCE MEASUREMENT IN CONSTRUCTION LOGISTICS

Logistics is the umbrella term covering materials management and physical distribution (Gattorna and Day 1993), while a lean delivery emphasises a cost-effective and on-time handover with no delay or quality issues. Measurement of logistics is an important step to performance improvement. Performance measurement is a process of quantifying the efficiency and effectiveness of past actions, while a performance measure is a parameter used to quantify the efficiency and/or effectiveness of past actions ((Neely, Adams et al. 2002). In the early 1990s, project success was considered to be linked to performance measures, which in turn were linked to project objectives. At the project level, success was measured by the project duration, monetary cost and project performance, the so called project management “iron triangle” (Atkinson 1999). In addition to these basic criteria, researchers advocated that measures for construction project success should also include project psychosocial outcomes (such as participants’ satisfaction level, and safety), time-dependent dimensions, and perspectives of stakeholders (i.e. owner, developer, contractor, user and the general public) (Shenhar, Levy et al. 1997, Lim and Mohamed 1999).

Previous studies indicate that performance measurement has a notable effect on the development and effectiveness of benchmarking (Costa, Formoso et al. 2006). This is mainly because tracking performance identifies uncompetitive management practices which promotes investigation of changes. Sillanpää (2015) claimed that measuring the supply chain is the basis of developing it. KPIs are general indicators of performance that focus on critical aspects of outputs or outcomes. For performance measurement to be effective, the measures or indicators must be accepted, understood and owned across the organisation (Collin 2002). Also, only a limited and manageable number of KPIs is maintainable for regular use. Having too many and/or too complex KPIs can be time and resource consuming, data collection thus has to be as simple as possible. Another essential criterion of a KPI is that it can translate practices and measures into practical knowledge and make it possible to identify and adopt superior performance standards (Costa, Formoso et al. 2006).

Wegelius-Lehtonen (2001) suggests a framework for performance measurement in construction logistics, that categorised the eight measurements (project time efficient, value added, subcontracting percentage, number of invoices per day, amount of small invoices, disposal costs, reply percentage of tenders, and amount of changes in subcontract) into two dimensions: use of measure and focus of measure. Further development of this framework has not yet occurred, which suggested that the indicators were not effective enough to practice at construction sites. Indeed, the construction firms do not usually have continuous data collection systems for logistics measures (Vogl and Abdel-Wahab 2014). In New Zealand, the practice in industry is in line with this claim (Page and Norman 2014). Research points towards the fact that the construction industry does not effectively address, or have the skills to solve, logistics problems. At present, the lack of knowledge is masked by a lack of immediacy in recognising that there is a problem at all. It is recognised that major barriers about awareness of logistics costs include invisible logistics costs, disconnect between investment in construction logistics and benefit, and no recorded data relating to logistics performance (Blumenthal and Young 2007, Omar, Hassan et al. 2009).

3 RESEARCH METHODOLOGY

The guiding purpose of this study was to contribute to the knowledge about measuring logistics performance by setting a KPI using the number of vehicle movements to the construction site. The focus of the work was on identification of the main performance aspects measured by the total numbers of vehicle movements. It also sought to understand why vehicle movements can be used as a KPI, as well as questions of how to use the vehicle movements in improving logistics performance. A case study with a qualitative and quantitative approach was used as this approach is appropriate when the research problem requires understanding of complex phenomena that are not controlled by the researcher and when the research questions have a how and why nature (Yin 2009).

It is important to select a critical case that can explicitly demonstrate. The choice of a commercial project in the largest city (by population and area) in NZ reflects typical problematic issues for construction logistics which critically demonstrates the “how-problem” (Yin 2009). The case study described in this paper was a commercial project hosted by a University located in central Auckland, implying special requirements in terms of logistics and physical distribution. Auckland is notable for its “Urban Sprawl” (Ministry of the Environment 2005). The city also has a substantial reliance on road transportation since public transport system has historically not kept up with population growth needs. The \$100 million project consisted of a 13 level tower block with a rooftop plant room surrounded by a lecture theatre and student facility. The new construction integrated several existing buildings on campus. The construction had three stages: ground works, structure, and fit-out. The contract was fixed price, with the client being allowed certain flexibility in the scope without extra charge.

On-site observations were performed during construction, as well as during weekly coordination meetings held between the main contractor and its subcontractors. These were documented through notes, photographs and audio recording. The depicted scenes gave an opportunity for participants to reflect on specific situations in retrospect. As noted by Scott and Garner (2013), observing behaviour gave opportunities to make sense of a larger context and draw conclusions that the individual subjects might have had difficulty noticing. Extensive observations were also made on the construction site to confirm information retrieved in the literature; the on-site observations also enabled information gathering that were unable to gather otherwise.

Special attention has been paid to the numbers and patterns of vehicle movements, since it was expected that appropriate interventions to improve construction logistics could be identified through analysing these elements. The vehicle movements were recorded by the gates-person on the site. Details such as delivery company name, date, time, truck type, materials, and activities were noted on printed tables. These details were then transferred to electronic documents and analysed using MS Excel and MS Access.

These data were analysed as a whole, reduced to focus on the main objective of the paper and then presented in a synthesised form.

4 KEY FINDINGS

For the period of construction, the total number of vehicle movements to the observed site was approximately 6,300. These vehicles were from 257 different firms. Vehicle movements were recorded in total for 334 days over 58 weeks. The different project stages and particular construction processes had profound signatures in the types, numbers and frequency of delivery vehicles entering the site.

Vehicles arrived at the site were classified in four categories, small (short and light two-axles vehicle, such as car, van and utilities), medium (short towing three to five axles vehicle, such as car with trailer), large (medium and heavy vehicle, 5.5 to 14.5m with two to four axles), and very large (long and heavy vehicles, 11.5 to 19.0m with three to six axles) (AUSTROADS 2006).

Similarly, time of delivery was analysed using same batch of data. The deliveries occurring throughout the day following no specific pattern. The histogram appears to be multimodal and skewed normal. The histogram also shows that almost one fifth of arrivals occur before 8:00 am while 55.8% of the arrivals occur during either in the early morning (08:00am to 10:00am) or early afternoon (12:00am to 2:00pm). Indeed, vehicles arrivals on delivery points start after 6 and increase rapidly before peaking at the time interval between 9am to 10am. Then, taper down as time passes creating a strongly skewed distribution. In the studied project, 67.8% of deliveries took place before midday.

The deliveries were most carried out from 8am to 11am (38.2%), which overlaps with the peak time of city traffic from 7am to 9am. These truck movements not only put extra burden on the existing saturated city traffic, but also reduce logistics efficiency. Some truck drivers complained about the tight space for manoeuvring in the city roads during peak traffic. These construction vehicle movements impose negative economic, social and environmental impacts by adding to the problem of congestion and environmental pollution.

Vehicle movements of each subcontractor were then further analysed to measure various aspects of logistics performance. In this paper, the data of ready-mix-concrete (Supplier A) are used to demonstrate that vehicle movement can be utilised to measure transportation costs. Figure 1 illustrates the delivery time carried out by Supplier A. The deliveries were mostly carried out during 2pm to 3 pm (135 of 988 deliveries), and 9am to 11am (127 and 116 deliveries respectively). The diagram indicates that supplier A attempted to avoid the peak times of city traffic. It was confirmed by site manager that Supplier A was very cautious about concrete pouring time. They coordinated with the main contractor before each pouring day and tried to avoid traffic peak hours delivery. It is not surprising since ready-mix-concrete is a time sensitive product.

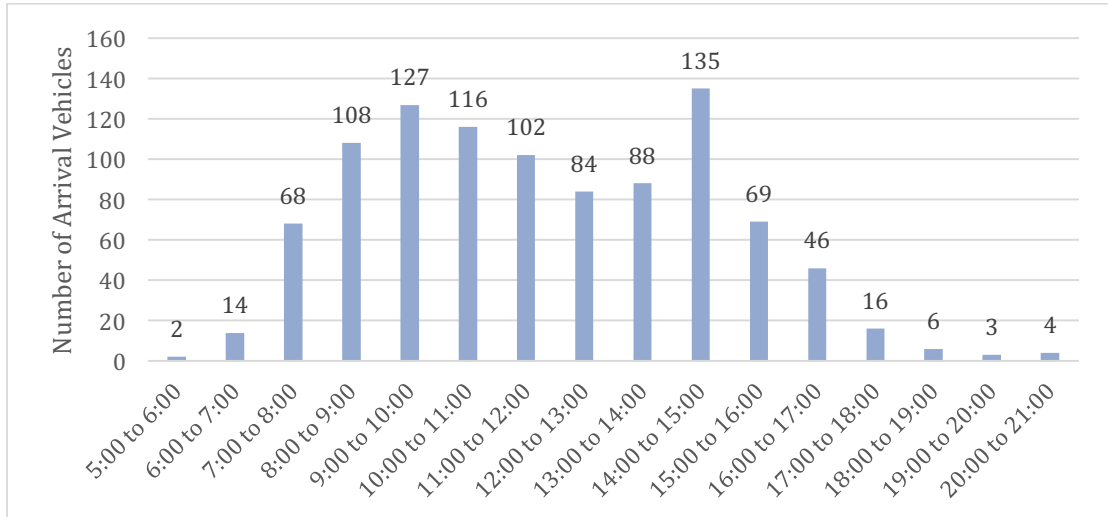


Figure 1: Vehicle arrival time -- Supplier A

$$Cost_{Transportation} = \sum_{n=1}^i CO_i \times D_i$$

Where: $Cost_{Transportation}$ is the total transportation costs, CO_i is the vehicle operating cost of the i^{th} trip, D_i is the distance between the site and the depot of the i^{th} trip.

The vehicle operation costs vary with the size of the vehicle. For example, using the data for the ready-mix-concrete supplier, 952 large vehicles and 36 very small vehicles were made into the site. The concrete plant is located 4.1km away from the construction site, giving 8.2km for a round trip. There is no data for concrete mixer truck operating costs in New Zealand; the counterpart in the United States were adopted for this research (Zagula, Hinkle et al. 2012). The estimated operating cost for a concrete mixer is approximate \$9.2/km, which includes fuel, maintenance, accident repair, road call, drum chipping and driver’s wages. Similarly, for a small vehicle, estimated operating cost is \$1.2 covering standing costs, fuel, tyres, service, and registration. Hence, the transportation costs for Supplier A for this project is \$112,495. The total amount of concrete supplied to the project is 4,865m³, costing \$1.05m. Accordingly, it is calculated that the transportation costs are 10.8% of the product selling price.

In the construction industry, the choice of material was primarily made on the basis of lowest per unit cost “as delivered”. The cost of transportation was not isolated, and thus cannot be measured. Using data recorded at the site of vehicle movements, the “invisible” transportation costs for each firm and the whole project were able to be identified. The transportation costs lean to higher end of percentage of the production selling price comparing to previous research (4 to 10%, according to Coyle, Bardi et al (2003)).

5 DISCUSSION

The main aim of this paper was to propose using vehicle movements as a KPI for monitoring and improving logistics performance, considering that KPIs are seen to be essential to measure and control construction performance.

Based on the empirical analyses and the generic body of knowledge concerning logistics and lean construction, the key findings indicate the construction logistics

management practices in the studied project would be regarded as “traditional” in that they are typically uncontrolled, disruptive and uncoordinated. The congested delivery time slot is evidence that there was not much communication or coordination regarding logistics among the subcontractors and material suppliers. These traditional practices are mainly caused by industry related issues. The construction industry is a project-oriented industry with many players. All major players, such as main contractors, subcontractors, and material suppliers, look at the logistics process from their own point of view. From the logistics process aspect, the studied project can be seen as independent project stages with different actors without a common goal. Thus, implementing performance measurement provides an opportunity for benchmarking and performance control.

Furthermore, the data analyses provide insights on the underlying drivers of performance. This is achieved by tangible and intangible inputs to leading performance measures that can be used to predict logistics performance, which may offer industry guidance on how to improve performance. Equipped with the information, such as peak delivery time, firms can evaluate the busiest delivery hours at the site and schedule deliveries accordingly to avoid long waiting times. The findings also give a snapshot of the interface between site activities and various material and plant supply chains, which is essential in lean construction (Vrijhoef and Koskela 2000).

Data analysis in this project demonstrates that the proposed indicator is simple and straightforward to establish a project logistics performance measurement system and incorporate the measures into the project routine. It is evident that measures can be translated into practical knowledge effectually by using a simple spreadsheet. Since the indicator focuses on data at the operational level, the interpretation of the data is straightforward and highly applicable to site management. Also, the proposed measurement is relevant to management in their daily work and is a means for continuous performance improvement on projects. The translation from practices and measures into practical knowledge makes it possible for the management team to identify and adopt a best performance standard.

6 CONCLUSIONS

This paper has discussed initiatives to develop a performance measurement indicator for benchmarking logistics performance in construction projects. Vehicles delivering materials and removing waste at the construction site physically link the supply logistics and site logistics. Vehicle movements thus could reflect the potential issues in both types of logistics. Using the numbers of vehicle movements as a KPI, the evidence provided in the case study demonstrates the indicator can effectively and efficiently describe and monitor site logistics performance. This study has pointed out benefits and opportunities for taking initiatives and implementing such a KPI.

The work presented here assesses the ability of vehicle movement as a KPI in measuring the “invisible” transportation costs. In this project, the transportation costs of ready-mix-concrete, which is JIT delivery, is more than 10% of the material selling price. It is reasonable to assume that the project transportation costs would be much higher than this number, since the majority of the contractors delivered materials ad hoc. Based on the implications drawn, the findings of this study have the potential to be implemented by construction management companies building recorded databases and thus to increase the likelihood of logistics management adoption by the construction industry.

It is arguable that logistics is far more than transportation costs. Thus, the major limitation using vehicle number as KPI is its ability of measuring restricted aspects of

construction logistics. However, the research suggests the proposed indicator is simple and well designed to establish a project logistics performance measurement system and incorporate the measures into the project routine. It could be used as a starting point to measure the “invisible”, bring the awareness to the industry and promote performance benchmarking at the operational level.

Moreover, the data presented in this paper focusing on one construction project. More inquiries are required in the form of case studies, such as other projects located in various geographic context, to generalise the material delivery pattern. Future studies also need to investigate whether firms with different supply chains characteristics demonstrate similar transportation costs and logistics efficiency

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OFF-SITE GUARDING: LOOK-AHEAD SUPPLY SCHEDULING FOR RISK INDICATION WITH BIM

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Abstract: Modern Information and Communication Technology (ICT) make it possible to re-organize the information flow and enhance the physical flow of the Construction Supply Chain (CSC). Considering the resource status and potential risks that exist in the CSC, this paper first explores the current CSC re-organization caused by the application of Building Information Modelling (BIM) and related beneficial conditions created by ICT. It then tackles the problem of controlling risk effectively by off-site guarding the upstream of the CSC. Based on the selected approach, the concept and basic mode of a look-ahead supply schedule is proposed. Finally, results to a use case demonstrate the applicability of a look-ahead supply schedule for a resource loaded construction project.

Keywords: Look-ahead schedule, CSC, ICT, BIM, off-site guarding.

1 INTRODUCTION

A consensus about a stronger link between the lean management philosophy and the information technologies has been revealed as an important issue for the field of architecture, engineering, construction, and facility management (AEC/FM). Previous efforts and outcomes, which have been made to explore how manufacturing concepts can be transferred into the construction context to improve the productivity performance (e.g., Koskela 1992), become more practical with the support of modern Information and Communication Technology (ICT). From the perspective of the Supply Chain Management (SCM), it has been affirmed that the current practices and researches effectively lead to the advanced controlling and management of CSC as an integrated value-generating flow, rather than only a series of individual activities (e.g., Vrijhoef and Koskela 2000a; Sacks 2016a). Besides, modern ICT makes it possible to detach information flows from physical flows (Christiaanse and Kumar 2000a), thus providing a chance to break the barriers of the physical constraints in CSC.

Planning is essential in construction management. The key information of an ICT-enabled CSC can be captured to enhance the reliability of construction planning, especially for the task of look-ahead planning (Chua et al. 1999a; König et al. 2012; Song and Eldin 2012). While traditional scheduling tools do well in project-level planning, e.g. Critical Path Method (CPM) to create a master schedule, recently, the Last Planner (e.g., Ballard 2000a; Sacks et al. 2010a) and similar systems successfully improve the look-ahead planning and commitment planning. However, the existing construction planning encounters either insufficient details of resource status and potential risks, or details

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provided just for one-of-a-kind CSC in which information and experience is hard to transfer to other types. The research teams (RT-272, RT-315 and RT-344) organized by the Construction Industry Institute (CII) recommended and developed Advanced Work Packaging (AWP). Currently, AWP as an emerging planning approach is promising to improve the integration of CSC and the risk mitigation (Ponticelli et al. 2015).

Considering the supply resource status and potential risk existed in CSC, this paper first explores the current CSC re-organization caused by the application of Building Information Modelling (BIM) and related beneficial conditions created by ICT. Then, this paper defines risk controlling for the CSC upstream interface. The main participants, processes and activities of the CSC upstream are also clarified. Based on these definitions, the concept of look-ahead supply scheduling is proposed. Finally, there is a case to provide a profile for the basic understanding of the risk controlling mechanism of the look-ahead supply scheduling.

2 PROBLEM STATEMENT

Although there is a growing body of evidence that proves that ICT and BIM have enhanced traditional planning (e.g., 4D/5D BIM, real-time tracking) (Bryde et al. 2013), the basic aspects of construction planning have to be further improved: 1) it is built upon the basis of a transformation model; 2) makes use of scheduling techniques with assumptions: a) preparation for an activity has always been adequately made before the activity's schedule time; b) each activity is to be duly accomplished (Chua et al. 1999b).

The transformation model has been criticized by researchers from the perspective of the Lean Construction philosophy. Meanwhile, the Last Planner System (LPS) has been continuously developed to support better look-ahead planning and committing planning (Ballard 2000b), which is capable of breaking the constraints of the above assumptions. In most of the current LPS or related systems, the resource applying has been set as a simple constraint without a good traceability, but the peculiarity and complexity of CSC were ignored. To improve it, Sacks et al. (2010b) suggested the trade contractor's manager to select and claim the building elements in a BIM system, in order to transfer the responsibility to the person who actually is most familiar to the off-site production process. However, the look-ahead mechanism has not been improved adequately. For example, the supply problem of building component M is identified in the first weekly meeting of a three-week look-ahead schedule of construction task N, as shown in Figure 1:

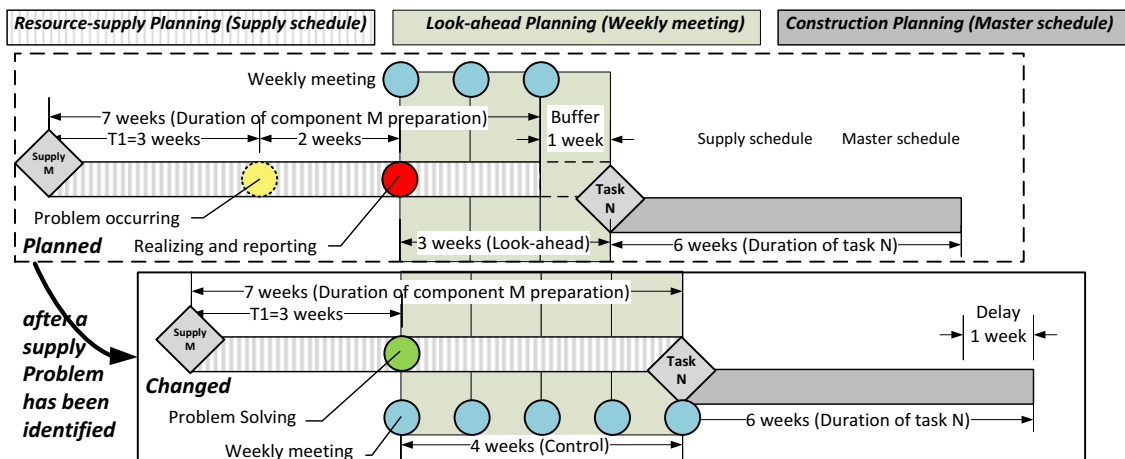


Figure 1: Inefficiency in current CSC look-ahead planning

Hypothetically, the solution can be immediately put into effect. But the problem has occurred just two weeks before the first weekly meeting, thus it takes four weeks to solve this problem (e.g., re-production). Although there is already one week time buffer of the component M applying for Task N, it will still cause a one week delay in the construction master schedule. An emergency measure (e.g., replacement of supplier) can be taken when the problem is identified, but this option is often unavailable or unmanageable.

Consequently, there are two inefficient aspects of current CSC look-ahead planning to indicate the risk and further to avoid the construction delay and loss:

- the pre-processes and lead-time of the required products are different, and general duration of construction activity-based look-ahead schedule is hard to match it, e.g., even in a look-ahead planning, the long lead-time may turn pre-controlling into post-controlling;
- the activities of on-site construction and off-site production and transportation are separated, but the risks are shared and even transferred incrementally with a Bullwhip Effect. It means the post-controlling is inefficient to avoid loss.

Therefore, an efficient look-ahead supply schedule should be developed to provide real-time information for the look-ahead construction planning and indicate the risk along the whole CSC. Currently, there are favourable conditions to support it: 1) better understanding of Production theory and SCM theory: for instance, CODP (Customer Order Decoupling Point) approach makes the off-site production processes more detailed and structured; 2) the utilization of ICT: it changed the current organization of CSC, especially when BIM was adopted and developed in the construction industry.

3 OFF-SITE GUARDING CONCEPT FOR THE CSC UPSTREAM

Christiaanse and Kumar (2000b) summarized the related literature and explained the ICT-enabled re-organization of the supply chain. It is feasible to collect and process the CSC information electronically, in advance or in parallel with the physical production flow. BIM can integrate processes throughout the entire lifecycle of a construction project. Project stakeholders have prior access to influence the on-site construction. An example of CSC re-organization in BIM scenario is shown as Figure 2:

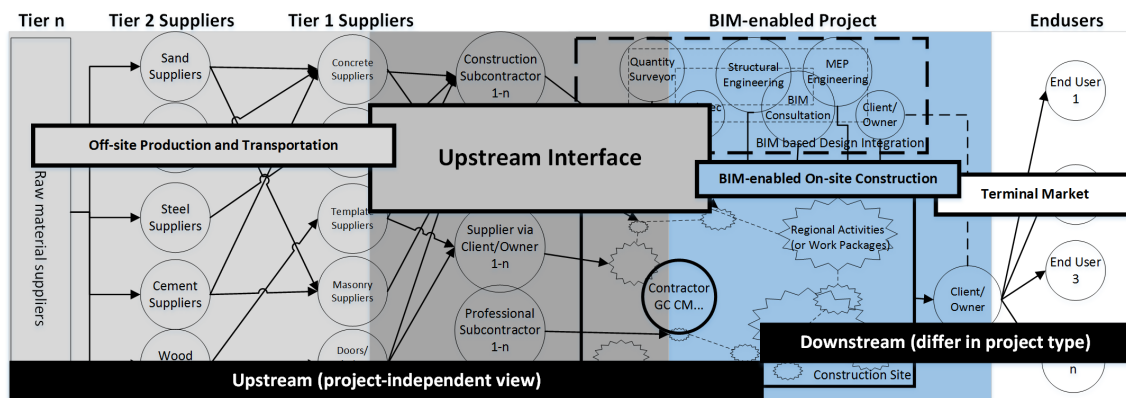


Figure 2: CSC upstream interface in BIM scenario

As the first role which has already been defined by Vrijhoef and Koskela (2000b), the focus of the upstream interface is on the impacts of the supply chain on-site activities. In

BIM scenario, the upstream interface is the main issue of controlling the supply risk. The main participants of the upstream interface are (see Figure 3): 1) off-site participants: including General Supplier (suppliers via the general contractor), Appointed Supplier (suppliers via the client/owner), Subcontractor (responsible for one or more suppliers), other type of participants with similar function and responsibility. 2) on-site participants: including General Contractor, Construction Manager, other type of participants with similar function and responsibility; 3) joint participants (if any): including Trade Manager, Joint Logistics Manager and other type of participants with similar function and responsibility.

Present BIM systems can provide an informative and interoperable environment for on-site construction and become more friendly to on-site participants and joint participants. However, the off-site information has not been adequately grasped and processed in BIM to support on-site construction.

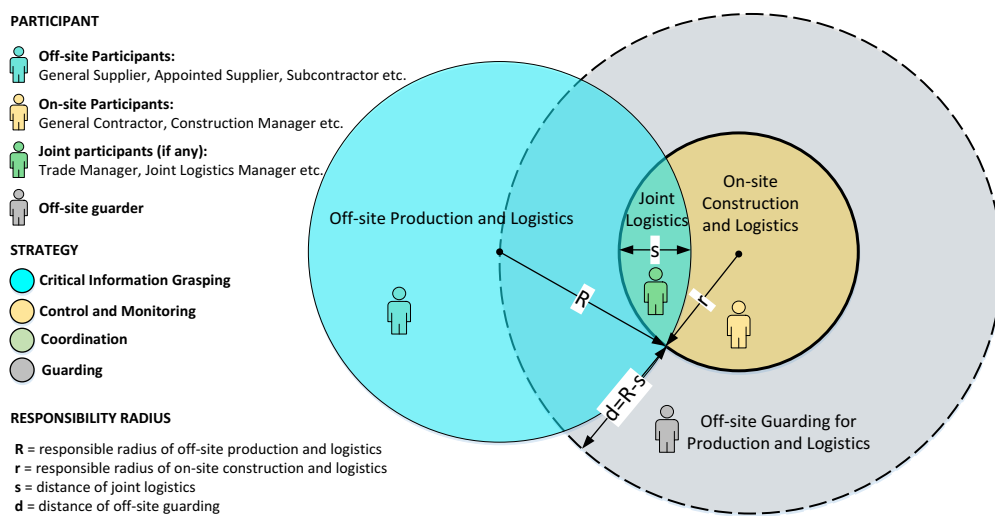


Figure 3: Participants, responsibility radius and strategy of the off-site guarding

3: Participants, responsibility radius and strategy of the off-site guarding

For a holistic and look-ahead CSC risk controlling a reactive guarding mechanism is needed, as shown in Figure 3. The off-site guarding area can be interpreted as distance and time buffering to correct errors and solve problems, in order to avoid the interruption of the on-site construction. The off-site guarder refers to the person, group or even an information agent (e.g., extended BIM), which is able to grasp key information from the CSC upstream, analyze the risk degree for on-site construction in advance. In this paper, the concept of off-site guarding and the application of BIM to indicate risks is proposed.

4 LOOK-AHEAD SUPPLY SCHEDULING FOR GUARDING

In the ICT-enabled CSC upstream, a look-ahead supply scheduling for off-site guarding is necessary and achievable. The basic mode is designed as following:

- objects and activities: the required supply items for on-site construction are the main objects of look-ahead planning, including material, machinery, special building components etc., which comprise the physical flows of the CSC upstream. Along with the physical flow, there are a series of activities, e.g., production, transaction, transportation etc. In the look-ahead supply schedule, the production activities are most unfamiliar and uncontrollable for the on-site construction

manager, while the transportation activities have been improved prominently by modern sensing and tracking technology (e.g., Costin et al. 2012). Thus, the off-site production activities are the main activities of look-ahead supply scheduling.

- processes: the off-site production activities are to be expressed as the CODP-based processes, to schedule the lead-time of specific supply objects. Per the CODP-based classification, there are four types of processes with different lead-time from long to short: engineered-to-order (ETO), followed by made-to-order (MTO), assembled-to-order (ATO), finally made-to-stock (MTS).
- risk identification and state-transition: the risks in the CODP-based process need to be identified by checking. The high-frequent checking is aimless and wasteful, so that a state-transition checking is applied. The state-transition information needs to be collected from direct suppliers and manufacturers, and the checking system is responsible to calculate the risks, as following:

$$R_d = \sum_{i=1}^n (s_i * \sum_{j=1}^m tf_j) \quad n = \text{the number of check points}$$

m = the number of the additional events at a certain check point

s = the probability of the additional events occurring

tf = the float time of each additional event

- linking for look-ahead: the dynamic supply schedule needs to be linked with the construction schedule to indicate the risks in CSC upstream, which will be transfer into on-site construction activities.
- BIM model view: the construction manager is quite familiar with on-site construction processes but not good at handling the off-site production, so that the look-ahead risks are design to be visualized in BIM model.

In this pattern, the look-ahead supply schedule has the following basic functions: 1) it introduces off-site production into on-site construction by linking the items' lead time; 2) it provides more distinct supply information to distinguish risks to avoid supply delay or logistic disorder; 3) it proves more detailed time parameters for a construction task but will not disturb the construction sequences.

5 CASE STUDY

The case study that was investigated, has been developed by the Zejin Real Estate Development Co., Ltd. The project is located in Chongqing City, China. The problem has occurred in the process of hollow floor system construction. The 500/500/280 mm GBF-embedded-filler was the one of the major material of the hollow floor. The GBF-embedded-fillers is placed on the floor to improve the floor's void ratio. It also accelerates the construction schedule. The problem of the delay of the supply of the material occurred. At the beginning, it was late between one and up to two weeks. Later, the supply was late for a month. This matter led to the idling of the labour forces and the damage of the framework that contained steel reinforcement under high-temperature conditions. The causes finally led to project delay and cost increase. Although the kind of fillers is an MTO product and the production process is not complicated, it is a new material for use in the Chinese residential construction. There was no experienced supplier in the Chongqing region and the general contractor has not prepared any preventive measure.

5.1 Linking the CODP supply schedule with construction schedule

The following look-ahead supply schedule is suggested in this use case. As shown in Figure 4, the related construction tasks can be defined: 1) floor slab formwork and rebar binding; 2) GBF-embedded-fillers installing and concrete casting. Each construction task needs different types of materials or equipment based on the CODP-classification.

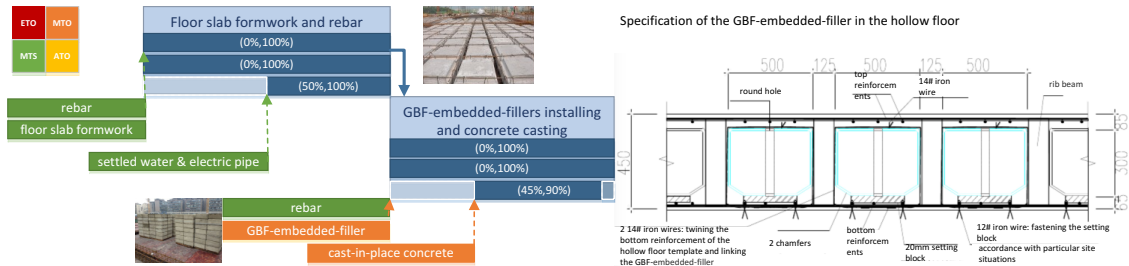


Figure 4: CODP-based schedule of the GBF-embedded-filler

The specific CODP-based process is designed to provide the necessary detail. It supplies a series of key state-transitions and makes the off-site production flow clear and manageable. However, in this use case, the construction manager did not get the key information from the supplier and consequently caused a construction delay. To avoid the problem in the future, it is necessary to define and check the specific MTO production process of the GBF-embedded-filler in advance.

5.2 Process definition and state-transition for supply risk identifying

To grasp the key information of state-transition is the task for a general contractor or construction manager in the off-site guarding stage. There are three state-transition check points in the MTO process of the GBF-embedded-filler, as shown in Figure 5:

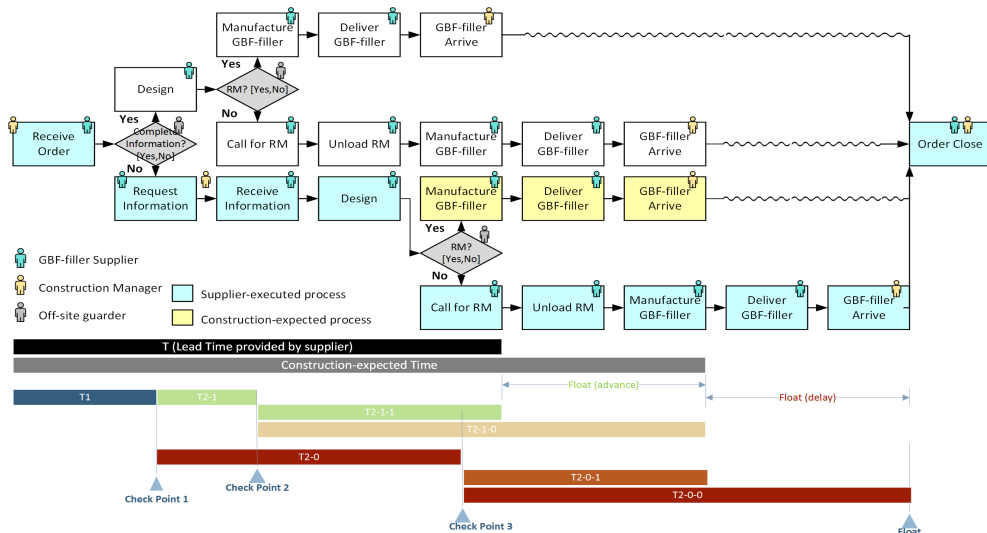


Figure 5: State-transition checking of the GBF-embedded-filler

There are also three off-site guarders of state-transition, and they are responsible for keeping robust information flow and providing key information for look-ahead planning. In this ICT-enabled CSC upstream, they are set as the information agents rather than the

natural person, to play a role in BIM system. Every state-transition checking can work out the risk level, which will be stored in the off-site guarding information agent. This checked and stored risk level information will be visualized in BIM system for construction manager's look-ahead planning and controlling.

In this case, the general contractor has already asked the supplier at the first check point, and the supplier promised it after completing the design information. However, the following supplier-executed process and the construction-expected process was not met, as shown in Figure 5. The second state-transition has not been checked: if the raw materials (RM) get ready or not? The supplier met the problem after the design phase without giving any information to the general contractor. If the general contractor would have known about the situation in advance, he possibly could have slowed down the construction task of floor slab formwork and rebar binding to avoid the damage to the framework containing the steel reinforcement in the high-temperature condition.

5.3 Supply risk indication in BIM for construction look-ahead planning

The supply risk indication in BIM model view is easy for the general contractor and subcontractors to understand. Zeng et al. (2015) have discussed how to add CODP-based parameters in BIM and how to express the risk value. The function mock-up is shown in Figure 6:

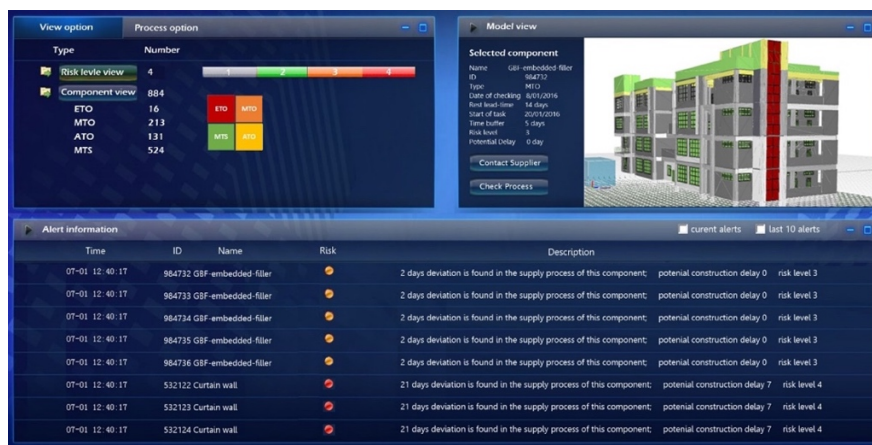


Figure 6: Function mock-up of supply risk indication in BIM

There are two elements in identifying the supply risk: 1) BIM model view, and 2) supply process inquiring. In the view option, the risk level view and the component view can be selected. The risk level view is shown in the right window. The model view will indicate the supply risk in a colour scheme and provide the basic information of the selected components. There is also an alert window, which contains the information about time, component name and ID, risk level and delay description. If it is necessary to find out details to the supply problem, the 'check process' function will help and a new window of the CODP-based process opens for further checking.

6 CONCLUSION

This paper explored the current CSC re-organization caused by the application of BIM. The novel information created by ICT defined the off-site guarding in the CSC upstream. Based on these definitions, the concept of look-ahead supply scheduling is proposed. Finally, a case study provided the basic understanding of integrating the functionality of

CSC upstream interface and the risk controlling mechanism of the look-ahead supply scheduling in practice.

Findings are that generating a look-ahead supply schedule does not interrupt the behavioural pattern of the on-site construction manager for the look-ahead planning and weekly meetings, but BIM enriched with supply information provides more completed and real-time information for decision making. However, further methods need to be developed and tested to build a robust look-ahead supply linkage. This then will enable users to allocate and control the activities and resources more efficient and ultimately causing lower risk to the project.

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SAFETY, QUALITY, AND THE ENVIRONMENT TRACK

Track Chair:

Christine Pasquire

Nottingham Trent University

ANALYSIS OF THE INFLUENCE OF LEAN CONSTRUCTION AND LEED CERTIFICATION ON THE QUALITY OF CONSTRUCTION SITES

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Abstract: Adequate planning of construction sites guarantees better efficiency, productivity, quality on the development of all work activities, optimization of the physical available space, workers' safety and motivation in performing their duties. The objective of this paper is to verify the influence of Lean Construction and LEED Certification on the quality of construction sites. The aspects analyzed were Temporary Facilities, Safety, Material Handling and Storage at construction sites by using a checklist developed by Saurin and Formoso (2006). Forty construction sites in the Metropolitan Region of Fortaleza (MRF), Brazil, were analyzed. The results pointed to a direct relationship between the implementation of Lean Construction and LEED Certification and the overall quality of work at construction sites. The concepts of Lean Construction are linked to a better quality of material handling and storage, temporary facilities and safety at construction sites. Also, the LEED Certification influences to a better quality of material handling and storage. Those two aspects combined make the construction site safer and more efficient, reduce material waste and cost, as well as increase the quality of the services executed.

Keywords: Lean Construction. LEED Certification. Construction Sites. Construction Quality. Construction Safety.

1 INTRODUCTION

The layout planning of a construction site involves identification, dimensioning and adequate allocation of the temporary facilities (Abotaleb et al 2016). This planning is considered to be a highly difficult problem given its complexity (Lien and Cheng 2012). A construction site with a high-quality planning directly affects the construction processes: it diminishes worker's travel time, promotes safety and improves the handling of materials and equipment. That, in turn, increases efficiency and reduces cost, especially for large constructions (Hamiani and Popescu 1988; Tommelein et al 1992).

According to Koskela and Dave (2008), the Lean approach is a new way of analyzing the waste in the production system as well as reducing, or eliminating this waste for better efficiency. The LC aim is to reduce the waste and the cycle time, improve the efficiency, and maximize the value for the client (Ballard et al 2012). These objectives contribute for a good-quality and well-planned construction site by analyzing the similarities between the objectives of LC and the benefits of a high quality site. In this same scenario, the LEED Certification can be an alternative with the same influence on

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the site. That is possible because, according to the Green Building Council Brasil, the LEED Certification focuses on sustainability and environment preservation.

Therefore, it is hypothesized that there is a direct relationship between LC and LEED Certification, and the quality of the construction site. So, this paper objective is to verify this relationship between LC and the LEED Certification, and the quality of construction sites. For that, an analysis was made using the same criteria for different construction sites in the Metropolitan Region of Fortaleza (MRF), Brazil.

2 THEORETICAL BASIS

2.1 Construction Sites

Ning et al (2011) affirm the construction sites layout planning was recognized as a critical stage on the construction planning. This is a decisive process that addresses problem and opportunity identification, solution development and the choice and implementation of the best alternatives.

To Serra and Oliveira (2003), a logistic approach must be considered during all the development of the production cycle of the project, i.e., from its conception to the execution phase.

A construction site with a good quality planning allows for a reduction in travel time, minimizes unnecessary material transportation, and significantly impacts the economy, safety as well as other aspects of the construction (Mawdesley et al 2002).

2.2 LEED Certification and Lean Construction in Construction Sites

A sustainable building or green construction focus on increasing natural resources efficiency through constructive measures and procedures aiming at reducing construction impacts, without negatively affecting people's health or the environment, while saving money (Krygiel and Nies 2008).

The LEED Certification emerges from considering this sustainable concept. The latest Guide Reference (LEED) (2009) has incorporated more instruments regarding the necessities with care at construction sites.

The LEED certification has sustainability and the preservation of the environment as its main objectives (Green Building Council Brasil). Analyzing these objectives, the certification might have a big influence on the logistics in construction sites, especially in material handling and storage, enabling the correct arrangement of material resulting in loss reduction, as well as the correct collection and destination of these materials by using the most adequate paths. Therefore, LC is one of the philosophies that can contribute to the proper fulfilment of the prerequisites of the LEED Certification.

Womack and Jones (2004) argue that LC is so called because it reduces the quantities when compared with mass production. Therefore, it leads to a reduction in workers' effort, production space, equipment investment, planning time to develop new products, production places inventory and final product delivery problems. Accordingly, Wu and Wang (2016) argue that this LC philosophy is related to activities that add value to the product or process, and to the reduction of time consumption, expenses and resources.

Considering all aforesaid, LC can have a direct influence on material handling, since it generates a reduction in waste and costs and an increase in productivity. It can also influence on the quality of temporary facilities to better serve the production, adding value to the process and the client. Lastly, it can have an influence on safety at the

construction site, avoiding extra costs caused by workplace accidents, resulting in a safer and more efficient, in addition to affecting directly the clients' satisfaction.

2.3 Quality Prerequisites for Construction Sites

Good planning is necessary for a construction site to have high quality standards. That is especially true regarding temporary facilities, storage, construction safety and material handling. Analyzing the "Norma Regulamentadora 18 (NR 18)" (Regulatory Norm 18) and the work developed by Saurin and Formoso (2006), some requisites are established for each of the items contained in the three main categories, as shown below:

- Temporary facilities: typologies, hoardings and galleries, entries, office on site, sanitary facilities, locker rooms, warehouse, accommodation, eating area, kitchen; laundry and recreation area;
- Safety at construction sites: stairs, ladders, ramps and walkways, safety measures against falls from height, electrical installations, personal protective equipment (PPE), site safety signage, fire protection, crane and scaffolding;
- Handling and storage of materials: handling and storage of materials and personnel (elevator towers, material elevators, elevator for people), material storage and stocking, areas of circulations, tidiness and cleanliness.

In 2006 Saurin and Formoso developed a checklist to analyze 40 construction sites in Rio Grande do Sul, Brazil. This checklist divided the site into the three categories presented previously (Temporary Facilities, Safety at Construction Sites, and Material Handling and Storage). These categories are divided into items, and these into elements, totalizing 128 elements in the complete checklist. The options for checking are "Yes", "No" or "Not applicable".

After answering all 128 elements, a grade is given to evaluate the performance of each of the three categories analyzed according to Equations 1, 2 and 3 below:

$$IIP = \frac{PO}{PP} \times 10 \quad (1)$$

$$IS = \frac{PO}{PP} \times 10 \quad (2)$$

$$IMAM = \frac{PO}{PP} \times 10 \quad (3)$$

Where:

IIP is the index of performance concerning Temporary Facilities;

IS is the index of performance concerning Safety at Construction Sites;

IMAM is the index of performance concerning Material Handling and Storage;

PO are the points obtained, i.e., all the elements marked "Yes" for each of the items, worth one point per "Yes";

PP are the obtainable points, i.e., all elements marked as either "Yes" or "No", excluding those marked as "Not Applicable", worth one point every "Yes" or "No".

Then the overall grade is calculated for the Construction Site, also known as "Índice de Boas Práticas de Canteiros de Obras (IBPC)" (Good Practices at Construction Sites Index) for each construction, according to equation 4 below:

$$IBPC = \frac{IIP + IS + IMAM}{3} \quad \#(4)$$

It is important to highlight that these grades vary from 0 to 10, where 10 is the grade for best performance.

3 METHODOLOGY

In order to verify the influence of LC and LEED Certification on the quality of construction sites, 40 sites from the MRF from 19 different companies were analyzed. Vertical and horizontal constructions in different phases (foundation/excavation, structure/masonry or wall covering/finishing) were observed.

For this analysis a checklist developed by Saurin and Formoso (2006) was used for each of the construction sites. With all the information recorded, grades were given for each of the three main categories: Temporary Facilities, Safety at Construction Sites, and Material Handling and Storage for each site following equations 1, 2 and 3. After that, following equation 4, the overall grade was calculated for each of these sites.

With all grades in hand, a comparative analysis was made regarding the performance of these sites related to the LEED certification and to the presence of LC. Four graphs were generated with the overall grades and the grades of the items that belonged to the three main categories analyzed.

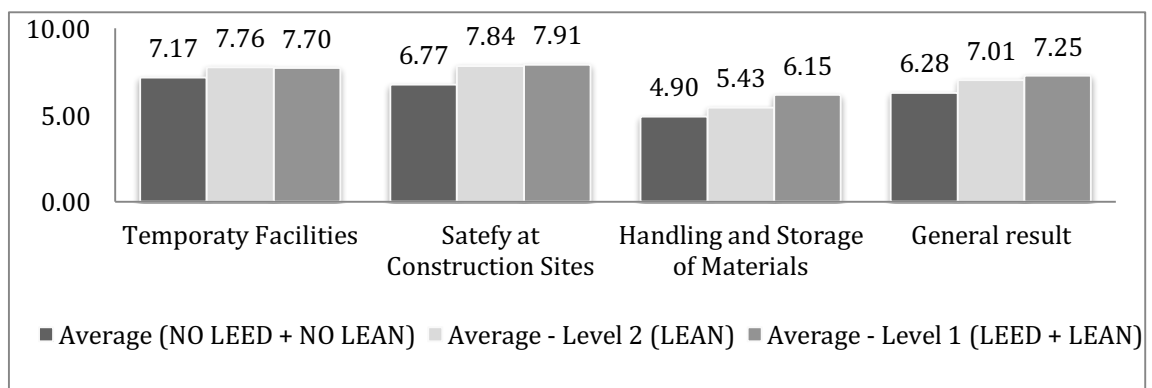
The division was made into 3 levels: level 1 sites, the ones whose their companies have LEED certification and LC; Level 2 sites, the ones with LC only; and sites with none of the two elements being considered.

We analyzed 8 sites level 1, 10 sites level 2, and 22 sites with none of the two elements. Furthermore, pictures were taken to keep a record of each item analyzed in all construction sites for a better understanding of the real situation analyzed and discussed along this paper.

4 RESULTS AND DISCUSSION

Next, the results and graphs regarding the overall grades and the grades for Temporary Facilities, Safety at Construction Sites and Material Handling and Storage will be discussed.

Analyzing Graph 1, it is seen that level 1 sites present the best results overall, except for Temporary Facilities category, with a difference of only .06 points in relation to level 2 sites, result that will be analyzed in detail in item 4.1.



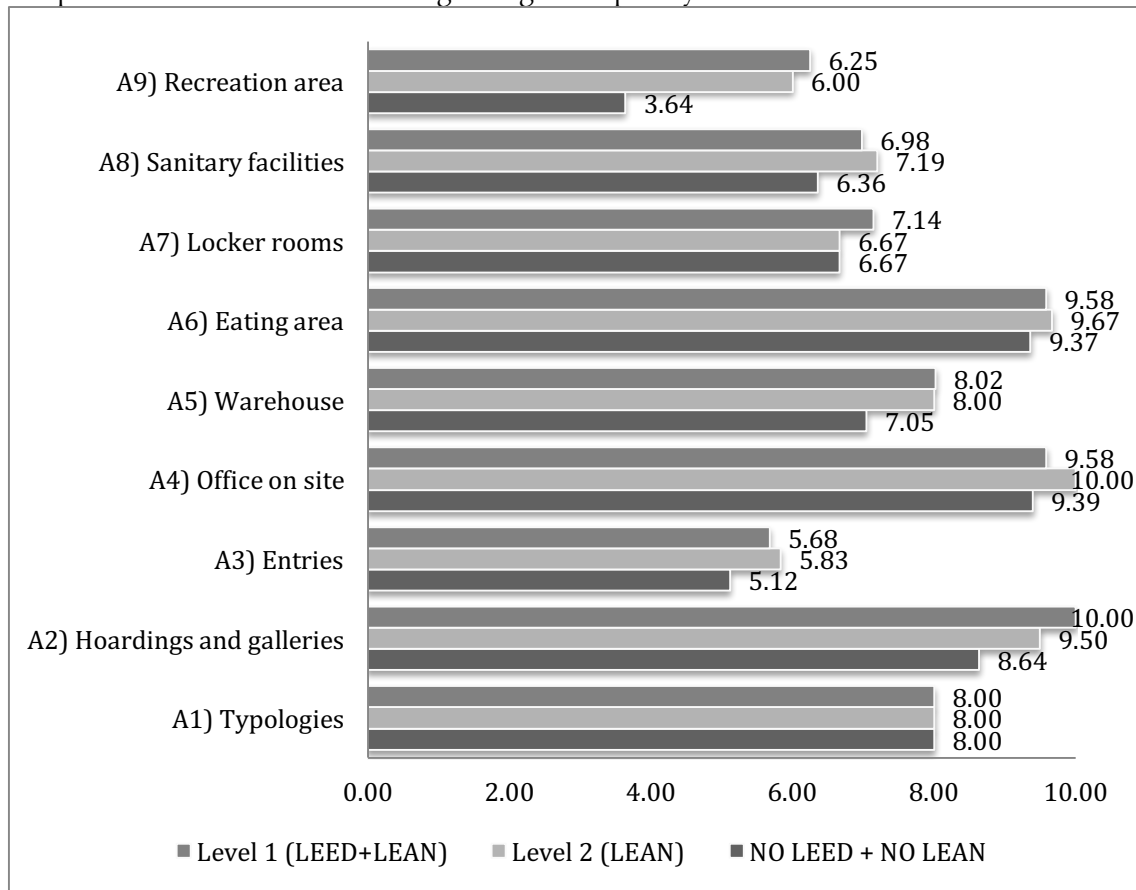
Graph 1: General results for construction sites analysed regarding the LEED certification and Lean Construction

It was concluded that both LEED certification and LC influence to a better performance at construction sites. The former, regarding the environment and sustainability, relates to the improvement of material storage logistics, whereas the latter, by seeking a reduction of waste and costs and improvement of productivity, influences directly on material arrangement and transport, temporary facilities quality for better serving the productive process and, lastly, construction sites safety, as a protection to human resources avoiding extra costs due to worksite accidents. This, in turn, results in a more efficient production and increases workers' safety, as well as directly influences clients' satisfaction.

It is important to highlight that applying LC principles and obtaining and maintaining the LEED certification require a series of internal and external audits. Which, in turn, influence on meeting the checklist pre-requisites, that are similar to the ones from the Norms and certifications. Next, a detailed analysis will be made of the three categories from the used form.

4.1 Temporary Facilities

Graph 2 shows the results regarding Temporary Facilities of construction sites.



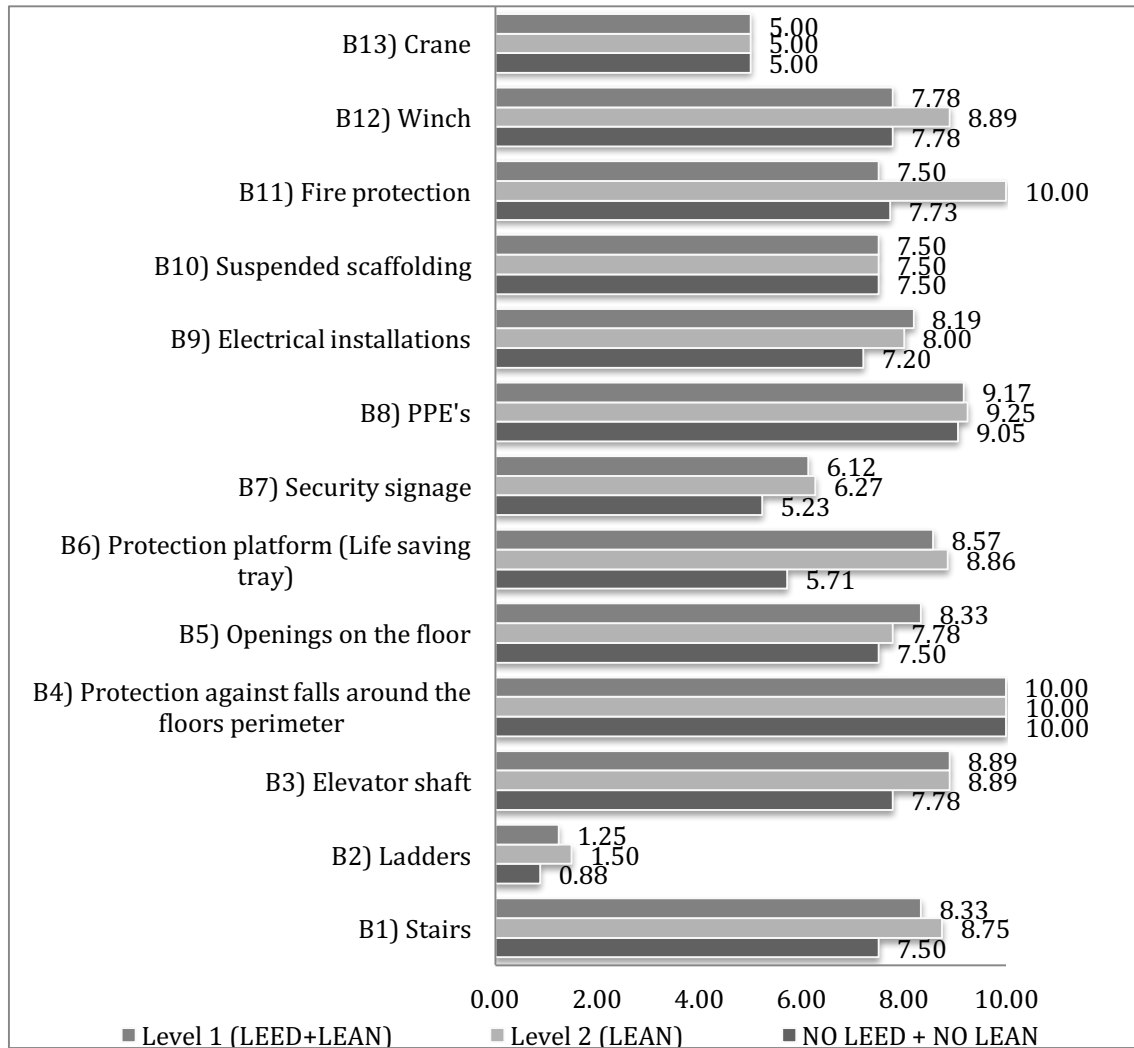
Graph 2: Results regarding temporary facilities

The item regarding worksite entries was not highly graded in none of the levels, whereas the item regarding eating area and offices received the highest grades in all categories. It is verified that levels 1 and 2 constructions show better results. That shows the real influence of LC on temporary facilities, since aiming at better serving the productive process allows greater results in this category.

Concerning temporary facilities, it is important to observe that level 1 sites showed better results in some aspects, whereas level 2 sites showed superior results in others. This leads to the conclusion that the LEED certification does not influence significantly on the quality of temporary facilities, as expected. This is so due to the fact that this certification has, as its main topics, the environment and sustainability, having bigger influence on items referring to material storage and transportation.

4.2 Safety at Construction Sites

Graph 3 shows the results related to the items from Safety at Construction Sites.



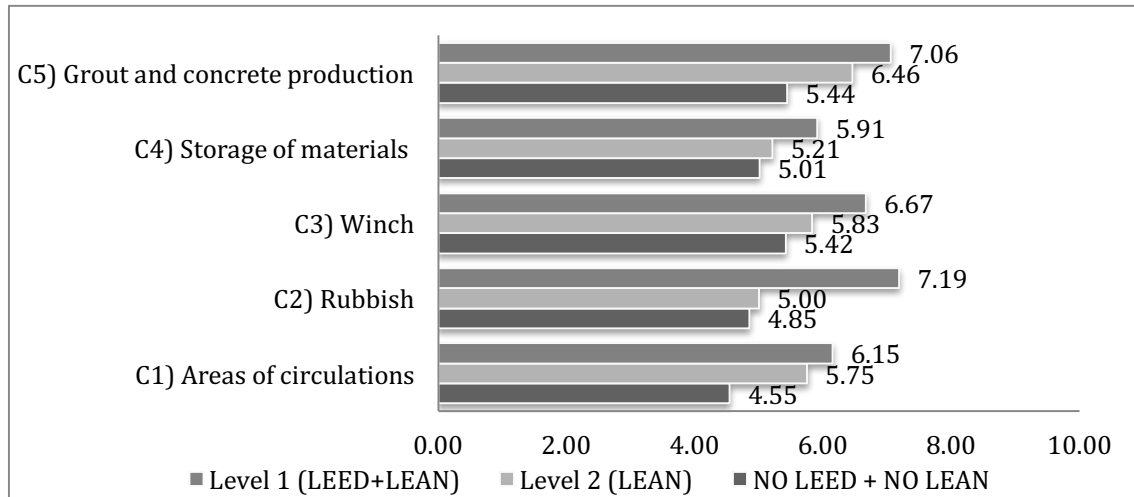
Graph 3: Results related to Safety at Construction Sites

The lowest grade for all levels was given to the ladder item. On the other hand, the highest graded item was related to PPE's and fall protection around the floor perimeter. As expected, level 1 and 2 sites presented higher grades than those without the LEED certification and LC. However, in some categories, level 2 constructions presented higher grades than level 1 constructions. That can be explained the same way that it could for Temporary Facilities: as a consequence of the LEED certification being more focused on the environment and sustainability, it does not influence, in a significant way, on construction sites safety for not addressing it.

Despite of that, it is relevant to point out the LC influence on safety, hence protecting workers from potential accidents and the generation of additional costs making the production more efficient and influencing the clients' satisfaction.

4.3 Material Handling and Storage

Graph 4 shows the results related to Material Handling and Storage.



Graph 4: Results related to Material Handling and Storage

Overall, the grades for this category were very low in all the items. However, all grades for this category were superior for level 1 sites, unlike the temporary facilities and safety at construction sites.

Therefore, the obtained numbers prove the LEED certification significantly influences on material handling and storage. By having requisites regarding the preservation of the environment and sustainability, the certification ends up demanding the adequate material storage and better transport logistics, which are precisely the points required in this category.

The direct influence of LC is also verified in this category since by aiming at reducing waste and costs and increasing productivity, it directly influences material arrangement and transport.

5 CONCLUSION

Analyzing the results of this study, it was possible to conclude that LC has a direct influence on Temporary Facilities, Safety at Construction Sites and on Material Handling and Storage. Moreover, the LEED certification has a more direct influence on material handling and storage. That way, it is possible to affirm that LC and LEED certification have a direct impact on the quality of construction sites.

In order to improve this research, the authors suggest adding some elements to the checklist that are very important and were not approached in this analysis, such as industrialized mortar control and storage of ceramics, paints, countertops and other finishing items. Moreover, the options of filling the checklist with fractioned grades from 0 to 1, instead of with “yes”, “no” and “not applicable”, makes the evaluation fairer for when a specific element presents itself partially in accordance with the demand. That change would make it possible for a better and fairer evaluation of the situation in each

construction site. It would also be interesting to undertake a more representative study, with more than 40 construction sites in different states or countries.

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WHY LEAN PROJECTS ARE SAFER

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Abstract: Some evidence exists that lean projects are safer, but we don't understand why. Providing an explanation is one of the objectives of the Construction Safety Research Group formed by the Project Production Systems Laboratory (P2SL). In this paper, we describe the research program of the group and its findings in year one of three, including an explanation why lean projects are safer that is grounded in the principle: Respect for people.

Keywords: Lean Construction, Human Error, Research, Respect for people, Safety

1 INTRODUCTION

There is evidence that projects managed on a Lean basis are safer than those managed with traditional practices—(Thomassen 2003; Saurin et al. 2004; Nahmens and Ikuma 2009; Leino 2010) and we don't know why. Some facts: 20% of all industrial deaths occur on construction projects. A construction worker over a 45-year career has a 75% chance of experiencing a disabling injury and 1 in 200 chance of being fatally injured on the job according to data presented at the American Public Health Association's 139th Annual Meeting⁴. According to the U.S. Occupation Safety and Health Administration (OSHA⁵), 4,386 worker fatalities in private industry was reported in 2014 and 899 of those were in construction. The leading causes of worker deaths were reported to be falls, electrocution, and being struck by or caught between objects account for the vast majority (60.6%) of these deaths in 2014. Eliminating these fatal four could save 545 workers' lives in the United States every year. This tragedy happens every year despite safety programs, OSHA inspections and training, stand-downs, posters and project safety officers. This research proposal moves beyond motivation and training to find a different perspective, a new approach that increases productivity and reduces harm.

2 CONSTRUCTION SAFETY RESEARCH GROUP

In order to rethink safety management and explore links with lean philosophy and methods, P2SL formed a Construction Safety Research Group in April 2016. Eight

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⁴ <http://www.safetyandhealthmagazine.com/articles/construction-workers-experience-higher-rates-of-injury-premature-death-study-2>

⁵ <https://www.bls.gov/iif/oshwc/cfoi/cftb0294.pdf> Accessed March 5, 2017

general contracting firms are participating, with one outside the U.S. The fundamental objectives of the group are adopted from Mitropoulos et al., 2005:

- 1) to figure out how best to prevent putting people into hazard, and
- 2) recognizing that there will inevitably be plan failures, to figure out what can be done to prevent injury when people are put into hazard.

After 8 months of reading, observing and discussing, we have found what appears to be a fundamental reason why lean projects are safer: When projects live by the lean principle *Respect for People*, they reduce the frequency with which construction workers are placed in hazardous situations, and they reduce the frequency with which they are harmed when they do find themselves in hazardous situations.

This paper explains how Respect for People improves safety on construction projects, both through planning and preparation, and through intercepting errors before they cause harm. The explanation is plausible and is grounded in academic research: Behaving in accordance with the principle promotes psychological safety, which has been shown to promote learning behaviors in work groups, which in turn promotes improvements in group performance (Edmondson, 1999; Chan et al. 2003; Bossche et al. 2006; Carmeli and Gittell 2009; Mossman 2015).

The sections of the paper after this point are 3) the lean principle *Respect For People*, 4) Preventing Construction Workers From Getting Into Hazardous Situations, 5) Preventing Construction Workers Who Get Into Hazardous Situations From Being Harmed, 6) How Respect For People Improves Safety, 7) Conclusions and 8) References.

3 RESPECT FOR PEOPLE AND PSYCHOLOGICAL SAFETY

Respect For People is a fundamental lean principle applicable to all types of organizations and production systems, both project-based and non-project-based (Ohno, 1988; Oppenheim et al. 2011; Cardon and Bribiescas 2015). In Liker's presentation of the principle, it is understood to mean challenging and helping workers and suppliers to improve their capabilities, particularly in problem solving and process improvement (Liker, 2004).

3.1 Psychological Safety

The construct *psychological safety* was developed by Professor Amy Edmondson, who validated the hypothesis that 'learning behaviors mediate between psychological safety and work group outcomes' in Edmondson (1999). Bossche et al. (2006) reported that psychological safety is crucial for the engagement of learning behaviours in teams, which leads to better team performance.

Edmondson's video, titled Psychological Safety⁶, starts with a story about a nurse on night duty in a hospital. She is taking medication to a patient, but becomes concerned when she sees the dosage, which is very much higher than normal. She thinks to herself "Maybe I should call the doctor and ask if this is the correct dosage." Then she remembers how that doctor reacted when she questioned one of his decisions before, and begins to talk herself out of calling—"Well, this patient is undergoing an experimental treatment. Perhaps the dosage is appropriate after all." She doesn't make the call.

⁶ <https://www.youtube.com/watch?v=LhoLuui9gX8>

The doctor's behaviour discourages subordinates on the medical team from speaking up; in this case, speaking up about the possibility of an error. It seems apparent that she and others on the medical team would also be reluctant to share ideas about better ways of working.

We propose that behaving in accordance with the lean principle of Respect For People promotes psychological safety and hence work group performance, including construction safety, through the impact of individual and team learning behaviors. We further propose that learning behaviors reduce injuries and occupational illnesses by reducing the frequency and extent of differences between work situations as planned and those situations actually encountered during execution. And lastly we propose that learning behaviors reduce injuries and occupational illnesses by increasing work groups' abilities to 'catch' errors before they cause harm.

We provide arguments for these proposals in the following sections.

4 PREVENTING CONSTRUCTION WORKERS FROM GETTING INTO HAZARDOUS SITUATIONS

There appear to be two basic ways to 'engineer out' hazards, through design of the product to be constructed and design/execution of the construction process:

1. Prevention through Design (Gambatese et al. 2005; Manuele 2007; Toole and Carpenter 2011).
2. Task Planning⁷ (Mitropoulos and Cupido 2005)

4.1 Prevention through Design

Prevention through Design is an initiative of the United States' National Institute for Occupational Safety and Health (NIOSH), defined as: "PtD encompasses all of the efforts to anticipate and design out hazards to workers in facilities, work methods and operations, processes, equipment, tools, products, new technologies, and the organization of work. The focus of PtD is on workers who execute the designs or have to work with the products of the design. The initiative has been developed to support designing out hazards, the most reliable and effective type of prevention. PtD aims to eliminate hazards and control risks to workers to an acceptable level "at the source" or as early as possible in the life cycle of items or workplaces."⁸

4.2 Task Planning⁹

The planning of construction tasks starts in the design phase, following the lean principle to design both product and process simultaneously. Product design leads, but only in the role of first person to speak in a discussion. The 'level of detail' criterion in process planning is fitness for purpose; i.e., sufficient that the constructors are confident they can build the product design safely and to quality requirements.

Refinement and further elaboration of process design occurs nearer in time to execution; first in planning for each construction phase (pull planning), then just before

⁷ For lack of space, we omit the common safety management methods such as enforcing rules, use of visual warnings and correcting unsafe conditions.

⁸ <https://www.cdc.gov/niosh/topics/ptd/> accessed 12/27/2016

⁹ This section is derived from Ballard and Tommelein 2016.

execution, the responsible foreman and crew agree individual roles and adjust the plan for context (weather; concurrent work; access and egress routes for workers, materials, equipment; the skill sets of workers assigned to the task, etc.). The key elements of effective task planning are these:

- Product and process design are done together
- The people directly involved in doing the construction work are the ultimate process designers
- Processes and operations are designed for quality, safety, time and cost; not separately for each.

5 PREVENTING INJURY WHEN CONSTRUCTION WORKERS DO GET INTO HAZARDOUS SITUATIONS

Safety theorists such as Rasmussen (1997) and Perrow (2011) argue that workers will find themselves in hazardous situations despite all attempts at prevention. The challenge then is how to get them out of such situations without harm to themselves or others. The commercial aviation industry, among others, has developed methods for ‘catching’ and defusing errors before they cause harm (Leiden et al. 2001). In her research on medical teams, Edmondson (1999) found that team members who feel psychologically safe voice more concerns about the safety of patients or colleagues, and yet commit fewer medication and other errors than medical teams who don’t feel psychologically safe with one another and with their supervisors.

5.1 Stopping the Line

Sidney Dekker argues that the systems within which work is performed are not inherently safe, and that work as found never exactly matches with work as planned (Dekker 2014); a way of saying that ‘designing out’ hazards cannot be fully achieved. Whether this is or is not always the case, the possibility of a difference makes it necessary that direct workers have the authority to ‘stop the line’ when they detect such mismatches between plan and actual (Howell et al. 2002). This may happen before execution begins, as when a foreman or craftworker examines the work location and finds an unexpected obstacle or hazard. It may also happen during execution, as the progress of the work reveals or produces a hazard.

It is becoming more common that construction projects have a stated policy that anyone can stop the line when they have a concern for safety. Some distribute Safety Training Observation Programme (STOP) cards (DuPont 2017) and promise no retribution for using them, including protection from retaliation by supervisors.

6 HOW RESPECT FOR PEOPLE IMPROVES SAFETY

We propose that behaving in accordance with the lean principle Respect for People improves safety by creating the feeling of psychological safety needed for learning behaviors within construction crews and project teams that result in these outcomes:

- design of products that are safer to construct
- reduced frequency and extent of differences between construction work as found and work as planned

- higher frequency of direct workers stopping the line when they have a concern for the safety of themselves or others

Appealing again to the work of Edmondson, here is what she lists as “learning behaviors” (Edmondson, 1999):

- Asking for help
- Talking about errors
- Seeking feedback
- Sharing information
- Experimenting

The causal relationship between these behaviors of team members and outcomes is perhaps sufficiently apparent, but a bit more explanation may be helpful. Consider the team of designers and constructors working together to create a design for a product that meets the needs of its users within the constraints of the buyer, and that also is safe to construct. Experience has shown that success requires that the team ‘ask for help’, ‘talk about errors’, ‘seek feedback’, etc. They must work together as a team; which is very different from the old-fashioned idea that constructors could assure “design constructability” by acting as inspectors of product designs already produced.

As for reducing the difference between work as found and work as planned, a project team and construction crews functioning as learning organizations is vital. The activities of learning organizations are visible in pull planning, in speaking up when there is a possibility that a constraint cannot be removed in time for task execution, in foreman and crew putting the finishing touches on a plan for the day, and in crew members working together to figure out how to move forward with task execution safely, even if that involves stopping the line.

7 CONCLUSIONS

Arguments have been offered for the claim that Lean projects are safer because they follow the lean principle *Respect For People*, which creates the feeling of psychological safety within the project team, which in turn is a precondition for individual and team learning behaviors such as experimenting, requesting feedback, talking about errors, and asking questions. These learning behaviors have been shown in academic studies to result in improved team performance. The specific mechanisms proposed for improving safety are better planning and increased agility in recognizing and reacting to plan inadequacy. Better planning results in reduced frequency and extent with which work as found during execution differs from work as planned. Agility in reacting to plan inadequacy is evident in the frequency with which errors are identified and ‘defused’ prior to causing harm, and in the success of countermeasures preventing reoccurrence.

7.1 Limitations and Future Research

A number of hypotheses have been proposed and arguments provided for them, but the hypotheses need to be tested and the causal mechanisms in the chain from ‘Respect For People’ to ‘reduced harm’ need to be further elaborated in future research.

Of special importance is the role supervisors play in creating or impeding psychological safety. Rother (2014) and Mann (2014) connect Standard Leader Work with activating the principle *Respect For People*. Empirical research is needed to

understand how the role of construction industry supervisors at every level, from foreman to project manager to company executives, is understood and what is being done to develop the knowledge and skills they need to carry out their roles. If Rother and Mann are correct, supervisory behaviour is the link between lean principles and the economic, environmental and social outcomes that come from continuous learning and continuous improvement.

The more general issue that needs further research is the relationship between safety and the lean philosophy of organizational management. Lean has most often been associated with economic benefits, with less research done on the environmental and social elements in sustainability. Do current formulations of the lean ideal adequately capture these relatively neglected benefits? The same question applies to current formulations of lean principles, which are intended to serve as guides to pursuit of the ideal. We hope to have made a contribution to the inquiry into these questions, but do not pretend to have settled them.

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PRINCIPLES FOR SAFETY PERFORMANCE MEASUREMENT SYSTEMS BASED ON RESILIENCE ENGINEERING

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Abstract: The emergence of new technologies and new types of risks, in which the relationships between people and technology are complex and dynamic, challenge the models and techniques used to measure safety performance. Traditional approaches has little predictive value to potential hazards and do not reveal the cause-effect relationships that could drive system improvements. Thus, this study discusses the use of the Resilience Engineering paradigm in the design of safety performance measurement systems, so that these are capable to anticipate potential hazards, monitor and manage risk continuously and learn throughout the life-cycle of the system. Resilience Engineering is relevant from the Lean perspective because it is useful to devise ways to balance safety and pressures to meet production and efficiency goals. This paper presents preliminary results of a systematic literature review on the principles to design safety performance measurement systems based on the Resilience Engineering paradigm. Five principles have been identified across several industries as contributors to improve safety performance: management commitment, awareness, anticipation, continuous learning and flexibility.

Keywords: safety performance measurement, resilience engineering, systematic literature review

1 INTRODUCTION

Safety performance measurement is an essential part of safety management systems, since it provides information on the performance of those systems, with the aim of supporting decision-making on safety issues. Traditional approaches to measure safety performance are based on statistical analysis of incident data, which is often referred to retrospective or lagging indicators, such as number of injuries, accident rates, accident costs and damages associated to poor safety performance (Sgourou et al., 2010). Lagging indicators are related to reactive monitoring, measuring after unwanted events or showing when a desired safety outcome has failed (Øien et al., 2011). Frequently, companies choose indicators that facilitate benchmarking with other organizations or that provide results in the short-term, often resulting in performance measurement systems that do not support decision-making related to the company strategies and to critical processes (Formoso and Lantelme, 2000). Those traditional approaches have been criticized for not revealing the cause-effect relationships that could drive system improvements (Carder and Ragan, 2003).

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Since the 1990s, there is a set of particular measures that have been used as key safety indicators by the industry and by government agencies, such as the Lost Time Incident Frequency (LTIF) and Lost Time Incident Severity (LTIS). These measures only reflect the occupational safety status without any information on improvements in management (Hale, 2009; Harms-Ringdahl, 2009; Leveson, 2015). However, the impact of those measures in accident prevention has been relatively limited, and some industries continue to have a very poor performance. Although there is a wealth of guidance on safety performance indicators (e.g. HSE, OECD, CCPS, OSHAS), most of those publications do not define a precise method and they do not discuss how to control over potential events. Another limitation is that most of them are based on existing accident models and theories based on the assumption that safety can be increased by guaranteeing the reliability of the individual system components (human as well as machine), and that if components or even layers of defence do not fail, then accidents will not occur.

Moreover, there is an increasing complexity in many industrial operations, due to the growing number of different players and interdependences, and uncertainty both in process and goals, which have a strong influence on the final safety outcomes. In turn, the emergence of new technologies and new types of risks challenge the models and techniques traditionally used to measure safety performance. The Systems' Theory perspective suggests that, in organizations whose stability is dynamically emergent rather than structurally inherent, safety is something that a system does rather than something that a system has, so accidents emerge from the complexity of people's activities in an organizational and technical context (Hollnagel et al., 2006).

In recent years, emphasis has been shifted into social system approaches driving the focus of safety from plant and systems towards people and human-oriented theories, such as human factors (Reason, 1995), behaviour-based safety (Van de Kerckhove, 1998), safety perceptions and attitudes (Krause, 1999) and socio-technical systems theory, which aims to optimise interactions between human, technology and environment (Dekker et al., 2009). Resilience Engineering is grounded in the latest one, being associated with the organization's ability to learn and adapt by creating safety in an environment of failures and losses while compensating decisions and multiple objectives (Hollnagel et al., 2006; Wreathall, 2006).

Resilience Engineering has been a recurrent topic into IGLC community related to safety, uncertainty and variability of construction projects (Schafer et al., 2008; Leino and Helfenstein, 2012; Saurin et al., 2013; Saurin and Sanches, 2014; Saurin, 2015). From a lean perspective, all accidents are waste and add no value to clients. In turn, accidents add variability to the production process resulting in major disruptions to the workflow. Resilience Engineering is aligned with the Lean perspective, as it looks for evidences on how people at work fill the gaps in specifications to create safety in a context of increasing production demands that needs reliable workflows.

This paper presents preliminary results of a systematic literature review on the core principles to design safety performance measurement systems, based on the Resilience Engineering paradigm as a proactive approach to improve safety management. This systematic literature review considering papers published in the last 18 years.

2 RESEARCH METHOD

Systematic literature reviews are strongly recommended for supporting the theoretical progress of scientific disciplines in general, as they identify over as well as under

explored areas, in addition to constructs that should be refined (Tranfield et al., 2003). The research question that guided this systematic literature review was: Which are the principles to design a Safety Performance Measurement System based on the Resilience Engineering paradigm?

The first search was carried out on 6 databases: Science Direct, Web of Science, Scopus, Taylor and Francis Online, American Society of Civil Engineers (ASCE) and Emerald Full Text. These databases include the main journals on Safety Management and Resilience Engineering. The keywords used in the databases were: Safety Performance (Safety and (performance measurement or measurement system or measures)); Principles (or criteria or attributes) and Resilience (or Resilience engineering). Initially, 102 papers were selected. Inclusion and exclusion criteria were then applied in relation to the title and summary of the papers in order to refine the selection list. For inclusion, the articles had to be written in English, focus on a set of measures or criteria for safety performance measurement and introduce the concept or foundations of Resilience Engineering. The excluded papers focused on other aspects of "safety performance measurement" or "resilience", for example, referring to composite properties of materials, stability of skeletal structures, radiation and fire supplies, among others. After this refinement, 63 articles were selected. A second analysis was then carried out, based on the field of application, method and findings. A literature coding was performed in a database, including: paper title, publication year of each paper, journal title, country or region (in which the studies were conducted) and principles or criteria of resilience engineering. The first round of evaluation over the principles was performed by the first author, and it was cross checked by the third author by random sampling. In case of discrepancies, authors discussed to arrive at a consensus and replicated the same decision rules across all the papers collected. Out of the 63 articles, 47 were finally selected.

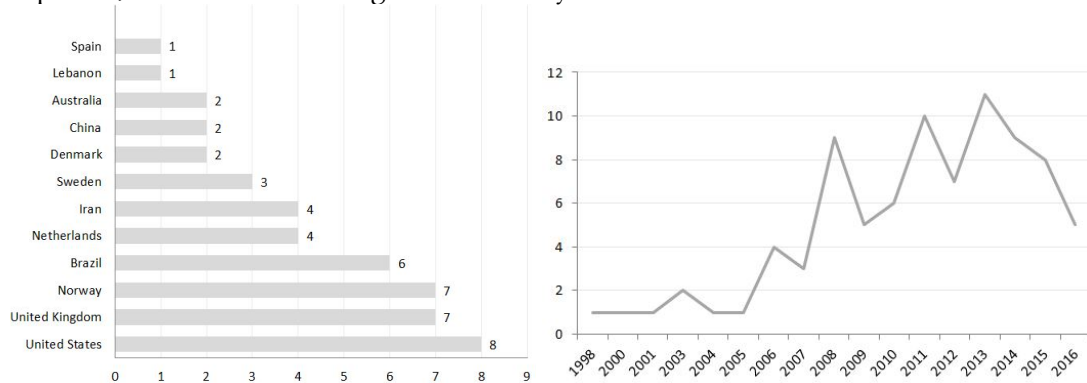
3 RESULTS

3.1 Data analysis

Regarding the origin of papers, more than 60% of them came from the United States, United Kingdom, Norway and Brazil (Figure 1). The data analysis also indicated that the resilience engineering paradigm has become increasingly adopted in the last 18 years, especially since the first Resilience Engineering Symposium in 2006, as those events concentrate a large number of studies in this area (Figure 2). Concerning to the journals, 27% of them came from Safety Science, 16% from Reliability Engineering and System Safety, 14% from Journal of Loss Prevention in the Process Industries, 12% from Journal of Safety Research, 10% from International Journal of Industrial Ergonomics and 10% from Cognition, Technology & Work. The remaining 11% are from symposiums proceedings. Another characteristic of the analysis is that the majority (68%) of the papers were based on qualitative approaches and empirical data.

Other significant result of the systematic literature review is concerned with the different areas of expertise found. The distribution of principles is across six domains such as: chemical and petrochemical industry (28%), aviation and air transport (25%), nuclear power and electricity distributor (21%), railways and road transport (12%). Those domains are well-known for their complexity and hazardous technologies, which make them, target fields for the use of resilience engineering. Nevertheless, other domains regarded as complex are still under explored, such as construction (8%) and

manufacturing industry (6%). Thus, five principles of resilience engineering have a broad consensus across the domains as contributors to improve safety performance because they are able to identify potential concerns, focus on proactive aspects of safety rather than only reactive, identify vulnerabilities and provide information about effectiveness of safety management, such as: management commitment, awareness, anticipation, continuous learning and flexibility.



Figures 1 and 2: Origin of analysed papers and Number of publications per year.

3.1.1 The SPMS should be designed with Management Commitment in a Systemic approach

One core principle for effectively measuring safety performance is having the commitment of top management, in which safety is considered as one of the main goals of the organization (Rasmussen and Svedung, 2000). Recent studies in the aviation and air transport industry suggest that managers' commitment should be based on a systemic approach so that all the interactions between system components and external factors are considered. It is necessary to model how the system elements and activities interact to produce the expected safety outcomes, identifying the strengths and weaknesses of the system (Leveson, 2004; Dijkstra, 2007; Woltjer et al., 2013). In an empirical study in construction industry, O'Toole (2002) argues that there is a connection between the safety management approach and workers perception, while Mohamed (2002) found that there was a positive relationship between the perceptions of the safety climate and self-reported safe work behaviour. Saurin et al. (2013) suggest that safety management is inseparable from the management of other dimensions of the organization, such as production management. In this sense, management commitment in all dimensions of the organization can contribute, for example, to assess the trade-off between safety and production. Studies in the petrochemical industry (Lekka and Sugden, 2011; Azadeh and Zarrin, 2015) described situations in which workers and senior management were genuinely committed to improve safety. In that context, the leadership of top managers and their commitment to safety have resulted into effective initiatives, such as re-designing the organisation procedures and the development of measures to monitor management commitment (e.g. resources invested in safety; decisions informed by safety concerns rather than production, among others). Carvalho et al. (2008) and Labaka et al (2015) carried out empirical studies in nuclear power plants, concluding that managers should be committed to the resilience-building process as well as promote a safety and resilience-based culture. Results from those studies showed that managers are not only responsible for deploying resources for training, but also for developing leadership skills and establishing new measures that reinforce appropriate attitudes and behaviours in the

company (e.g. number of management walk-arounds per month/year; number of management meetings dedicated to safety per month/year, among others).

3.1.2 The SPMS should monitor the Awareness of the System

Managers and employees should be aware of the current state of the defences in the working environment as well as the system's boundaries (Hollnagel and Woods, 2006). According to Wu et al. (2007), leadership skills must be developed through workers awareness of safety activities. In a study undertaken in the manufacturing industry, Costella et al. (2009) concluded that awareness is critical for the assessment of sacrifice judgments and for the anticipation of future changes in the environment. Results from interviews indicated the existence of belated awareness in which the workers and managers become aware of the risk after tragic events. In the same study, the lack of support by managers and resources, and the lack of awareness of some hazards resulted in the lack of safety planning from the early conception of products and processes. Based on a study carried out in the chemical industry, Shirali et al. (2013) proposed, an indicator that attempts to measure the degree of awareness, based on a survey, (e.g. awareness of organizational, human and technological risks, awareness of all safe ways to do a job, among others). At investigation revealed that the awareness and anticipation was very low, resulting in a decrease of plant resilience. Saurin et al. (2013) proposed a set of principles for the construction sector that has a strongest link with the principle of awareness. One of the main conclusions of that study was that safety performance measurement systems should make the organization, teams and individuals able to identify relevant signals and design the future. The study of Lekka and Sugden (2011) in an Oil refinery highlights good practices to increase the levels of awareness. For instance, the organization provided safety awareness workshops, which contributed to the consciousness of the differences between process safety (described in terms of 'leaks' or 'spills') and occupational health and safety (such as trips or slips). Another initiative identified in that investigation was renewing the procedure system, drawing on relevant national and international guidelines, clarifying the purpose of the different types of procedures and training staff in writing procedures to ensure that the documents were clear and brief. This process led to a reduction in the number of procedures (from 14,000 to 1000) and an acknowledgment that the procedures were an accurate reflection of the job. Huber et al. (2012) devised a method for develop safety and resilience indicators for an air taxi system. The principle of awareness was the basis of some indicators such as: information sources to assess the current state of operations, and frequency for updating information about the current state of operations. According with Hale and Heijer (2006) awareness is also important for the assessment of the trade-offs between production and safety. Woltjer et al. (2013) in the air traffic sector recognized that the effects of multiple goals are critical for understanding the variability that arises in daily operations.

3.1.3 The SPMS must be able to Anticipate threats to cope with the unexpected

This principle is related to the principle of awareness, as anticipating threats and the preparation for coping with them is necessary to be aware on the performance of the system and the state of the barriers against accidents. Awareness also allows the anticipation of changes in risk situations. This principle is referred in the literature to different terms such as anticipation, preparedness, early detection and mitigation of failures. Wehbe et al. (2016) evaluated the safety performance and network resilience to risks by studying safety interactions among the construction team in three mega-projects in Middle East. Results indicated that networks with better interaction and structure

have higher resilience to anticipate risks. In the chemical industry, Shirali et al. (2013) proposed some measures related to this principle such as: group meetings or workshops in the areas of safety/resilience to expect potential problems in the future; budget spent on improving safety or resilience and preparedness to deal with future problems; among others. The results of the interviews revealed that many units did not have a comprehensive plan to cope with failures related to the future. Azadeh et al. (2015) identified managerial shaping factors in petrochemical plants using Resilience Engineering principles. The results showed that management commitment and anticipation were the most important factors for the organizations. The study of Dinh et al. (2012) in the chemical industry assessed the resilience of a design process or operation by using a set of measures: ability to recognize abnormal conditions and execute appropriate actions; number of redesign processes; number of safety needs during an operation; inherently safer design to neutralize potential failures (e.g. interlocks); among others. Øien et al. (2010) proposed a method for the development of early warning indicators based on Resilience Engineering for the offshore industry. The REWI method was grounded on ideas taken from the Leading Indicators of Organizational Health (LIOH) used within the nuclear power industry. Potential indicators were proposed in a series of workshops with scientists with various backgrounds (engineering, psychology, organizational theory and human factors). The early warning indicators regarded to anticipation were: risk and hazard identification; lessons learned from own experiences and accidents and lessons learned from others experiences and accidents.

3.1.4 The SPMS should encourage Continuous Learning not only from incidents, but also from normal work

According to Reason (1995), the best way of minimizing failures is by learning how to detect and assess the significance of latent failures before they combine with other contributors to produce unwanted outcomes. Based on a study undertaken in chemical plants, Shirali et al. (2013) suggested to use the principle of learning culture, how much an organization tries to learn from incidents, as a resilience indicator. For instance, results of revisions made during occurrence of the events in the organization can be used for the corrective actions. Peçiflo (2015) assessed the learning level of six manufacturing enterprises in Poland, through a set of questions based on resilience principles. That study concluded that values of learning level did not have significant variation in enterprises with occupational health and safety management system and without it. This reveals that learning referred not only to the procedures and motivation programs, but also to the significance of the participation in the learning process.

Lekka and Sugden (2011) applied a qualitative approach to explore the types of resilience practices implemented in an oil refinery in the United Kingdom. That organization was working towards a learning organization by encouraging incident reporting and systematically analysing near misses and incidents. For instance, to ensure that accidents and near misses were communicated to staff across all hierarchical levels, toolbox talks were implemented. They were used as a means of disseminating the key learning points arising from previous incidents to the workforce. The organization also had corporate systems in place to capture and share knowledge about past incidents, such as a repository of root cause analysis. Saurin et al. (2013) proposed that safety performance measurement systems should, as much as possible, be close to real-time monitoring at different hierarchical levels, contributing to reduce the time lag between events, their analysis and lessons learned.

3.1.5 The SPMS should monitor the System's Flexibility to adjust to variability

Some authors refer to this principle as flexibility, while others refer as adaptive capacity and redundancy. Woltjer et al. (2013) in the air traffic sector, define adaptive capacity as the flexibility to get the information and conditions that enable attention management, problem detection and balance goals using different means and methods. Costella et al. (2008) and Saurin et al. (2013), adopt this principle arguing that, since resilience engineering assumes that error are inevitable, the system must be tolerant to them and should be able to discern between positive and negative variability, so that the former is reinforced, and the second, minimized (Hollnagel, 2009). Costella et al. (2008), in the manufacturing industry, indicate the lack of flexibility in the absence of fail-safe devices in machines with the highest risks, which would make the limits error-tolerant. Saurin et al. (2013), conclude that the system design should support the natural human strategies for coping with hazards, rather than enforce a particular strategy. This implies studying what people actually do and then considering whether it is possible to support that through design (Hollnagel and Woods, 2005). For instance, a mechanism to comply with this principle is to design error-tolerant boundaries, adapt procedures through the differences in the execution method specified in trainings and the methods used in practice, and encourage autonomy of the teams to make important decisions without having to wait for management instructions. In the chemical industry, Shirali et al. (2013) tried to understand how the system restructures itself in response to various changes and variabilities, assessing the facilities and procedures for dealing with unexpected events. Results from 88 questionnaires between supervisors and operators showed that the scores of the flexibility indicator in all units were lower than management commitment, learning culture and awareness. Johnsen et al. (2009) in railway sector adopt the principle of flexibility as the redundancy of the system in having different ways of performing a function. By assessing the flexibility of a railway network, the authors realise that redundancy was not fully implemented in face to technical and organizational constraints. Some recommendations were developed, in order to improve flexibility such as, redundancy implemented in technology (e.g. the GSM-R switch used by the European Rail Traffic Management System to transmit data between trains and railway regulation centres) and redundancy in organizational or human abilities (e.g. by increasing permanent manning in safety critical areas, improve common mental models of risks and risk communication between stakeholders and prioritize daily training, in order to increase knowledge, experience and flexibility). This demands management actions in order to allocate resources and promote collaboration and co-ordination within the organization.

4 DISCUSSION AND CONCLUSIONS

This paper discusses how the Resilience Engineering paradigm can contribute to improve safety performance measurement systems, by proposing a set of principles to design them. The literature review pointed out that this paradigm is a way to understand how people create safety in complex systems, by developing capacities to anticipate and absorb pressures and variations. Five resilience engineering principles have been explored in studies carried out in different industries to improve safety performance: management commitment, awareness, anticipation, continuous learning and flexibility. Those principles are interrelated and reinforce the need to use measurement in continuous improvement cycles. They also complement criteria that any performance

measurement system should meet (e.g. the need for indicators to have goals or targets; develop indicators simple and easy to use, among others) (Crawford and Cox, 1990; Kaplan and Norton, 1992; Neely, 1999; Lantelme and Formoso, 2000; Bourne and Neely 2003; Costa and Formoso, 2004; Kanji, 2010). However, those generic criteria do not address the particularities of safety and place more emphasis on the design of specific indicators (often inconsistent with company strategy), rather than address the overall design of the performance measurement system. Therefore, there is a need for safety performance measurement systems able to anticipate potential hazards, monitor and manage risk continuously, and learn through a systemic life-cycle. The literature review showed that there is no repertoire of safety principles and indicators based on resilience, which are broadly adopted in the academic community. Also there are many different terms that are adopted by different authors. Although some principles have been successfully applicable in aviation and process industries, further studies are necessary in other domains regarded as complex systems, which are still underexplored, such as the construction industry. Based on this literature review, some important trends can be proposed for this research topic: (i) as resilience engineering has been advocated as an alternative for the management of safety in complex socio-technical systems, understand the nature of the complexity of construction projects it will be promising in order to investigate how resilience could be supported; (ii) explore how these principles can be used within the existing methods to measure safety performance in construction projects; and (iii) analyse how these principles can contribute to the reinterpretation and improvement of the safety management practices in construction projects.

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Green Building and Lean Management: Synergies and Conflicts

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Abstract: The construction industry is one of the largest, most important and resource-intensive economic sectors, and at the same time one of the largest environmental polluters. About 30% of greenhouse gas emissions, approx. 40% of primary energy consumption and approx. 50% of waste is attributable to the building stock (DGNB 2013). In the future, the implementation of sustainable building concepts will gain more importance. The construction industry needs to improve resource efficiency, productivity, waste production and customer value.

The aim of this thesis is to present approaches considering the contribution of Lean methods in the context of Real Estate sustainability.

Keywords: Lean Management, Green Buildings, sustainability, synergies, conflicts, implementation strategies.

1 BACKGROUND

1.1 Fundamental ideas of Green Building (Real Estate Sustainability)

Bourdeau et al. (1998) identify the following sustainability criteria: energy efficiency, recyclability, non-toxic materials, value retention, flexibility, long useful lives, use of local resources, information dissemination, use of by-products, intangible services, mobility considerations and support for the local economy. In addition to new and more efficient technologies, the emphasis is on minimizing emissions, waste generation, energy and resource consumption, without compromising comfort and living standards.

1.2 Fundamental ideas of Lean Management

Lean production contains five core principles (Womack/Jones 1996): specification of value from the customer's point of view, analyzation of production processes (value stream), ensuring an effective process flow, pull production: produce what is demanded by the customer when it's demanded and continuous improvement of all processes. For the implementation of the principles Lean offers a number of tools. However, Lean is a philosophy and cannot be reduced to a set of tools (Herrala et al., 2012). Lean also requires that products and processes are designed at the same time. For that matter, it is not only determined what has to be achieved, but also its successful realization (Arroyo et al. 2012).

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2 SYNERGIES BETWEEN LEAN AND SUSTAINABILITY

1. **Economical advantages:** Improved productivity can save construction costs. These savings can compensate for the increased number and greater complexity of sustainable components and technical systems (Saggin et al., 2015).
2. **Competitive Advantages:** The implementation of Lean and sustainability principles leads to competitive advantages (Womack and Jones 1996) as companies analyse their production processes and optimize the use of resources, improve quality and reduce costs. This results in a high level of customer service and increases the company's profitability.
3. **Waste disposal:** Both philosophies regard the elimination and handling of waste as a great potential to achieve their goals.
4. **Improving quality:** Sustainability demands top quality. Lean also strives for perfection via continuous improvement so production is halted as soon as an error occurs and the problem is solved immediately. In this way, waste can be eliminated from the process as resources are treated with greater care, resulting in less rejects and less material consumption.
5. **Focus on people:** Involvement and support of employees through responsibility and decision-making skills lead to motivation, identification with work and operation, implementation of own ideas, interest in constant improvement, motivation, fun at work, acquiring new skills, further education, interest in quality and productivity. This investment in people also promotes social sustainability.
6. **Continuous improvement:** The culture of systematic, continuous improvement is focused on the elimination of waste in any form (time, process, material, people, etc.). Continuous improvement is not a goal, but perpetual steps towards perfection. Sustainable development in particular offers great potential and sources of innovation that can be analysed and realized through continuous improvement.
7. **Positive correlation between indicators:** Lean and sustainability targets have their own indicators. In some cases, a direct positive correlation can be observed. For example, production time shortening and avoidance of unnecessary transports are positively linked to the sustainability indicators of energy consumption and carbon emissions (Johnsen et al., 2016).
8. **Transparency:** According to Womack (2003), transparency is the ability of all actors in a system to discover the potential for value creation. Both Lean and Green Building projects promote transparency through visualization and documentation.
9. **Long-term and holistic implementation:** One-off and isolated applications of Lean methods as well as sustainability measures do not lead to success.

3 CONFLICTS BETWEEN LEAN AND SUSTAINABILITY

1. **Focussing on different dimensions of sustainability:** Lean aims at adding value at the lowest possible costs. The emphasis is on improvements in cost-intensive areas such as processes and people. Sustainability costs, on the other hand, are defined as value-adding investments in a better quality of components. Higher costs for ecological building materials, plants and processes have priority over short-term economic aspects as these investments subsequently lead to operational savings over the lifecycle and an increased market price. The limitation of financial resources, however, pushes for low construction costs, which hinders a growing market share of Green Buildings.

2. **Life Cycle Consideration:** Lean focuses primarily on the production process. Sustainability is considered as part of the entire lifecycle. The LCA takes into account all processes along the lifecycle of the building and its components. Green Buildings are geared up to the longest possible service life in order to be used not only by the customer, but also by future generations without restricting their needs.
3. **Value definition:** Centralized constraints are the lack of a superior value-understanding and the predominance of a customer-oriented perspective of value (subjectivity) (Salvatierra-Garrido et al., 2011). According to Koskela (2000), Lean is a systematic approach to meet customer values regardless of the degree of sustainability. Consequently, the effect of Lean depends on the customer, his sustainability aims and his requirements in value. Sustainable values can be generated considering a minimal building structure, maximum building efficiency, efficient energy use, reduced waste and a healthy and productive environment for the inhabitants (Horman et al. 2004). Intangible properties such as brand and image also contribute to customer values.
4. **Just-in-Time:** JIT is crucial for Lean's goals. Establishing a precisely coordinated production and material flow, throughput times and capital binding can be reduced, stock can be superfluous and thus the production costs can be reduced. The demand-oriented orders according to JIT result in reduced batch sizes causing more frequent transports and therefore higher energy consumption and emissions (Rothenberg et al., 2001, Bae and Kim, 2008).
5. **Different definitions of waste:** Lean defines waste as any action that consumes resources (labour, surfaces, machines) in some form, but does not generate value (Koskela 1992) and focuses on the elimination of production waste. These include in particular waiting times that result from the delay of an earlier activity, inefficient space division, low productivity of the crew, inadequate equipment, delay in information flow, non-availability of material, and external situations such as heavy rain. Waste also contains the production of non-ordered goods, error corrections, excess processing, movement, transport and storage.

Sustainability, on the other hand, tries to avoid environmental waste (air emissions, solid waste, waste water, noise, over-lighting, excessive use of resources and excessive consumption). Environmental waste can also have social implications. These include suboptimal working conditions, a lack of education and training, undermining social acceptance and lack of social dialogue.

Additionally, environmental, social and production waste is not always proportional. There are also production processes in which time and costs can be reduced, but no significant improvements or even worsening of environmental waste (energy consumption and emissions) can be generated.

6. **The success of Lean practices depends on the technology and the area:** Lean's success in sustainability is dependent on the methods and tools used as well as the intended areas of environmental improvement. For example, the value-stream model (VSM) can identify environmental impacts of production processes, but does not bring environmental advantages in itself. The same applies to 5S. On the other hand, cell production leads directly to the reduction of the electricity consumption and TPM can directly reduce the oil discharge. The use of SMED does not bring about any significant environmental improvement.
7. **Requirements of Lean to Employees:** Lean tools are in fact no more than a structured framework for the development of people to improve their problem-solving ability. A key role is played by employees. This role is seen by some as

exploiting, as the high process pressure and labor flexibility overtaxing the workers (Hines et al., 2004). Considering that certain practices are specific to the culture transferring the concept is very difficult. (Williams et al., 1992).

8. **Stationary production versus on-site construction:** Due to the fundamental differences between factory and on-site construction, there are different frameworks and requirements for the process organization:
 - **Process structure:** As production is moving through the product under construction, the workplace, conditions and the executives constantly change.
 - **Procurement by call for tenders:** In the project-based construction industry, the contract is concluded with the most cost-effective provider. This creates a temporary organization and a fragmented value chain due to many different actors.
 - **Responsibilities:** Construction project managers have a wide range of responsibilities. They focus on the customer, the construction, design problems, change orders, costs (payment of the suppliers) and the income side of the project.
 - **Uniqueness:** Changing framework conditions and uniqueness of the projects make it difficult to implement stable and standardized processes.
9. **Losing the pursuit of growth:** In direct contrast to environmental management, there is a growth-oriented management, which cannot be sacrificed for ecological reasons, as it is the basis of our social system.
10. **Lack of performance indicators:** Lean focuses on brilliant processes and non-performance indicators, as the hypothesis is that results are correct when the process is right.

4 IMPLEMENTATION STRATEGIES OF LEAN TO GENERATE BENEFITS FOR SUSTAINABILITY

1. **Implementation at all company levels:** The transformation into a Lean company requires a lot of commitment and everyone's participation in the introduction of the new principles in company culture and organizational structure. The bottom-up implementation approach has been useful for Lean actions. A top-down implementation is not sustainable because the actions (if any) are performed by hierarchical pressure and not by a true continuous improvement culture. Fragmented tooling, no person-centered approach, and inadequate lead indicators do not correspond to Lean principles (Berroir et al.).
2. **Broadening the definition of waste:** Lean's greatest potential for Real Estate sustainability is to avoid the common goal of waste. In Lean theory, environmental and social waste is scarcely taken into account. Sustainability, on the other hand, uses a narrow approach, which leaves many opportunities unused since many intangible aspects are not regarded as waste.
3. **Prefabrication:** Prefabrication can be a promising procurement method for sustainable construction. It can be optimized by the use of numerous Lean principles (Parrish 2012).
4. **Modularization:** This is an extended form of prefabrication. Serial prefabricated modules, i.e. individual rooms are delivered to the building site including windows, tiles, sockets and tables. The advantages are savings in construction costs (up to 40%), a sharp reduction in construction time, efficient production processes, less noise and high flexibility through any extensibility. In the future, buildings could be created at the customer's request and churned out without compromising. Lean

principles could then be transferred to the construction industry without major changes in order to achieve similar successes as in the automobile sector contributing to a higher sustainability of buildings (Müller 2016).

5. **Innovative types of contracts and methods for project definition:** Actually, the chosen type of contract and methods for the project definition of a construction project have no direct effects on sustainable construction. Nonetheless, they can promote innovation and sustainability by the elimination of contractual barriers and improved communication between stakeholders. The following Lean methods can be implemented in this case: multi-party contracts, integrated project teams, performance-based contracting and design build operation maintainers (Horman et al., 2004, Dahl et al., 2005, Bae et al. 2007).
6. **Design methods:** The design phase is crucial for a project's success, affecting the entire service life. The design of Green Building projects is particularly critical as raw materials, resources and construction technologies are relatively innovative and require comprehensive coordination for the best application. In order to minimize environmental impacts and energy consumption in the construction of sustainable buildings, several Lean design methods can be implemented. These include i.e. Integrated Design, Design for Maintainability (DFM), Set-Based Design, Target Costing and 3D Modeling (Bae et al., 2007).
7. **Using more efficient project tools:** Many workplace conditions or methods, such as the critical path, are not able to deliver high-quality projects on time and within the budget (Abdelhamid 2004). In order to improve project performance and increase efficiency new, more targeted instruments must be developed. Lean offers a conceptual basis and the potential for novel methods and tools for sustainable building. In recent years, the following methods have been developed: Construction Site Management, Big Room, Daily Huddle Meeting, Integrated Project Delivery, Lean Project Delivery System, Target Value Design, Time-of-Time Planning, Location-based Management System and Choosing by Advantages.
8. **LastPlanner® System:** The LastPlanner® system can contribute some essential core points of Lean Management to construction, i.e. process consistency, increasing the reliability of all work and information flows, applying the pull principle, transparency, recognition of obstacles in time and working in an integrated project team.
9. **Building Information Modelling:** BIM is an effective process to achieve leanness and sustainability. BIM acts as a catalyst to build up synergies between Lean principles and sustainability. It helps optimizing design and construction using visualization, information, exploration of alternatives and identification of errors and conflicts (Ahuja et al., 2004).
10. **Value Stream Mapping:** Value Stream Mapping is very practice-oriented and fundamental for evaluating where and how other Lean tools and techniques can be applied in production. It illustrates various different processes and information flows in the design and construction process and therefore allows a better understanding of the generation of the value stream. Traditionally, VSM evaluates process time and stock levels to define value and waste, as these factors are critical for economic purposes. However, this Lean method can not only be used for economic purposes, but also for social and environmental purposes by inserting downstream data into the map. Not only time and stock, but also a waste of resources, pollutions, resource use, security and interaction can be depicted (Bae et al., 2007). The most efficient and sustainable way to use VSM is when the card is created together with the

employees. This increases the awareness of action plans, improves communication and information exchange, reduces errors and rework and clarifies responsibilities and interdependencies.

11. **Kaizen:** Kaizen provides the basis for an overall process approach for sustainable project development and thus plays a key role in improving the current state of sustainable methods. As a result of constant improvements, ever higher standards are set and made a rule. All sustainable indicators can be improved further.
12. **Processes for measuring sustainability and Lean:** In the construction industry, there are few performance measurement instruments that can link Lean efforts and sustainable results directly, since it is difficult to measure all sustainable effects of Lean implementation.

The following instruments are used to measure and quantify the sustainability advantages of Lean: Value Analysis, Overall Equipment Effectiveness and Carbon Value Efficiency. A model for quantifying the degree of Lean implementation in construction is the Lean Construction Quality Rating Model (LCR). The evaluation is based on a questionnaire that evaluates the five principles of Lean Thinking according to Womack and Jones as well as the eleven principles of Lean Construction according to Koskela (Hofacker et al., 2008). With the help of the Sustainability Construction Index (SCI), the sustainable performance of the work on construction sites can be monitored. This is measured by the indicators environmental performance, management system, working conditions as well as profitability and the value added (Vieira et al. 2011). In order to promote the degree of implementation of Lean and sustainability, research should be intensified and new methods of measurement should be developed. Only by verifiable facts companies can be convinced of the many advantages of the two philosophies.

13. **Expansion of the magic triangle in project management:** Traditional planning and construction focuses on the mutually influencing factors cost, time and quality as well as the all-encompassing factor of customer satisfaction. Sustainable planning and construction also pursues the following objectives: minimizing the scarcity of resources, minimizing the environmental impact and creating a healthy building fabric (Kibert 1994).
14. **Politics:** In order to promote the realization of sustainability stronger incentives and legal requirements are useful. Legislation must create clarity by bringing together various regulations, strategic plans and sustainability initiatives. Especially in the public sector, law restricts the companies in compiling the project team.
15. **Expansion of the production function:** The traditional production function limits the chances for the improvement of sustainability (Koskela et al. 2009). It is a functional description of the correlation between production factors used and the maximum quantity achieved using a given technology.
16. **New professions:** The Architectural Technologist is the creative partner in the value chain linking planning and construction. He considers the technical side of the design and ensures the desired functions. He also monitors quality assurance, costs and deadlines. (Emmitt, 2001).
17. **Value stream analysis:** Considering the value stream analysis, it is not sufficient to optimize individual processes. However, a correct investment in a part of the system (the longest value stream) can bring several advantages to the whole system.

5 CONCLUSION AND DISCUSSION

The analysis of core ideas shows that the philosophies Lean and sustainability are two separate mature initiatives in the construction sector with seemingly significant overlaps. Through a common integration framework, the potential weaknesses of one philosophy can be balanced with the potential strengths of others. Many researchers have identified the use of Lean Management Principles to increase environmental performance (Huovila and Koskela 1998, Horman et al., 2004). An application is possible both in the case of new construction, restoration as well as in the case of upstream and downstream areas. Lean has a positive impact on sustainability indicators, such as less stress, less health problems, increased productivity, more efficient use of resources and improved quality. The emphasis is on the disposal of waste, avoiding pollution and maximizing value for the customer.

Lean and sustainability are relatively new and complex philosophies. Due to the uncertainty regarding costs and actual benefits, there is some resistance to the introduction. Many companies have failed to implement, because it is difficult to spread the new organizational culture and mindset across the enterprise. The most common error is a tool-focused implementation that neglects the human aspect. The prerequisite for the successful implementation of Lean processes is the understanding of how the existing system works. In addition, an integrated design process and an early participation of the most important project participants are indispensable for the early integration of sustainable concepts as well as the commitment of the owners to sustainability.

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