

REPUBLIC OF TÜRKİYE
YILDIZ TECHNICAL UNIVERSITY
GRADUATE SCHOOL OF SCIENCE AND ENGINEERING

**A MULTIAGENT SYSTEM BASED DECISION MAKING
FRAMEWORK FOR LEAN CONSTRUCTION
SCHEDULING**

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DOCTOR OF PHILOSOPHY THESIS

Department of Civil Engineering

Civil Engineering Program

Supervisor

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A thesis submitted by Emine Ebru ALTAN in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY is approved by the committee on 05.03.2024 in Department of Civil Engineering , Civil Engineering Program.

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Emine Ebru ALTAN

Dedicated to Aya for her incredible understanding and support

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LIST OF ABBREVIATIONS

AI	Artificial Intelligence
AHP	Analytic Hierarchy Process
AR	Augmented Reality
BIM	Building Information Modeling
BOCR	Benefit Opportunity Cost Risk
CPM	Critical Path Method
DT	Digital Twin
ERP	Enterprise Resource Planning
GIS	Geographic Information System
HSE	Health Safety and Environment
IoT	Internet of Things
JIT	Just in Time
LC	Lean Construction
LIDAR	Light Detection and Ranging
MR	Mixed Reality
PDCA	Plan Do Check Act
PM	Project Management
PMBOK	The Project Management Body of Knowledge
QA/QC	Quality Assurance Quality Control
VR	Virtual Reality
3D	3-Dimensional
4D	4-Dimensional
6D	6-Dimensional

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A Multiagent System Based Decision Making Framework For Lean Construction Scheduling

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Department of Civil Engineering

Civil Engineering Program

Doctor of Philosophy Thesis

Supervisor: Prof. Dr. Zeynep IŞIK

An important factor in the success or failure of a project is project planning and control. Since planning activities involve a certain degree of uncertainty, the best way to deal with them is to adapt to the uncertainty and rely on experience for solutions. Approaches such as lean planning, Last Planner system, Plan-Do-Check-Act cycle support this issue by making problems visible early. However, problems arise from weak connection between different plan levels and the slow approach to determining constraints causing a turn from proactivity to reactivity. At the same time, access to and exchange of information are also important problems. To overcome these problems, real-time automated management of operations is required. For this reason, framework for an innovative project planning and control system that facilitates real-time collaboration, data sharing and communication has been proposed. Requirements of the system have been identified as a visual system that combines lean construction practices with innovative construction progress control technologies, artificial intelligence and the digital twin concept, so as to provide users with up-to-date visual information about the status of the project and to help make decisions on project planning and resource allocation while supporting lean construction practices. The workflow in the proposed framework consists of 6 processes based on the "should-can-will-did" principle in the Last Planner System.

These processes express the workflow between users and the system and together implement the plan-do-check-act cycle. Multi agent sytem are used for work plan coordination for their quick respose to unexpected changes in planning with their adaptation, agility and modularization qualities. Proposed fremwork has been validated by expert interviews and found to achieve visualization of the process, increased communication, coordination and integration between processes by involving whole team, decision making support and waste reduction.

Keywords: Lean construction, digital technologies in construction, digital twin, multi agent systems, system framework



Yalın İnşaat Planlaması İçin Çoklu Ajan Temelli Karar Verme Çerçevesi

Emine Ebru ALTAN

İnşaat Mühendisliği Anabilim Dalı

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Bir projenin başarısında veya başarısızlığında önemli bir faktör proje planlaması ve kontrolüdür. Planlama faaliyetleri belli bir düzeyde belirsizlik içerdiğinden, bunlarla baş etmenin en iyi yolu belirsizliğe uyum sağlamak ve çözüm için deneyime güvenmektir. Yalın planlama, Last Planner sistemi, Planla-Yap-Kontrol Et-Önlem Al döngüsü gibi yaklaşımlar, sorunları erkenden görünür hale getirerek bu konuyu desteklemektedir. Ancak farklı plan seviyeleri arasındaki bağlantının zayıf olması ve kısıtların belirlenmesine yönelik yavaş yaklaşım nedeniyle proaktiviteden reaktifliğe geçişten kaynaklanan sorunlar ortaya çıkmaktadır. Aynı zamanda bilgiye erişim ve bilgi alışverişi de önemli sorunlardır. Bu sorunların üstesinden gelmek için operasyonların gerçek zamanlı otomatik yönetimi gereklidir. Bu nedenle, gerçek zamanlı işbirliğini, veri paylaşımını ve iletişimi kolaylaştıran yenilikçi bir proje planlama ve kontrol sistemi çerçevesi önerilmiştir. Sistemin gereksinimleri, yalın inşaat uygulamalarını yenilikçi inşaat ilerleme kontrol teknolojileri, yapay zeka ve dijital ikiz konseptiyle birleştiren, kullanıcılara projenin durumu hakkında güncel görsel bilgi sağlayan görsel bir sistem olarak belirlenmiştir, böylece yalın inşaat uygulamalarını desteklerken proje planlaması ve kaynak tahsisi konusunda karar alınmasına yardımcı olmak amaçlanmaktadır.

Önerilen çerçevede iş akışı, Last Planner Sisteminde "yapmalı-yapılabilir-yapılacak-yapıldı" prensibini temel alan 6 süreçten oluşmaktadır. Bu süreçler, kullanıcılar ve sistem arasındaki iş akışını ifade eder ve birlikte planla-yap-kontrol et-harekete geç döngüsünü uygular. Çoklu ajan sistemi, adaptasyon, çeviklik ve modülerlik özellikleriyle planlamadaki beklenmedik değişikliklere hızlı müdahale edebildiği için iş planı koordinasyonunda kullanılmıştır. Önerilen yapı, uzmanlarla yapılan görüşmelerle doğrulanmış ve sürecin görselleştirilmesini, tüm ekibin katılımıyla süreçler arasında iletişimi arttırdığı, koordinasyon ve entegrasyonu desteklediği, karar verme desteğini ve israfın azaltılmasını sağladığı belirtilmiştir.

Anahtar Kelimeler: Yalın inşaat, inşaatta dijital teknolojiler, dijital ikiz, çoklu ajan sistemleri, sistem çerçevesi



1

INTRODUCTION

The tools used for project management on construction sites mainly focus on planning (Gurevich and Sacks, 2014). Construction work is generally planned by specifying activities, their durations, their assigned resources and forming dependency relationships between these activities. When executed, these activities are expected to start at the earliest time possible with the assumption that all resources assigned to them will be available. However, as the construction progresses, construction schedules require changes due to unpredicted events and uncertainty both in duration and variation.

1.1 Background

Construction scheduling is generally done by computer tools that use critical path method. However, these schedules are not adequate for production planning and control since they do not consider the availability of a resource. Therefore, field workers prepare their own work plans which usually consists of work to be done, people, equipment, and material assignments. Therefore, rather than using the traditional push driven approach in construction scheduling, a pull driven approach that aims to produce products in an optimum time, optimum cost and optimum quality improves the performance of construction process (Tommelein, 1998). In traditional planning process value generation and workflow concepts are ignored, so it is not possible to address wastes in construction (Tserng et al., 2013).

Lean concept, created in manufacturing industry in Japan, is a production philosophy focused on value, value stream mapping, flow and pull. Main purpose is to improve production performance by defining each step in a process as a customer and to provide them with exactly what they needed at the exact time they needed it (Stern, 2017). Value is increased by eliminating waste which are categorized as: overproduction, waiting, unnecessary transport, overprocessing, excess inventory, unnecessary movement, and defects (Liker, 2004; Womack and Jones, 1990).

Lean is a philosophy that should be applied systematically and integrally to all the processes in an organization to attain best performance. There is no agreement on definition but agreement on the characteristics that define the concept which are:

- Maximum value with minimum waste
- Constantly evolving, continuous improvement
- Uninterrupted flow
- Systems view
- Being not just purely process oriented but also people oriented (Banawi and Bilec, 2014; Cesarotti et al., 2019; Forbes and Ahmed, 2011; Gao and Low, 2014a; Hines et al., 2004; Magnani et al., 2019; O'Connor and Swain, 2013; Shah and Ward, 2007; Tommelein, 1998; Womack and Jones, 2003)

Lean construction is the application of lean concepts, tools and techniques to design and construction. Koskela studied the adoptability and conceptualized lean construction as a flow process made up of conversion activities which are the activities that add value to a product and flow activities which are activities that do not add value to a product (Forbes and Ahmed, 2011). Three main characteristics that distinguishes lean construction from traditional techniques are: aim to lessen any kind of waste, intent to decrease variability to ensure uninterrupted flow and having material on site only when necessary (Erol et al., 2017).

Benefits associated with implementation of lean construction include reduction in waste, schedule, cost, risk, and workflow variability, improvement of efficiency, quality, processes, inventory control, project delivery method, health and safety, supplier relationship and stakeholder cooperation, increase in labor productivity and performance and employee satisfaction, generation of better customer value, reliability and profitability (Ansah and Sorooshian, 2017; Babalola et al., 2019; Forbes and Ahmed, 2011; Sarhan et al., 2017).

Many professionals start practicing lean construction by implementing Last Planner system (Alves and Tsao, 2007). Last Planner is the most well-known and powerful planning and control system among all lean construction tools (Gao and Low, 2014b). Last Planner is a method developed by Ballard (Ballard, 2000) which is a crew level planning tool that analyzes constraints to shield weekly work

assignments (Chua et al., 2003). Last Planner attempts to resolve unseen constraints and eliminate uncertainties to improve work plan reliability by employing pull flow (Chua et al., 2003; Sacks and Harel, 2006).

Lean construction scheduling methods are used for improving production control as they support faster response and reduced uncertainty and constraints (Olivieri et al., 2019). Waste, variability, and collaboration are the three features that separate lean from traditional systems (Ghosh and Burghart, 2019).

Construction 4.0, which is an important part of fourth industrial revolution, is involved with the application of innovative technologies such as automation, prefabrication, 3D printing, Augmented Reality, Virtual Reality, sensor networks, internet of things and more. All these innovative systems are part of or enabled by Cyber Physical systems or digital twin information systems that assist in automated data collection, simulation and analysis, visualization, more effective project control and more efficient and safer construction projects. Cyber Physical systems can track labor, equipment, material, construction progress with the help of sensing devices and deep learning technologies (Pishdad-Bozorgi et al., 2020).

Digital twin is a form of cyber physical system that integrates components between virtual and physical spaces and interconnects them. Ideally, digital twin is a concept of having a real time digital equivalent of the physical product. Digital Twin is defined by interaction and union of the digital and physical worlds. There is no commonly accepted definition for digital twin, however, the definitions all consider digital twin as a dataset representing the state of a system and its development over time (Chevallier et al., 2020; Lu et al., 2020a). The connection between the virtual and physical is ensured by different forms of data and the data from physical to virtual is considered to be raw whereas the data from virtual to physical is considered to be processed (Boje et al., 2020).

Digital twins for construction are preferable because they can reduce waste by effective decision making and dependable what if scenario analysis. Digital twins offer a solution to bring together lean thinking, computing, and monitoring technologies in construction (Sacks et al., 2020a). Many systems have been developed in lean construction practices that apply improved visualization, innovative progress control technologies and artificial intelligence systems.

Innovative concepts such as automation, prefabrication, 3D printing, AR, VR, sensor networks, IoT etc. are all part of or enabled by digital twin information systems that assist in automated data collection, simulation and analysis, visualization, more effective project control and more efficient and safer construction projects (Sacks et al., 2020a, b; Kan and Anumba, 2019; Natephra and Motamedi, 2019; Olatunji and Akanmu, 2015; Sawhney et al., 2020; Hlady et al., 2018; Boje et al., 2020). Implementation of lean principles and Industry 4.0 techniques such as DT support each other and these concepts are interdependent where application of one facilitates the other (Florescu and Barabas, 2022).

Increasing complexity and demand for higher productivity is increasing the interest in potential applications of digital technologies in construction (Sacks et al., 2020a, b; Kan and Anumba, 2019; Natephra and Motamedi, 2019; Olatunji and Akanmu, 2015; Sawhney et al., 2020; Hlady et al., 2018; Boje et al., 2020). There is a common view that construction in the future is likely to be intelligent and combination of information systems and sensors will make that possible (Sepasgozar et al., 2021).

Several researchers agree that major causes of problems in construction planning and control are inadequacy of traditional PM theory, and improper applications of information technologies (Sriprasert and Dawood, 2002). Last Planner, although really effective implementing tool, requires significant support for project teams by dedicated facilitators over the long term, which is difficult to maintain. However, in their absence the teams revert to traditional practices (Choo et al., 1999). Digital twins' ability to improve integration, facilitate information sharing, enable accessing up to date data and support collaboration and coordination between participants will support successful implementation of lean principles (Forbes and Ahmed, 2011) and application of lean construction scheduling methods.

1.2 Aim of Thesis

Aim of this thesis is to develop a framework for visual project progress monitoring and decision support system based on multi agent systems and digital twin for lean project scheduling, that helps minimize waste of materials, time, and effort in order to generate the maximum possible amount of value. Objective is to uncomplicate lean construction scheduling system implementation by organizing it through

constraint analysis, sustainable commitment, integration between processes, and stronger understanding by clearer communication and higher connectivity between parties. Requirements of the system are identified through literature review and benefit, opportunity, cost, risk analysis. Successful implementation will provide practitioners with a guide to develop a tool to control the project and to implement lean principles in a construction project, which will enable constraint free assignments to the project team, which in turn will help reduce production wastes and improve site productivity. By the use of a visual system, real time updating of construction progress will be possible so a digital twin of the work progress will be formed. Proposed framework will assist in developing a tool which will facilitate data input, communication and provide the project management team and site personnel with a tool to follow site works in real time and effective project control.

1.3 Hypothesis

Lean Construction methods, mainly the Last Planner System, usually depend on information retrieval from all parties. The proposed system aims to connect planning systems and heterogeneous data. Multi agent system that is integrated in the platform aims to support planners and management in negotiation intensive approaches, like offering decision support on optimal duration, sequencing of tasks etc. The proposed system aims to enable proactive modelling, tracking and optimization of construction works and their relevant resources.

In line with lean project management's aim to handle decision making by continuous communication and having project team react by a set of methods (Levitt, 2011), proposed system will enable close collaboration between parties and faster reaction so that the project delivery system will be more effective and efficient by improved integration, information sharing, access to up to date data and decision making assistance.

A number of systems that are combined with lean construction practices have been proposed that apply 3D models, augmented reality, digital twin concept, innovative progress control technologies and artificial intelligence systems. Although there are studies that focus on scheduling decision support, visualization of site works, real-time progress monitoring, systems that supplement lean construction scheduling; this study aims to integrate all these concepts.

Study will contribute to digitalization of construction industry and Construction 4.0. Users of the developed system will be able to follow site works in real time, perform more effective project control, communicate and collaborate more effectively and apply lean principles more easily. Improvement in quality, time and cost are the expected benefits.

1.4 Research Flow

The methodological approach adopted in this study is Design Science Research where the main outcome is the development of an artefact rather than exploring or describing existing systems. The research flow can be seen on Figure 1.1 where each stage of the research is described with used methods and outputs.

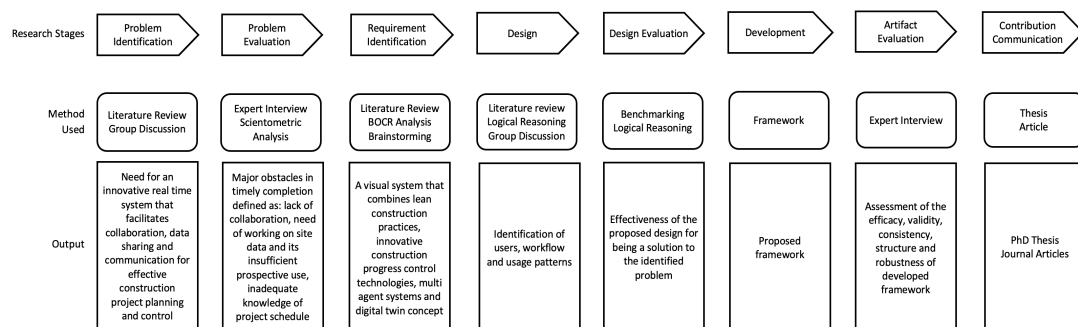


Figure 1.1 Research flow

The first step is problem identification which is done through literature review and group discussion. The output of the problem identification step is the identified problem. Next step is evaluation of the problem which is done through expert interview and scientometric analysis. The output of the problem evaluation stage show that the problem is irrelevant so at the following stage requirements are identified through literature review, benefit opportunity cost risk analysis and brainstorming. The output of requirement identification stage show the requirements for the framework. The research flow can be seen on Figure 1.1 where each stage of the research is described with used methods and outputs that is going to be proposed. Following step is design which is done through literature review, logical reasoning and group discussion. As the output of this stage users, workflow and usage patterns are identified. Next stage is design evaluation which is done through benchmarking and logical reasoning where the output shows effectiveness of the proposed design. At the next step the proposed framework is developed

followed by artefact evaluation which is done through expert interviews to assess the proposed framework for efficacy, validity, consistency, structure and robustness. Finally, the contribution communication is done through this thesis and scientific articles.



2

LEAN CONCEPT

This section defines lean and explains the history and development of the concept, its fundamentals, comparison to traditional systems and its implementation.

2.1 Defining Lean

Lean is a philosophy that should be applied systematically and integrally to all the processes in an organization to attain best performance. Lean is also viewed by many as a goal, as a constant change process and as a set of tools and techniques. Its implementation changes the way an organization operates, welcoming change and striving for continuous improvement, more than just simply eliminating waste (Kovvuri et al., 2016). Lean thinking can be expressed by aligning production with demand, integrating suppliers and involving workforce in improvement activities in addition to eliminating waste (Lyons et al., 2013).

There is no agreement on definition of lean but agreement on the characteristics that define the concept. According to Hines et al. lean is constantly evolving and any definition made will be valid in a certain point in time (Hines et al., 2004).

According to Lean Enterprise Institute, lean means producing more value for customers with less resources. It focuses on eliminating waste from the entire value stream rather than unique operations. The aim is to understand customer value and increase it by a perfect value production processes that has zero waste (What Is Lean?, n.d.).

According to Womack and Jones, being lean requires a way of thinking that aims at making product flow uninterruptedly through value adding processes, a pull system that starts with the customer demand and replenishes as much as the next operation needs at short intervals, and a culture where everyone aims continuous improvement (Womack and Jones, 2003).

According to Tommelein, lean production has a systems view where waste is just not produced by individual systems but by the value stream and aims at adding value to a product as it moves through the process steps by avoiding, eliminating or reducing these wastes (Tommelein, 1998).

According to Koskela, lean is a way to create production systems by generating maximum value by minimizing waste of material, time and effort (Forbes and Ahmed, 2011).

According to Banawi and Bilec, lean is a business strategy that has a main goal of minimizing waste which is anything that does not add value (Banawi and Bilec, 2014).

According to Cruz-Villazon, lean philosophy is complementary element to existing project management techniques, that focuses on creating value and eliminating waste (Cesarotti et al., 2019).

According to O'Connor and Swain, lean is a way of doing business, a high-performance method for managing that aims to maximize creation of customer value by reducing or eliminating all forms of waste (O'Connor and Swain, 2013).

According to Paez et al., lean enterprise can be seen as a socio-technical system that aims to increase production performance to maximum with minimum amount of resources (Gao and Low, 2014a). Magnani also defines lean as a socio-technical system, which is not just a purely process oriented strategy but also a people-oriented strategy (Magnani et al., 2019). Shah and Ward, also describe it as an integrated sociotechnical system, whose main goal is to eliminate waste by reducing variability (Shah and Ward, 2007).

According to Hines et al., in lean, the focus is on the final customer and understanding lean as a whole, both at strategic and operational levels, is important to provide customer value with right tools and strategies (Hines et al., 2004).

According to Hopp and Spearman, lean is the production of products or services with minimal buffering costs which are obvious waste, and variability. Three types of variability buffers are inventory, capacity, and time (Hopp and Spearman, 2004) and if there exist any type of variability in the process there will also be waste (Hopp, 2018).

Lean thinking should start with a deliberate attempt to accurately define value in terms of specific products, offered at specific prices to specific customers. Specifying value precisely is the crucial first step in lean thinking. Providing wrong product or service the right way is waste (Womack and Jones, 2003).

Although value is created by the producer, it is meaningful when it is defined by the ultimate customer in terms of a specific product. The product should meet the customer's demands at a specific time and price (Womack and Jones, 2003).

Determining the value stream for each product is the second step in lean thinking. Value stream is the set of all the particular actions essential to bring a specific product through the three critical management tasks: problem solving, information management and physical transformation. Value stream analysis typically shows three types of actions: steps that create value, steps that create no value but are inevitable and steps that create no value and are evitable (Womack and Jones, 2003).

Ohno identified 7 kinds of waste: Transport, waiting, overproduction, defect, inventory, motion, and extra processing. Lean offers different tools to help identify these wastes and value stream mapping is one of them (Banawi and Bilec, 2014). The eighth kind of waste included by Liker is unused employee creativity (Liker, 2004).

After the value is defined, value stream is mapped and wastes are eliminated, next step in lean thinking is to make value creating steps flow and let customers pull value from the producer. The harder the value is pulled, flow gets faster which uncovers the unseen wastes in the value stream, which leads to perfection (Womack and Jones, 2003).

One piece flow has a few benefits. It builds in quality, creates flexibility, increases productivity, frees up floor space, improves safety, improves morale and reduces cost of inventory (Liker, 2004).

2.2 History and Development of Lean Concept

The term lean is accredited to John Krafcik, a researcher at International Motor Vehicle Program at Massachusetts Institute of Technology, which was created to study the differences between Japanese manufacturing methods and mass production (Forbes and Ahmed, 2011). Lean was chosen as a term because the Japanese used less of everything and produced higher quality cars with greater variety (G. Ballard and Tommelein, 2012).

Lean thinking was first brought to attention by Womack and Jones to describe the philosophy of production processes they studied at Toyota Motor Company. Their philosophy focused on value, value stream mapping, flow and pull (Stern, 2017). The production system of Toyota used less of resources and time and produced higher quality products with greater variety and less inventory (Gao and Low, 2014a).

After World War II Toyota urged to catch up with the United States in 3 years and this became Toyota's goal. Mass production system did not fit with Toyota's circumstances, so under the leadership of Eiji Toyoda and Taiichi Ohno, Toyota adapted from Ford Motor Company's mass production system that was based on continuous flow. The aim was to increase productivity and decrease costs without increasing production quantity and having the flexibility to satisfy customer demands. Basis of Toyota production system is absolute elimination of waste, anything that uses resources but creates no value. The system is supported by two pillars which are Just-in-Time manufacturing and autonomation meaning machines that can prevent production of defective parts. A visual tool called Kanban was developed to pull production according to customer demands and achieve Just-in-Time production. Kanban carries 3 categories of information: pick-up information, transfer information and product information (Ohno, 1988).

Toyota took the teachings of American quality pioneer W. Edwards Deming very seriously. He gave quality and productivity seminars in Japan and taught that fulfilling and exceeding customer demands is everyone's task in an organization; customers being both internal and external customers. Each step in a process was defined as a customer and was to be provided with exactly what they needed at the exact time they needed it. Deming's principle of next process being the customer is one of the most important expressions in Just-in-Time production (Liker, 2004).

14 principles of lean, explained by Liker in his book, are organized in 4 broad categories (Liker, 2004).

1. Long term philosophy

Principle 1. Base management decisions on long term philosophy even at the expense of short-term financial targets

2. Right process will produce right results

- Principle 2. Create continuous process flow to expose problems
- Principle 3. Use pull systems to refrain from overproduction
- Principle 4. Level out the workload
- Principle 5. To get quality right the first time, build a culture of stopping to fix problem
- Principle 6. Standardized tasks are foundation of continuous improvement and employee empowerment
- Principle 7. Use visual control so no problems are hidden
- Principle 8. Use only reliable and thoroughly tested technology that serves your processes and people
- 3. Add value to the organization by developing your people and partners
 - Principle 9. Grow leaders who understand the work, live the philosophy and teach it to others
 - Principle 10. Develop exceptional people and teams who follow your company's philosophy
 - Principle 11. Respect your extended network of partners and suppliers by challenging and helping them
- 4. Continuously solving root problems drives organizational learning
 - Principle 12. Go and see for yourself to thoroughly understand the situation
 - Principle 13. Make decisions slowly, implement them rapidly
 - Principle 14. Become a learning organization through continuous improvement

Work team is the core of the lean factory. To build these efficient teams, workers need to be taught all the jobs in the work group they are in so that task rotation and filling in for each other is possible. They also need to obtain many additional skills and be encouraged to take action before problems get severe. Getting this kind of action from the workers is only possible when management actually values their workers and willing to give responsibility and make sacrifices to keep them (Womack et al., 1990).

2.3 Fundamentals of Lean

Lean does not have a manifesto or a list of principles that the industry agreed upon (Stern, 2017). Womack and Jones define lean manufacturing as a five-step process:

defining customer value, mapping value stream, making value flow, pulling from the customer and aiming perfection. Ohno defines it even more simply as reducing the time from customer order to collecting cash by eliminating non-value adding activities (Liker, 2004).

According to Howell and Ballard the principles of lean thinking and production are stopping the line, pulling the product, creating one piece flow, synchronizing and transparency to reach the goal of perfection through delivering a unique product instantly with nothing in stock (G. Howell and Ballard, 1998).

Sivaganesh et al. describe the fundamentals of lean concept as: understanding the customer's perception of value, eliminating waste to obtain a process flow of only value, processing thought and behaving in a different way with the provided tools, continuous improvement of all processes from initiation to delivery and respecting every member of the team (Sivaganesh and Ratnayake, 2019).

Two organizational features of a truly lean plant is to transfer maximum amount of tasks to the people who are actually adding value to the product and to have a system that detects defects and find their ultimate cause (Womack et al., 1990).

Lean production concentrates on waste elimination. It is based on Toyota Production System and principles of Total Quality Management. Focus is on getting the right amount of right things to right places at the right time. According to the nature of lean, simplifying work enough to manage, do and understand is important (Stern, 2017).

Continuous improvement is vital in lean, there is always an ongoing effort to improve processes, products, or services (Stern, 2017). Plan, do, check, act (PDCA) model, which is also called Deming cycle, a keystone of continuous improvement, is a systematic approach used in lean to solve problems. No matter how small they are, continuous incremental improvements are important in reaching the lean goal (Liker, 2004).

2.4 Comparison of Lean with Traditional Systems

According to Koskela there are two aspects to all production systems: conversion and flow. Conversion is the activities that add value and flow binds conversion activities together. Traditional management systems only consider conversion and

increasing their efficiencies whereas lean systems focus on decreasing or eliminating non-value adding flow activities (Koskela, 1993).

In lean, although explicit knowledge through standards, procedures and documentation is important to improve business, it is tacit knowledge that is critical. Tacit knowledge is know-how learned through practice. Tacit knowledge is particularly important in craftsmanship. Failure is accepted as long as reasons for failure and steps to take to avoid the failure are identified (Koskela et al., 2019).

Traditional project management sees the project as a collection of activities where lean thinking sees the project as one large operation. Project total cost and duration are more important than the cost or duration of any activity. Coordination is provided by the main schedule and workflow details are managed by people in the organization who support the project objectives (G. Howell and Ballard, 1998).

In design methods, there are four basic differences between mass and lean producers which are differences in leadership, teamwork, communication, and simultaneous development. Lean producers assign the work to a project leader who assembles a team whose members come from functional departments of the company. They keep their ties to their departments but during the life of the project they are under the project leader's control. By intense communication and simultaneous development of design stages, lean producers can complete a design faster than mass producers with fewer tools, lower inventories and less human effort (Womack et al., 1990)

Lean producers select their suppliers at the beginning of the product development, from a long-term supplier group, based on past relationships and proven performance rather than based on bids. They don't hand over the design details to the supplier, assembly parts produced by the supplier is entirely supplier's responsibility (Womack et al., 1990).

When a supplier fails in quality or reliability, the supplier is not dismissed by lean producers as done in traditional systems. Instead, part of the supplier's work is shifted to another supplier for a given period of time as penalty. Toyota and other companies consider this kind of penalty highly effective while keeping the long-term relationship fundamental to the system (Womack et al., 1990).

Lean is not a phased and individual approach but a collaborative one. It doesn't just aim to deliver the project but also to meet the customer demands. Lean is a culture and a way of doing business (Mehany, 2015).

2.5 Implementing Lean

According to Lean Enterprise Institute different types of works in wide range of industries have applied lean methods (G. Ballard and Tommelein, 2012). Successful implementation depends on leadership, finance, skills and supportive organizational culture (Zhou, 2016).

Transitioning to lean requires holistic approach, new knowledge, and cultural change. Rather than tools and technologies, management's ability to adapt to change is considered to be the main barrier in lean implementation (Zhou, 2016).

According to Hopp, the most common failure reasons in lean are lack of top management's commitment, resistance to change and over relying on tools without deeply understanding lean thinking (Hopp, 2018). Applicability of lean to automated processes is limited. Lean can be applied in their design and construction but has little place in their operation (G. Ballard and Tommelein, 2012).

For adapting and maintaining lean, an organization should be a quick learner and should invest in employee training, organizational infrastructure and cultural development to encourage advancement (Taylor et al., 2013). Generating ideas for improvement and implementing them will help an organization to make effective use of lean (Hopp, 2018).

This section covers the definition and history of lean construction, its comparison to manufacturing and traditional construction, lean project delivery systems, used techniques, waste, collaboration and implementation of lean construction.

3.1 Definition and History of Lean Construction

Construction industry, criticized for being wasteful, unsafe and inefficient, is project oriented and focuses on meeting budget, schedule, quality and safety goals (Mehany, 2015), (Tezel and Nielsen, 2013). Lean construction goes beyond these goals to improve the overall process by adding value to the customer and reducing waste and risk and increasing safety (Mehany, 2015), (G. Howell et al., 2017).

Lean construction is the application of lean concepts, tools and techniques to design and construction. Application of lean concepts requires a profound change of conventional structures both in organizational and behavioral extents and serious commitment at all levels for success (Johansen and Walter, 2007).

Koskela challenged the construction industry in 1992 by studying the adoptability of a manufacturing concept to construction and project delivery (Cesarotti et al., 2019). The term lean construction emerged from the first meeting of International Group for Lean Construction in 1993 (Tezel et al., 2020). Core principles underlying the philosophy are eliminating waste and variability, defining value from clients' perspective, defining the value adding and non-value adding activities, making the value adding steps flow uninterruptedly, making what the client pulls quickly and when it is needed, and continuously improving for pursuing perfection (Tezel et al., 2020).

Koskela conceptualized lean construction as a flow process made up of conversion activities which are the activities that add value to a product and flow activities which are activities that do not add value to a product (Forbes and Ahmed, 2011). Koskela saw transformation, flow and value as different views on production and stated that all should be adapted at the same time for effective systems management (Tommelein, 2015). This was the transformation flow value theory of construction. Improvements could be made by eliminating flow activities and making conversion

activities more efficient. He regarded three root causes for non-value adding activities: design, ignorance, and basic nature of production. He explained lean construction as a means to design a production system that aims to minimize waste to create maximum value and listed the following principles (Forbes and Ahmed, 2011):

- Lower the portion of non-value adding activities
- By systematically considering customer requirements increase output value
- Reduce variability
- Reduce cycle time
- Simplify by minimizing the number of actions, parts and links
- Maximize output flexibility
- Maximize process transparency
- Focus on the whole process
- Continuously improve the process
- Balance flow and conversion improvements
- Benchmark

Glenn Ballard developed the lean project delivery system to achieve the delivery of the product, maximization of value and minimization of waste. Five big ideas fundamental to the lean project delivery system are collaboration, increasing connection between all participants, perceiving projects as networks of commitments, optimizing the project as a whole rather than set of activities and coupling learning with action (Forbes and Ahmed, 2011).

Gregory Howell states that clear goals for the delivery process, maximizing performance at project level for the customer, concurrent design and process, application of production control throughout the product lifecycle are the essential features of lean construction (G. A. Howell, 1999).

Iris Tommelein describes lean construction as adopting the lean thinking mindset, where lean thinking is a philosophy that helps remove unwanted complexity from systems so more can be accomplished by using simpler systems (Tommelein, 2015).

The Construction Industry Institute names five principles of lean construction as customer focus, culture and people, workplace organization and standardization, waste elimination and constant improvement and built-in quality (Forbes and Ahmed, 2011).

3.2 Comparison of Construction and Manufacturing

Ballard describes construction as a type of fixed position manufacturing where constructed objects are too large to move through fixed workstations so mobile workstations move through constructed objects (G. Ballard and Tommelein, 2012).

Construction is a project-based production process that is mostly conducted outdoors as opposed to manufacturing where processes are conducted mostly in a controlled environment of facilities. Construction processes are determined by crews so there is potential for high variability. Durations are long as opposed to manufacturing (Forbes and Ahmed, 2011).

In manufacturing a product is developed for producing multiple copies of it whereas in construction only the prototype is produced and not any copies (G. Ballard and Tommelein, 2012).

Products of manufacturing industry can be used anywhere on the planet, but construction's products are location based and highly impacted by their environment and require adaptations (G. Ballard and Tommelein, 2012).

3.3 Comparison of Lean Construction with Traditional Construction

Three main characteristics that distinguishes lean construction from traditional techniques are: aim to lessen any kind of waste, intent to decrease variability to ensure uninterrupted flow and having material on site only when necessary (Erol et al., 2017).

Traditional construction techniques optimize performance by focusing on each activity whereas lean techniques optimize performance at the project level. Lean construction does not take the place of CPM or other tools but works within them to improve completion of tasks by short-term planning. (Forbes and Ahmed, 2011).

Traditional construction utilizes sequential engineering while lean construction utilizes concurrent engineering. While the focus is on optimality in traditional construction, the focus is on waste elimination in lean construction. Collaboration, both push and pull techniques, plan-do-check-act approach and acknowledgement of waste are important features of lean construction whereas different approaches are used in traditional construction (Koskela et al., 2019).

3.4 Lean Project Management – Lean Project Delivery System – Integrated Project Delivery

There are a number of methods for designing and delivering of construction facilities. Project delivery methods include (Forbes and Ahmed, 2011):

1. Design-bid-build
2. Design-build
3. Engineer-procure-construct
4. Design-construction management
5. Design-agency construction management
6. Fast-track construction
7. Partnering
8. Relational contracting / lean project delivery

The first 6 methods have been used for many years. Partnering is an earlier type of relational contract. Lean project delivery methods add lean methodology to partnering principles to minimize all types of waste (Forbes and Ahmed, 2011).

Lean Project Delivery System is an integrated project delivery method in lean construction developed by Ballard. It consists of five phases: project definition, lean design, lean supply, lean assembly, and facility use (Erol et al., 2017). It does not only intend to provide customers what they want but help them define it (G. Ballard, 2008). The main modules include lean design, lean supply, lean assembly, lean production and lean delivery system (Al-Aomar, 2012).

Integrated Project Delivery is used synonymously with lean construction methods which replaces design-bid-build model. Integrated Project Delivery brings together the designers, builders, and owners at the start of the project and work collaboratively. They all share risk and reward with the legal basis of a contract

called an integrated form of agreement (Santorella, 2017). Focus is on collaboration, waste minimization and integration (Dave et al., 2013).

3.5 Lean Construction Practices – Techniques Used

Lean project management aims to have the client handle decision making on a project by continuously communicating their project values and outcomes and any changes made in them. The project team reacts to these stated values and outcomes by using a set of methods (Levitt, 2011). Most common methods are listed below.

- Structured Problem Solving is a team-based method for pointing out and solving issues that have destructive effects on completion of a work activity. Techniques that can be used in structural problem solving include: A3 problem solving, fishbone analysis, 5-whys, and plan-do-check-act (O'Connor and Swain, 2013).
- 5S is an important method of lean which provides a structure for having, keeping and improving the organization and layout of a work area for ensuring operation safety and efficiency with minimal waste. 5S method consists of 5 steps which are sort, straighten, shine, standardize and sustain (O'Connor and Swain, 2013).
- Mistake-proofing or Poka-Yoke is a method to prevent errors or defects from occurring to eliminate the need for quality control. When a defect is discovered, not only is it removed but also the process is evaluated and changed so that possibility of making the mistake again is removed (Tommelein, 2008).
- Kanban is system that uses visual control generally in the form of cards or tokens for pull production by signaling a demand from the preceding work unit (Tezel and Aziz, 2017).
- The Last Planner System, which is at the heart of lean construction implementations, is a project planning a control approach based on management by means (Tommelein, 2015). It is a collaborative planning tool to increase the commitment of team members to achieve lean goals (Sarhan et al., 2017).

- Concurrent engineering is a systematic approach by a multidisciplinary team to get various tasks executed simultaneously by integrating design, construction, and other related processes (L. Zhang and Chen, 2016).
- Heijunka or workload levelling is a method used for levelling demand and variability of production and resource usage (Tezel and Aziz, 2017).
- Standardized work is a tool for developing a standard way for specific construction processes (Sarhan et al., 2017).
- Visual management provides transparency by enabling workflow and action plans to be seen on the job site by charts and signs (Forbes and Ahmed, 2011).
- Kaizen is a Japanese word for continuous improvement, meaning all processes should continuously be evaluated and improved (Sarhan et al., 2017).
- Value stream mapping is a map created by the team that shows their work and their work's connection to the works of others to document all the steps in a workflow that add value to the from the customer's perspective (Forbes and Ahmed, 2011).
- Just-in-time (JIT) delivery is based on the idea that inventories are regarded as waste, therefore units should be available only when needed (O. M. Salem et al., 2015).
- Integrated project delivery brings together the designers, builders and owners at the start of the project to work collaboratively for sharing both risk and reward (Santorella, 2017).
- Waste walk or Gemba walk refers to going to the actual place for finding the source of a problem, its cause and fixing it (Babalola et al., 2019).
- Obeya room concept helps participants understand each other's opinions and make faster decision by making use of A3 sheets hung up on walls of a large meeting room that describe different points of views of participants (Nascimento et al., 2018).
- Huddle meetings bring team members together to share their achievements and impediments and review the work done on that day (L. Zhang and Chen, 2016).
- 5 why method ensures effective root cause analysis for finding the underlying cause of an issue by asking why repetitively. It is an effective

waste processing method and ensures that issues do not repeat (Shetty and Rao, 2019).

- First run studies is a part of continuous improvement principle, that is used to redesign critical functions involved (O. Salem et al., 2005).
- Target value design is the practice of constraining the design and construction of a facility to a maximum cost (Dave et al., 2013).

3.6 Construction Waste

Sacks and Goldin define forms of waste in construction as: undesired products, rework, inventories, unnecessary activities, unnecessary movement of workers and materials, waiting for materials or information and products that do not meet clients' needs (Sacks and Goldin, 2007).

Hosseini et al. categorize construction process' waste in two: due to operations which include defects, rework and overproduction, and due to non-value adding works which include transport, waiting, inventories and improper methods (Hosseini et al., 2012).

Thürer et al, after systematic review of lean literature on waste, define waste as any system input that is not converted just in time to a customer valued output. They also define two types of waste: obvious waste which is waste that can be reduced without creating another waste and buffer waste which is waste that cannot be reduced without creating another waste (Thürer et al., 2017).

Minimization of waste in construction will directly affect cost, time and quality (Agyekum et al., 2013). Developing an attitude, designing to prevent, using prefabrication adopting proper procurement method and adopting site waste management plan are important in minimizing waste (Agyekum et al., 2013).

3.7 Collaboration

There is great cooperation between lean and collaborative working. Team working is a basic attribute of lean culture and for a construction project, collaborative planning and project management which brings together representatives of all parties in a construction project, is an important process that assists lean approach (O'Connor and Swain, 2013).

The Egan report, which is called Rethinking Construction, points to lack of collaboration in construction industry and recommends lean principles adoption. The lean construction approach, the Last Planner system arouses collaboration among stakeholders and commitment from project participants by developing a common understanding of project goals (Daniel et al., 2017).

Close collaboration between participants is required in lean so that a more efficient and effective system for project delivery is provided. Through collaboration it is possible to overcome fragmentation and gaps between expectations and reality. Lean is the utmost in collaboration and cooperation since lean methods are based on participative methods to improve interaction between project participants (Forbes and Ahmed, 2011).

3.8 Lean Construction Implementation – Benefits, Limits, Barriers

Because of high risks in construction and sensitivity to extra costs, construction companies proceed cautiously when considering innovation. Since many lean construction tools are heuristic, they depend on a discovery mindset and training and innovation has been slow (Stevens, 2014).

To successfully implement lean in construction: managers should treat people as important merits, aim to maximize project value, optimize value stream, create a project flow, create pull planning and pursue perfection (Tezel et al., 2018).

Lean construction implementation can be divided into three stages: waste and variability elimination, supply chain optimization and supply chain implementation (Tezel et al., 2018). In implementation four key factors should be considered: management commitment, focus on measurable and actionable improvement, involvement and learning (Koskela, 1992).

Important barriers in implementation are employee resistance, know-how absence, not having management support, sliding back to old working methods, having a narrow minded view of implementation, budget restrictions, lack of planning and coordination in implementation, inadequate control of entire value stream and training problems (Tezel et al., 2018).

A construction organization has to meet some prerequisites for successfully implementing lean principles. A willingness to depart from traditional methods and accept change is essential. Implementing lean during the earlier design stages will improve the effect of lean techniques. Commitment to continuous learning and training is important for future improvements. A quality-oriented culture is needed for application since lean construction techniques do not work in an atmosphere of suspicion, distrust and internal competition. A shared vision of beliefs and future state is important for having all stakeholders on the same page. Commitments to waste reduction, safety improvement, cost and performance measures are essential. Collaboration and cooperation between participants and use of information technology for improving integration, facilitates information sharing, access to up-to-date data and ability to make informed decisions (Forbes and Ahmed, 2011).

Benefits associated with implementation of lean construction include reduction in waste, schedule, cost, risk, and workflow variability, improvement of efficiency, quality, processes, inventory control, project delivery method, health and safety, supplier relationship and stakeholder cooperation, increase in labor productivity and performance and employee satisfaction, generation of better customer value, reliability and profitability (Babalola et al., 2019; Forbes and Ahmed, 2011; Ansah and Sorooshian, 2017; Sarhan et al., 2017).

LEAN CONSTRUCTION SCHEDULING

This section explains the concept of lean construction scheduling, its comparison to other methods, developed methods, its implementation, its benefits and disadvantages, and evaluation of lean construction scheduling methods.

4.1 The Concept

The tools used for project management on construction sites mainly focus on planning (Gurevich and Sacks, 2014). Construction work is generally planned by specifying activities, their durations, their assigned resources and forming dependency relationships between these activities. When executed, these activities are expected to start at the earliest time possible with the assumption that all resources assigned to them will be available. However, as the construction progresses, construction schedules require changes due to unpredicted events and uncertainty both in duration and variation. Therefore, rather than using the traditional push driven approach in construction scheduling, a pull driven approach that aims to produce products in an optimum time, optimum cost and optimum quality improves the performance of construction process (Tommelein, 1998).

As the time between planning and implementation increases, so does the variance of actual schedule and budget. Planning activities to be executed more than 3 months into the future is useless because of uncertainties and variations (Winch and Kelsey, 2005).

The difference between actual and planned time, quantity or rate is caused by variability and uncertainty in construction projects (Sacks and Harel, 2006). Lean construction scheduling focuses on improving plan reliability by generating constraint free tasks and short-term plans to address the problem of ‘separation of execution from planning’ (Dawood and Sriprasert, 2006). Delivering value is the main purpose while waste elimination is the by-product (Mossman, 2009).

4.2 Comparison of Lean Construction Scheduling Methods with Traditional Scheduling Methods

Construction scheduling is generally done by computer tools that use the critical path method. However, these schedules are not adequate for production planning and control since they do not consider the availability of a resource. Therefore, field workers prepare their own work plans which usually consists of work to be done, people, equipment and material assignments (Tommelein, 1998).

A general criticism of traditional construction planning is that the practice focuses on management of contracts and costs instead of production processes (Dawood and Sriprasert, 2006). In traditional planning, construction projects are first divided into activities or tasks. These tasks are placed in order of execution and necessary resources and durations are estimated. To reduce project costs and duration, contractors try to reduce the cost and duration of each task. However, during this process value generation and workflow concepts are ignored, so it is not possible to address wastes in construction (Tserng et al., 2013). One of the weaknesses of traditional methods is the assumption that prerequisites of each work package will be available at the time the work is scheduled to start (Sacks et al., 2007).

To address the resourcing of tasks, critical chain method is advocated by some, where critical chain is the longest resource constrained path (Winch and Kelsey, 2005). However, the critical path method is found to be ineffective for production level planning and control and communicating with the site team about planning activities (El-Sabek and McCabe, 2018).

Traditional systems view the project as a combination of activities whereas lean systems views the entire project as a temporary production system. Waste, variability and collaboration are the three features that separate lean from traditional systems (Ghosh and Burghart, 2019). Lean construction scheduling methods are used for improving production control as they support faster response and reduced uncertainty and constraints (Olivieri et al., 2019).

4.3 Methods Developed for Lean Construction Scheduling

Many professionals start practicing lean construction by implementing the Last Planner system (Alves and Tsao, 2007). Last Planner is the most well-known and

powerful planning and control system among all lean construction tools (Gao and Low, 2014b).

Last Planner is a method developed by Ballard (H. G. Ballard, 2000) which is a crew level planning tool that analyzes constraints to shield weekly work assignments (Chua et al., 2003). According to Ballard, a project is considered as a temporary production system, production control enables value generation, variability should be reduced and pull techniques should be used instead of traditional push systems (H. G. Ballard, 2000). Main steps advocated by the system are to plan in more detail as getting closer to executing the work, to prepare the work plan with those that perform the work, to remove constraints for making work ready and increasing reliability, to make reliable commitments and to learn from failures (F. Hamzeh et al., 2012).

Last Planner is a production and control system. It is based on lean construction principles where waste elimination and production variability minimization are the focus. Last Planner carries out a set of actions to increase the planning reliability and reduce the negative effects of variability. Last Planner starts with a master plan which is the long-term initial project plan that identifies overall execution strategy for the project. Based on targets from the master plan, a more detailed and manageable phase schedule is formed. Then the master plan or phase schedule is detailed to create medium term look ahead plan that is provided to identify activities to be completed in the following weeks and pulls the resources into the planning process. Look ahead plan shows the work to be done in a time frame such as six weeks. Look ahead plan is more than just task breakdown, it involves making work ready and if not implemented correctly, affects the end result. Based on lookahead schedule, each planner prepares weekly workplans. The short-term work plan is generated for scheduling of the work that will be done on-site, activities are only committed to the work plan if they can be performed, based on the evaluation of specific field conditions (Gonzalez et al., 2008; Song and Liang, 2011; F. R. Hamzeh et al., 2015; V. A. González et al., 2015).

Last Planner is a creative process, so it is a form rather than a formula. It attempts to resolve unseen constraints and eliminate uncertainties to improve work plan reliability by employing pull flow. It is a method that supports the timely realization of plans. Process starts from the first principle every time and is done

collaboratively, involving the workers in the work planning since they are the ones that create value for the customer Last planners are the people that are responsible for completion of assignments (O. M. Salem et al., 2015; Mossman, 2009; Sacks and Harel, 2006; Chua and Shen, 2005).

There are 4 functions involved in the Last Planner system: should, can, will and did. Should sets the goals, can solves constraints, will stands for what is scheduled and did stands for what is executed (Zegarra and Alarcón, 2017). A lean construction metric called percent plan complete is used to measure the plan reliability. It is the measure of how much of the planned work was actually completed, calculated as completed weekly scheduled tasks divided by total weekly scheduled tasks (Mitropoulos and Nichita, 2010).

Effective implementation of the Last Planner improves production performance and reliability while the workflow variability is decreased (Ochoa, 2014). It assist in collaborative planning and improves teamwork and proves to be dynamic method that provides forward information for control (Alsehaimi et al., 2014). Implementation results in increased productivity, shortened durations and cost savings (Russell et al., 2015).

Workplan is a method developed by Choo et al. that adopts Last Planner and leads users through stages of establishing a quality weekly work plan, that represents an element of a more detailed master schedule. Work packages have constraints that should be satisfied for them to be carried out. The constraints of a work package consist of contract constraints, engineering constraints, material constraints, labor and equipment constraints and prerequisite work and site conditions. Work package is released for construction after all the constraints are satisfied. Workplan guides users through the steps of the planning process that helps the users to work more accurately (Choo et al., 1999).

Chua et al. developed Integrated Production Scheduler, a constraint-based planning tool that also handles resource and information constraints in addition to the process constraints. This model is said to simplify collecting data and reduce inconsistencies in work plans (Chua et al., 2003).

Sriprasert and Dawood developed multi-constraint modelling, which is a collaborative, multi-constraint considering construction planning methodology that effectively handles uncertainty (Sriprasert and Dawood, 2003).

Choo et al. developed DePlan which is an integrated approach in design management that has the operational approach of Last Planner. DePlan consists of design planning, scheduling, and control (Choo et al., 2004).

Dawood and Sriprasert proposed LEWIS- Lean Enterprise Web-based Information System, a 'multi-constraint scheduling' method, rooted in the Last Planner, concerning four major types of construction constraints which are physical, contract, resource and information. They developed a multi constraint genetic algorithm application in MS Project and obtained a near optimum constraint-free schedule. (Dawood and Sriprasert, 2006)

Björnfot and Jongeling proposed the application of line-of-balance scheduling in combination with 4D CAD model as a method to improve workflow management. Line-of-balance technique is resource oriented as opposed to critical path model which is activity oriented. In line-of-balance method, project is broken down in physical sections and location is considered as a dimension for simpler planning of continuous resource use. 4D CAD models link activities with 3D CAD models and allow project parties to visualize and simulate work before it is executed on site. Implementation of the model helps uncover potential problems (Björnfot and Jongeling, 2007).

Sacks et al. proposed a Building Information Modeling enabled system based on Last Planner, called KanBIM to support production planning and control on construction sites. It is a software system that provides 3D visualization of process status which increases reliability and decreases variability while enabling real time feedback (Sacks et al., 2010). The use of KanBIM eliminated substantial amount of waste and improved workflow resulting in improved productivity (Gurevich and Sacks, 2014).

Construction Owners Association of Alberta developed Workface Planning which has become a contractual requirement on most of the industrial construction projects in Alberta, Canada. Main aim of Workface Planning is to deliver all necessary resources to the right places and people at the right time to avoid cost

overruns and delays and to keep onsite supervision team away from time consuming tasks to help them focus on supervising their crews. Workface Planners help superintendents to divide works into more manageable installation work packages, sequence and integrate these packages into the project schedule, align resources and remove constraints for executing these work packages and provide support in executing and controlling the installation work packages. At the end of the projects, lessons learned are documented to enable continuous improvement (Fayek and Peng, 2013).

Kim and Kim presented a computerized integrated project management system whose foundation is a scheduling system that adopts lean construction principles. Material management is linked to a detailed production plan and the system which follows the Last Planner, integrates manpower/equipment management and safety/environment/quality information. Implementation of the system increased productivity and accurate schedule planning ability while reducing demand variability, material inventories and supplier lead time (Kim and Kim, 2014).

Heravi and Rashid developed a lean construction plan based on waste elimination. Appropriate lean construction techniques were used to reduce specified non-value added processes and the Last Planner method was improved using critical chain method as a component of the developed plan. The performance of the studied project was shown to improve 19% by implementation of the developed lean construction plan (Heravi and Rashid, 2018).

Heigermoser et al. developed a BIM based construction management tool to integrate product visualization and processes, reduce construction waste and improve efficiency and reliability that supports Last Planner system. The tool links 3D model objects with construction schedule in an automated way. Use of BIM minimizes wastes and helps in implementation of lean by involving all participants earlier in the project and treat the project as one process (Heigermoser et al., 2019).

Bortolini et al. proposed a lean production principles-based site logistics and control model supported by 4D BIM for prefabricated systems. Implementation of the model was stated to contribute to work-in-progress reduction, increase productivity and reduce assembler's walking distance (Bortolini et al., 2019a).

4.4 Implementation

Implementation of a lean construction scheduling system is a very complex process because it does not just depend on the method itself but also how the implementation is organized (Mäki et al., 2020).

A key step in implementation is constraint analysis on planned activities. Work plans are susceptible to uncertainties caused by unresolved constraints which could be anything that hinders performance (Chua and Shen, 2005). Most common constraints are precedence constraints that determine the sequence of activities, resource constraints that are related to materials, equipment, labor and space, information constraints that are related to information availability such as shop drawings, design approvals and request for information etc. and contract constraints (Chua and Shen, 2005), (Sriprasert and Dawood, 2003), (V. González et al., 2010).

Use of buffering to eliminate process variations is also important in implementation. With good planning variability can be reduced, however all variability cannot be removed. Buffers are used for providing a cushion against negative effects of variability and disruptions, if used correctly they can absorb fluctuations. They can take one of the main forms of time, inventory or capacity. Time buffers assign slack to an activity, inventory buffers provide extra stock for supply variations and capacity buffers keep extra capacity like overtime or machinery. Inventory buffers, if used at optimum levels can reduce variability and improve performance, however if used more than the optimum level it may worsen the performance (F. Hamzeh et al., 2012), (Horman and Thomas, 2005).

Top management commitment and training of staff and workers is fundamental for successful implementation of a lean construction scheduling system (O. Salem et al., 2005).

4.5 Benefits and Disadvantages

In single piece flow pull scheduling, waste of rework is eliminated and work in progress is controlled (Sacks and Goldin, 2007). According to Sacks et al. lean construction is better at meeting needs of the customers than traditional approach since pull flow eliminates rework, work in progress is reduced and dependence between work teams is removed (Sacks et al., 2007). Benefits include cost savings,

increased work quality, reduced project time and less inventory and rework (Khanh and Kim, 2016).

Implementation challenges include lack of training, lack of management commitment, resistance to change, contractual issues and partial or late implementation (Lindhard and Wandahl, 2015). Involvement of many parties, low understanding of the concept, language issues and weak communication are also some of the barriers of implementation (Khanh and Kim, 2016).

4.6 Evaluation of Lean Construction Scheduling Methods

Tommelein used pull-driven scheduling for installation of pipe-spools and stated that the pull technique improved the construction process performance, especially in highly uncertain, fast track project that require assembly of unique parts (Tommelein, 1998).

Alarcon et al analyzed 77 Chilean projects to analyze the impact of Last Planner System on project performance. Percent Plan Complete of the projects increased over the three-year period. Up to 86% improvement in productivity was measured. The reliability of planning projects was improved. In almost all projects, performance improvements were observed (Alarcón et al., 2008).

Gonzales et al. performed a detailed study on how implementing Last Planner improves planning reliability and the effect of planning reliability on project performance. Last planner implementation increased planning reliability and helped achieve more control. Positive and strong relationships were found between activity and project performances and planning reliability (Gonzalez et al., 2008).

Court et al. reported that less onsite labor was achieved, no time slippage occurred that caused delay, labor reduction was achieved, fewer workers faced lower health and safety risks, workers' wellbeing and ergonomics were improved (Court et al., 2009).

Seppanen et al. found location-based management and the Last Planner to be complementary and stated that their combination should increase schedule conformance, productivity and decrease project durations and delay chains (Seppänen et al., 2010).

Liu et al. collected 134 weeks of production data from a pipe installation project and found that Last Planner reduces workflow variability thus increases workflow reliability which is significantly correlated with labor productivity. Their results showed that the key to productivity is to focus on keeping a predictable workflow (M. Liu et al., 2011).

Wambeke et al. examined the effect of using Last Planner system together with a risk assessment matrix for task duration variation reduction or elimination. They conducted a case-study for comparing the performance of two similar projects where one used Last Planner and the other did not. The productivity performance of the project that used the Last Planner was 35% higher than the traditionally planned project (Wambeke et al., 2012).

Gambatese et al. studied the impact of lean practices on safety and found that Last Planner promotes pre-task planning which exposes potential safety hazards (Gambatese et al., 2017).

Nguyen and Akhavian evaluated the effectiveness of integrated project delivery, lean principle and building information modeling in terms of schedule performance and cost. Based on the outcomes full integration of all systems had significant effect on schedule and cost performances (Nguyen and Akhavian, 2019).

Rincon et al. examined if there was any effect of stakeholders' behavior as autonomous agents, that make decision based on their interests rather than the project's, on performance of Last Planner system. They found out that stakeholders as autonomous agents affect the performance of Last Planner (Rincón et al., 2019).

Bartolini et al. developed a logistics planning and control model based on 4D building information modeling. Their data suggested that work in progress was reduced by 61%, productivity increased, manhours spent in transportation operations were reduced by 38% and average walking distance of each worker was reduced by 88% (Bortolini et al., 2019b).

Naticchia et al. developed a lean construction based, building information modeling integrated holonic management system, made up of holons which are autonomous software entities that can interact and respond to changes quickly for real time construction management automation. It was designed to automate the real time

management of operations, to deal with flows and resources and dependencies rather than just sequencing activities (Naticchia et al., 2019).

The main reason for the success of the Last Planner is the way it manages commitments. The use of Language-Action Perspective, which assumes that an organization works through successful management of small transactions, shows the importance of mutual understanding. Lack of two-way communication results in plans that do not match with the crew capacities (Viana et al., 2017).

Viana et al. propose that Language-Action Perspective, which is a way of representing an organization's commitment network where human work is considered as a commitment network, is suitable to explain the communication mechanism in short term planning meetings of Last Planner. It is concluded that two-way communication plays a vital role in mutual understanding and is important in obtaining plans that match the work force capacity (Viana et al., 2011).

Slivon et al. list commitments as a category of participants in the construction process. Commitments are composed of design and specifications, agreements, decisions, instructions, and external conditions-socially constructed reality. They state that in the Last Planner system weekly planning sessions participants make commitments and as they work to fulfill these commitments, they build trust with each other. With the trust, reliability and chances of success increases (Slivon et al., 2010).

Ghosh et al. studied social interaction patterns of participants of two construction projects, one implementing the traditional system (A) and the other one implementing the Last Planner (B). Participants of project B had a higher shared understanding about the project, were more cooperative, had a higher level of trust in each other and had higher involvement in decision making. Exchange of commitment was seen to be an important component of project B (Ghosh et al., 2019).

Castillo et al. analyzed the relationships between social network properties, Last Planner practices and construction project performance and concluded that higher implementation of the Last Planner system results in better performances. Although high connectivity between the members of an organization improves performance, this connectivity is required to be horizontally distributed, avoiding excess

centralized leadership. Command and control philosophy is a threat to the possible benefits of the Last Planner (Castillo et al., 2018).

Priven and Sacks studied twelve residential projects to measure the impact of the Last Planner and found that implementation of the system strengthens social networks and communication. It results in the establishment of social network connection in different groups where no or little connection would have been established without it (Priven and Sacks, 2015).



INTEGRATION OF DIGITAL TECHNOLOGIES AND DIGITAL TWIN

This section covers integration of digital technologies, interoperability and semantics communication, implementation of digital technologies in construction, relationship between digital technologies and lean construction, digital twin concept and its relationship with construction and lean construction and its application and benefits, opportunities, costs and risks associated with digital twins in lean construction.

5.1 Background

Integration can be divided as the integration of people and processes and integration of systems. To achieve the integration of people and processes, integration of systems is necessary (Hassan Ibrahim, 2013). An integral solution for management of construction projects is enabled by BIM with acquisition of construction data throughout their life cycle. The data collected is combined into a single model that is used by project participants as an information depository (Andújar-Montoya et al., 2020).

One of the most pertinent uses of BIM is supporting decision making in construction phase by identifying possible problems that may affect project performance in terms of cost, time, and safety through 4D models (Bortolini et al., 2019b).

Benefits can be grouped as preconstruction, design, construction, and post construction. Preconstruction benefits are cost, feasibility and design evaluation, performance, quality, and collaboration. Design benefits are visualization, automatic corrections, consistency, collaboration, cost estimation, energy efficiency and sustainability improvement. Construction benefits are quick reaction to changes, using the model as a basis for fabrication, early error discovery, synchronization of design and planning, better implementation of lean construction techniques and synchronization of procurement with design and construction. Post construction benefits are improved commissioning, integrated and improved facility operation and management (Sacks et al., 2018).

BIM encompasses the beginning point of digital construction site support by being a representative of digital twinning and thus an enabler of Industry 4.0 ideas (Schimanski et al., 2019).

Main purpose of BIM adoption is to enhance various aspects of construction design and management process such as waste minimization, supply chain assessment, offsite manufacturing etc. by effective communication, coordination, collaboration, and information management throughout the life cycle (Gbadamosi et al., 2019).

BIM enables application of different simulations and analyses which could help designers and planners to get rapid feedback at the design stage to interfere earlier than possible in traditional processes (Sacks et al., 2016). Implementing BIM successfully should both involve technical and managerial aspects (Jin et al., 2019). BIM is integrated to digital technologies such as Internet of Things (IoT), geographic information systems (GIS), radio frequency identification (RFID), laser scanning, cloud computing, virtual reality, augmented reality, mixed reality, blockchain, big data and 3D printing (Jin et al., 2019), (Aleksandrova et al., 2019), (Wong et al., 2018).

GIS integration has potential in applications such as managing planning process during design and preconstruction, enhancing site collaboration, information sharing and facilitating more efficient construction supply chain management (Jin et al., 2019), (Deng et al., 2019).

Integration of IoT with BIM has many promising possibilities one of which is the creation of a more realistic digital twin which is a virtual representation of components, construction processes and maintenance operations of a building through real time data streams throughout the lifecycle of the facility (Shahinmoghdam and Motamedi, 2019). BIM model can be connected to IoT through sensors to monitor the construction progress during construction or to connect the building to various systems to integrate energy and other disciplines after construction, during facility management (Aleksandrova et al., 2019), (Nykänen et al., 2017).

Integrating RFID, which is also considered as an enabling technology for IoT, has potential in applications such as security, safety, worker logistics, real time traceability and quality control (Jin et al., 2019).

Integrating virtual, augmented or mixed reality solutions with BIM allows quick digitalization of a BIM model for interactive experience (Aleksandrova et al., 2019).

Integrating blockchain with BIM improves cybersecurity, trust and protect intellectual property rights (Nawari and Ravindran, 2019). Blockchain can also enhance integration of BIM with IoT networks by increased cybersecurity, reliability and transparency (Lokshina et al., 2019).

Integration of digital technologies with BIM improves the quality of management of processes and facilitates decision making (Aleksandrova et al., 2019). Successful integration of BIM makes it viewed as an environment rather than a tool or a platform.

5.2 Interoperability and Communicating Semantics

Interoperability increases collaboration between team members and reduces the time needed to develop a building (Rakib et al., 2019). BIM interoperability is held back by contractual issues rather than technology (Amoah and Nguyen, 2019). Interoperability remains an important issue for the construction industry because of the collaborative nature of BIM. Exchange of information among companies and different disciplines makes interoperability a big issue (Steel et al., 2012).

Collaborative nature of BIM calls for interoperability which traditionally relies on file-based exchange formats, direct link based on Application Programming Interfaces or a common data environment called a BIM server where collaborative management is allowed at the building object level rather than at a file level (Sacks et al., 2018). For BIM tools to work together ability to transfer meaning is also needed besides ability to transfer information, meaning semantic interoperability is needed (Amoah and Nguyen, 2019). Semantic interoperability can be handled methodologically or technically by defining consistent modeling styles or by defining ontologies that enable transformation (Hu et al., 2016).

Interoperability is provided at the highest level by semantic interoperability since meanings are attached to conventional concepts. The key is to make sure during data transfer the relationship between different disciplines are maintained with minimum human intervention. Different semantic technologies exist such as

semantic web, artificial intelligence, classification and data mining (Karan and Irizarry, 2015). Semantic web was introduced in 2000's with the goal to turn current web into a web of data where the basic idea was to add semantic metadata to existing data so the meaning of data could be processed by machines. Web Ontology Language (OWL) and the Resource Description Framework Schema (RDFS) are the most frequently used semantic web languages to build ontologies. Semantic web technologies can be used to integrate and connect building component description information that can be read by BIM applications (Costa and Madrazo, 2015).

BIM's initial role was to exchange knowledge between design and construction phases but through research BIM's application extended over the lifecycle of the project, it evolved to include semantic information related to systems, processes and actors, integrating sensor data and artificial intelligence (S. Howell et al., 2017). Semantics of a building component are made up of its function, form and behavior which are represented by its shape, material properties, mechanical properties, functional classification, topological relationships, and aggregation relationships (Belsky et al., 2016).

Semantic enrichment development for models is stimulated by interoperability issues which hinders the use of BIM. Semantic enrichment improves the functionality of BIM (Sacks et al., 2017) by linking across different domains (Pauwels et al., 2017). Ideally the information from the models created in individual BIM applications could be easily shared and used, however there are some challenges due to the information being stored in native format of the application being used. Industry foundation classes product data model was developed specifically to support interoperability but because of the inadequacy in reliable data exchange, model view definitions were developed (Belsky et al., 2016).

BIM based construction management is growing and in theory the information needed can be obtained from BIM automatically. However, if the information contained in BIM is not full, the obtained information will remain very limited (S. K. Lee et al., 2014). Successful exchange is possible when semantically required description of each object is included in the exchange (Eastman et al., 2010). It is semantics that identifies the meaning of information and with it importing

application can create objects in its own schema with minimal effort by matching the semantics to predefined definitions (Venugopal et al., 2012).

5.3 Implementation of Digital Technologies in Construction

Effective implementation of digital technologies requires significant alterations in the way a construction company works and should have a bottom-up approach rather than a top down one to engage people in adoption, to improve people's skills and understandings, to manage change successfully and to minimize any potential change resistance (Arayici et al., 2011).

Since the early 2000s, BIM has had significant impacts on AEC industry stakeholders. Considering the slow pace and fragmented structure of the construction industry, BIM adoption is not completed in the industry, however public and private owners across the world increasingly mandate BIM use. BIM adoption entails demand for people with new skills and development of new management roles. automated code conformance and constructability checking, construction management functions, prefabrication encouragement, linking virtual BIM world to physical construction world via peripheral hardware and robotic construction are the most common technology trends in BIM. According to bibliometric study conducted by Xiao et al., combining virtual reality and augmented reality with BIM to address information retrieval, productivity and efficiency is a surfacing issue and they are also linked to lean construction by various nodes. They concluded that the ultimate goal of BIM is to “integrate physical smart objects and informational components to form situation integrated analytical systems which can respond intelligently to dynamic changes of real-world scenarios and offer data oriented lean solutions” (X. Li et al., 2017). Features of BIM in 2020s are lean construction integration, increased off-site production, construction automation, 3D printing, automated data exchange and virtual reality - augmented reality application usage. Features of BIM in 2030s are automated data processing, automated production, big data, IoT-based manufacturing and management, AI based design and engineering, automated data exchange and integration of BIM, GIS and smart cities (Sacks et al., 2018).

Ratajczak et al. state that BIM based construction management platforms allow participants to manage construction works and documents and monitor progress by

visualizing the 3D model. Increasing process automation by augmented reality can provide access to information in real time and improve decision making. They proposed a BIM based augmented reality application that is combined with lean construction practices called AR4C which helps site managers to automate their daily work and improve performance (Ratajczak et al., 2019).

Corneli et al. proposed an Augmented Reality (AR) system to enable information retrieval on-site and avoid information loss. The technician interacts with the real world and digital information contained in the BIM through a Head-Mounted Display AR interface. The objects in user's field of view and their placement in BIM is automatically recognized by a trained Deep Learning Neural Network. Tests were applied to fire extinguishers in a building and 45% of them were recognized by the system (Corneli et al., 2019).

Natephra and Motamedi developed a method to visualize live sensor data such as indoor air temperature, light intensity, and humidity captured by IoT agents in the AR environment which was built upon and stored in the BIM model (Natephra and Motamedi, 2019).

Lin et al. developed a real time 4D AR system for monitoring the progress of modular construction. The system compares the 4D BIM data linked as-designed AR model with the as-built ones. They validated the system with a scale model mockup components and stated that the system can help users in assembly sequence monitoring and schedule control (Lin et al., 2019).

Sacks et al. developed a BIM enabled construction project management software system based on Last Planner and stated that requirements for such a system are visualization of process, product and method, computation and display of work package and task maturity, support for planning, negotiation and commitment, pull flow control implementation and maintaining of workflow and plan stability (Sacks et al., 2010).

Although developed from individual conditions, BIM and lean construction share common concepts in implementation. BIM enables transparency collaboration and project process integration. BIM models can be used as a Kanban for production system and aid in reliable decision making through predictive information rather than descriptive information (Ma et al., 2018).

Reducing variability, reduces rework, helps dealing with complex products, enables stakeholders to participate in design and decision making, increases efficiency of design validation, increases efficiency of problem solving, increases consistency, improves performance, helps in early identification of issues etc. which shows that BIM and lean have a strong synergy (Sacks et al., 2010b).

5.4 Digital Technologies and Lean Construction

Many researchers explored the relationships between lean construction and different aspects of various digital technologies in construction.

Sacks et al. developed a matrix that shows the interactions between BIM functionalities and lean construction principles by analyzing evidence from previous practices and/or research. They identified 56 issues which implied BIM usage should be considered for enhancing lean outcomes and suggested their parallel adoption in small steps (Sacks et al., 2010a, b).

Dave et al. proposed an IoT integrated communication framework and explored opportunities and challenges from lean construction management perspective. Opportunities are listed as tracking resources, production planning and control and automated procurement; and challenges are listed as integration with other systems, consumption of information, information overload, technical challenges and training and motivation (Dave et al., 2016).

Saieg et al. conducted a systematic literature review to understand the synergies between and propose a way in which BIM, lean construction and sustainability coexist and complement each other. They identified the benefits, challenges, and problems in their integration. It is stated that the interactions between new information technologies and production systems enable more complex and better sustainable development of construction (Saieg et al., 2018).

Dallasega et al. proposed a construction planning and monitoring approach with real-time capability. Benefits of the proposed approach are listed as decentralized planning (pull principle from lean), reduction in lead time and stock, just-in-time and on demand delivery of made to order components, a self-control mechanism that supports project management and use of process templates in planning (Dallasega et al., 2018).

Terreno et al. studied the synergistic potential of a lean approach and BIM implementation in facilities management through an integrative literature review to explore challenges and barriers faced in implementation and potential of a proactive lean approach to counter them. The challenges are listed to stem from three main categories which are people, process and technology and these challenges are stated to necessitate to be addressed by a lean approach. Opportunities for a lean synergy with BIM facility management are stated to be in two ways which are detection and control of variability on project level by lean six sigma methodologies application and identification and elimination of waste in each process value stream on operational level by value stream analysis application (Terreno et al., 2019).

Sacks et al. proposed a digital twin construction information system workflow. They state that digital twin construction incorporates Plan-Do-Check-Act cycle using real-time feedback from monitoring technologies, archived information, and machine learning tools to which lean continuous improvement practices can and should be applied. Barriers to implementation listed are need for progress in AI tools, semantic enrichment of BIM models and their accessibility to machine learning tools and difficulty in change of traditional practices and workforce. Key areas identified to bring digital twin construction to fruition are improvement in data interpretation, appropriate data storage, analysis systems and business models (Sacks et al., 2020a).

The interest in potential applications of digital technologies in construction increased with the increasing complexity in projects. These studies show that there are strong interactions between lean construction and digital technologies. Digital twin can enable construction stakeholders to collect realtime data in an automated way through sensors and IoT and use this data to simulate different scenarios and perform advanced analysis and serve as a medium to visualize, simulate, manifest, observe and control the physical asset to achieve more efficient, effective, and safer construction projects (Pishdad-Bozorgi et al., 2020).

Concurrence of lean principles and all these innovative digital technologies which are brought together under the umbrella of digital twin shows that their combined use can make an impact on construction industry.

5.5 Digital Twin Concept and Fundamentals

Digital Twin is defined by interaction and union of the digital and physical worlds. On one side the physical item can be made more intelligent to adjust its behavior to virtual item's simulation actively in real time, on the other side virtual item can be made more realistic to show the physical item's real states (Tao et al., 2020).

Digital twin is defined as a form of cyber physical system that integrates components between virtual and physical spaces and interconnects them. Cyber physical systems are composed of physical and digital systems where a strong integration and coordination among virtual resources and physical components or processes are supported. Their operations are monitored, controlled, coordinated and integrated through computing and communication. Virtual resources are composed of sensing technologies, digital models, applications etc., whereas physical components can include physical resources or processes etc. (Olatunji and Akanmu, 2015). Five levels of cyber physical systems can be seen on Figure 5.1.

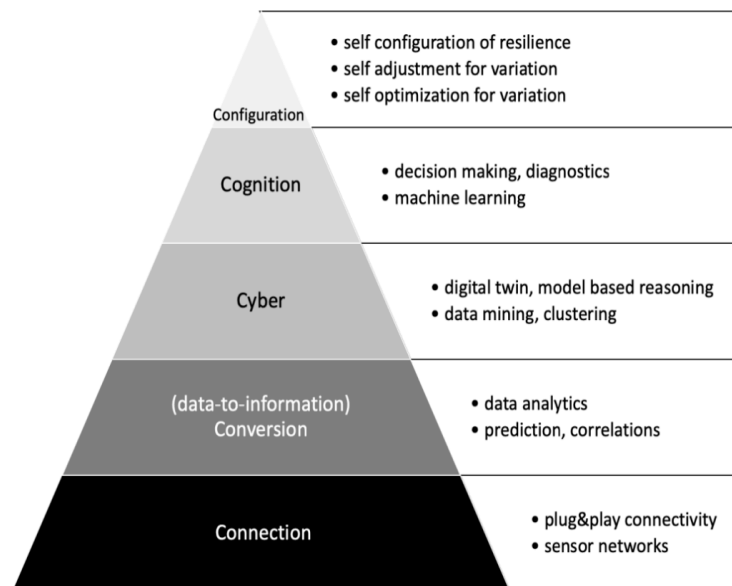


Figure 5.1 Five levels of cyber physical systems (J. Lee et al., 2015)

The smart connections level includes plug and play devices and sensor networks. Data collections and transfer should be as straightforward as possible. Data-to-information conversion layer includes processing of data collected in the previous level to use for forecasts, decision making support, correlations and statistics. Key concept in cyber level is digital twin, digital representation of a physical world

object where the data and analyses from previous layers are put into use. In cognition level, learning is taken a step further and artificial intelligence is made use of. Configuration level includes autonomy where self-learning autonomous cyber systems can respond to environment intelligently (J. Lee et al., 2015).

Twin concept came from Apollo program of National Aeronautics and Space Administration where a twin of a spacecraft launched into the outer space remained on earth during the mission to mirror flight conditions. Digital twin is the realistic virtual model rather than the same physical entity, it contains a physical asset's all the functions and states. (Tao et al., 2020). Digital twin was originally used in manufacturing industry to improve manufacturing process and monitor product lifecycle (Brilakis and Haas, 2020).

Digital twin is a form of cyber physical system that integrates components between virtual and physical spaces and interconnects them. Although there is not a commonly accepted definition for digital twin, it refers to a dynamic virtual model of a physical asset, process or a system through the involvement of IoT devices and information feedback from people. It is the interaction and union of the digital and physical worlds. The definitions all consider digital twin as a dataset representing the state of a system and its development over time (Chevallier et al., 2020; Kan and Anumba, 2019; Lu, Parlikad, et al., 2020b; Rasheed et al., 2020; Tao et al., 2020). Centre for Digital Built Britain's definition of a digital twin is "a realistic digital representation of assets, processes or systems in the built or natural environment" (Bolton et al., 2018). Boschert and Rosen define digital twin as a specific form of cyber physical system that refers to a near-real time digital replica of a component, product or system, which includes all information that could be useful throughout all lifecycle phases (Boschert and Rosen, 2016).

Three components that make up a digital twin are the physical entity, digital model that accompanies the physical entity throughout its lifetime and the connection that enables exchange of data between the two (Tao et al., 2020).

As seen in Figure 5.2, system connects physical and digital worlds by processing and integrating complex information from networked physical elements so that the physical world can be perceived, directed and controlled (Kline and Turk, 2019). Under optimal conditions, Digital twin will be identical to the physical asset in

terms of appearance and behavior with additional benefit of ability to predict (Rasheed et al., 2020). Although there is no commonly accepted one, all definitions consider digital twin as a dataset representing the state of a system and its development over time (Chevallier et al., 2020; Lu et al., 2020a).

Digital twin add value by enabling real-time monitoring and control, improved efficiency and safety, predictive maintenance and scheduling, risk assessment, improved synergy and collaboration, improved decision support and improved communication (Kan and Anumba, 2019; Rasheed et al., 2020) which also support lean practices by reducing waste, increasing value, transparency and visualization, supporting continuous improvement, developing people and improving production control.

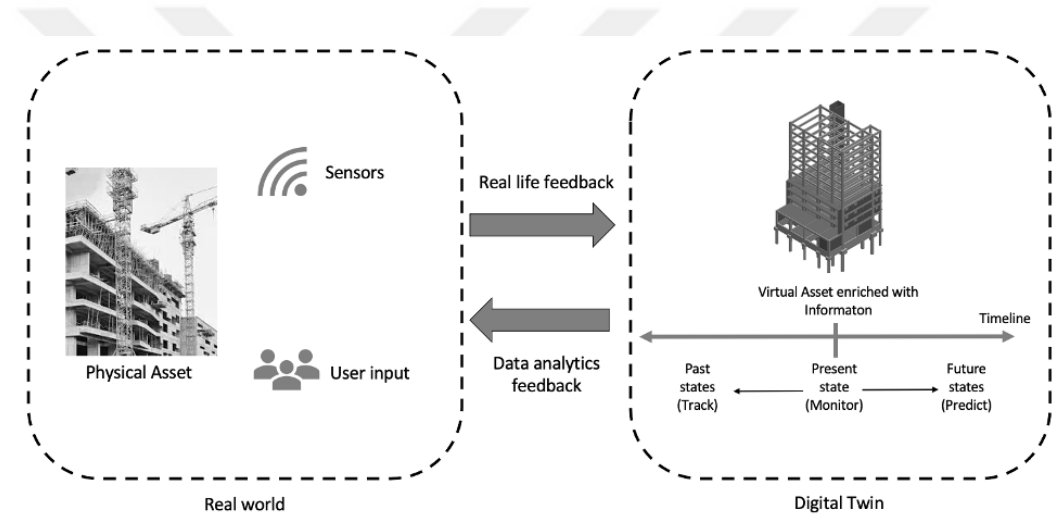


Figure 5.2 Characterization of digital twins

Technological requirements of digital twins can be analyzed at three levels which are device level, platform level and system level. Requirements at devices level are: connectivity, data exchange, identifiers and human interaction. Requirements at platform level are: inter-platform interoperability, connectivity, BIM integration, privacy and cyber-security. Requirements at system level are autonomy, real-time, reliability, time management, integration, resources optimization and adaptability (Anumba and Roofigari-Esfahan, 2020).

Digital twins have a bi-directional approach architecture based on four layers. The sensing layer is composed of data collection technologies and sensors. This layer provides access to sensed data and enables information entry through user interface. Communication layer enables data processing and communication. This layer

converts sensing layer data into formats that can be read by contents and application layer. Contents and application layer is composed of database and control applications. In this layer, information such as project management data is stored and analyzed and continuously updated with data collected from communication and actuation layers. Actuation layer contains digital prototype that is accessed through the user interface or through a mixed reality environment, where critical information for decision making or physical control of the physical environment can be provided through actuators (Sawhney et al., 2020).

Digital twins are able to mine hidden patterns and predict future trends about usage, failure and service, by the collected data from the whole product life cycle that is tracked, transformed, stored and processed by virtual models that accompany physical entities. It provides conceptualization, comparison and collaboration (Tao et al., 2020). Digital twin concept reinvents the way assets are planned, delivered, operated, maintained and managed due to its data analytics and decision-making capabilities (Lu, Xie, et al., 2020).

5.6 Digital Twins in Construction

In construction industry, digital twins are used to manage, plan, predict and demonstrate building, infrastructure or city assets (Lu, Xie, et al., 2020). In most digital twins, the starting point is a 3D model constructed by a 3D scan or a specialized software. Supplying data from the physical asset is the next step which is usually done through sensors installed on the physical asset. Improvement in quality and compression of data is essential for correct working of the digital twin. Safety and transparency of transferred data should be provided, and the collected data should be analyzed where AI plays an important role. Fast and effective communication between human and the machine is vital where augmented reality and virtual reality are considered to play an important part (Rasheed et al., 2020).

Different types of digital twins exist for different phases of a project: as-designed digital twin defines an asset's intended function, as-built digital twin reflects an asset's phase during its construction and as-is digital twin can be used for maintenance and operations (Brilakis and Haas, 2020).

Requirements of digital twins in construction include real time capability where construction activities can be monitored in real time, adaptability where the system can adapt to changes and uncertainties, being networked where an effective network of information between parties involved is provided, predictability where state of construction processes and resources are able to be qualitatively and quantitatively predicted, human in the loop where the system is instinctive and incorporates construction environment and behaviors of workers and reliability where the system is expected to function with high degree of accuracy (Sawhney et al., 2020). Construction progress monitoring through digital twin systems should include data collection, progress monitoring, activity monitoring and reporting (Anumba and Roofigari-Esfahan, 2020).

Technologies to capture as is or as built progress are radio frequency identification (RFID), photogrammetry, Lidar, laser scanning technologies, global positioning system (GPS), wireless sensor networks (WSN) and computer vision. Computer vision is an interdisciplinary area that trains a computer to translate and comprehend visual data through high resolution images or 3D point cloud models (Sawhney et al., 2020; Pučko et al., 2018).

The types of data or parameters that are shared between the physical and digital twins can be listed as form, functionality, health, location, process, time, state, performance, environment, and qualitative parameters (Jones et al., 2020).

5.7 Digital Twins and Lean Construction

Lean construction and digital twins in construction are two independent concepts; however adoption of digital twins in lean construction can increase the impact of lean practices by certain functionalities offered by digital twins that support lean construction. Digital twins add value by enabling real-time monitoring and control, improved efficiency and safety, predictive maintenance and scheduling, risk assessment, improved synergy and collaboration, improved decision support, product and service personalization and improved communication (Kan and Anumba, 2019; Rasheed et al., 2020; Tao et al., 2020) which also support lean practices by increasing value, reducing waste, increasing transparency and visualization, supporting continuous improvement, developing people and improved production control. Digital twins offer a solution to bring together lean

thinking, computing and monitoring technologies in construction. Functionalities offered by digital twins that support lean construction can be listed as follows:

Visualization: Visualization of design, construction platform and processes through integrated models helps stakeholders from different backgrounds visualize the project as a whole and enhances coordination, co-creation of policies and solutions, and proactive decision making. Operations can be prioritized, potential scheduling problems can be avoided, procurement process can be facilitated, clash detection can be improved, future problems can be foreseen more easily resulting in cost savings and waste reduction. By the dynamic visualization of construction conditions as built documentation can be formed, and quality, health and safety, and cost management can be improved. Comprehensive integrated models enable simulations and analyses to be performed as a whole, make knowledge discovery possible and enhance coordination (Sacks et al., 2020a; Kan and Anumba, 2019; Natephra and Motamedi, 2019; Lin et al., 2019; Olatunji and Akanmu, 2015; Sawhney et al., 2020; Rommetveit et al., 2019; Novack, 2019; Kaewunruen and Lian, 2019; Hlady et al., 2018; Khajavi et al., 2019; Xu et al., 2018; Pan and Zhang, 2021; Boje et al., 2020; Anumba and Roofigari, 2020).

Collaboration: Collaboration in real time enables qualified engineering, co-creation of sustainable solutions by different stakeholders, integration of various information from different parties which facilitates standardized processes, workflow, transparency, coordination and efficiency (Kan and Anumba, 2019; Olatunji and Akanmu, 2015; Sawhney et al., 2020; Novack, 2019; Kaewunruen and Lian, 2019; Pan and Zhang, 2021; Anumba and Roofigari, 2020).

Communication: Communication in a rich real-time manner allows for up-to-date real time information sharing, feedbacks, transparency, enhanced coordination, and increased learning. The formed sharable information platform can facilitate process standardization, enhance workflow, increase efficiency, enable collaborative ways of working and strengthen cooperation, resulting in waste reduction (Kan and Anumba, 2019; Lin et al., 2019; Novack, 2019; Kaewunruen and Lian, 2019; Hlady et al., 2018; Pan and Zhang, 2021; Anumba and Roofigari, 2020; Turner et al., 2021).

Prefabrication facilitation: Facilitation of pre-fabrication enables avoidance of potential schedule problems, correct positioning, and sequencing of components. Automation is possible through sensorized and wirelessly connected intelligent assets (Lin et al., 2019; Turner et al., 2021).

Decision making support: Data driven decision making based on robust and accurate data enables performance prediction, accurate estimation of costs and technical issues, ability to sustain same attitude throughout project life and early modifications. Decision making can be more proactive than reactive which helps improve workflow, save money and time (Sacks et al., 2020a; Kan and Anumba, 2019; Lin et al., 2019; Olatunji and Akanmu, 2015; Kaewunruen and Lian, 2019; Xu et al., 2018; Pan and Zhang, 2021; Boje et al., 2020; Anumba and Roofigari, 2020; Turner et al., 2021).

Schedule control: Schedule control in a real time manner enables checking task maturity and supports production control. Waste is reduced by decreased waiting, excess work, and material waste. Bottleneck diagnosis, progress prediction and proactive modelling is enabled resulting in increased efficiency, time and cost savings (Sacks et al., 2020a; Kan and Anumba, 2019; Lin et al., 2019; Olatunji and Akanmu, 2015; Rommetveit et al., 2019; Novack, 2019; Kaewunruen and Lian, 2019; Xu et al., 2018; Pan and Zhang, 2021; Boje et al., 2020; Anumba and Roofigari, 2020; Turner et al., 2021).

Enhanced site sensing / live data / progress monitoring / real-time monitoring: Enhanced site sensing enables real time site state, progress, quality and safety monitoring, real time problem identification and assessment, and supports production control. Increased access to verifiable and traceable data results in improved analytics, transparency, improved optimization, performance, efficiency, risk identification, quality, and safety. Labor can be monitored so that human error and non-productive time are reduced. Consistency with plans and specifications are ensured. Tracking material allocation and equipment utilization enhances optimization and constraint removal. Accuracy in data collection facilitates decision making, supports learning for better planning, estimation and managing enabling time and cost savings (Sacks et al., 2020a; Kan and Anumba, 2019; Natephra and Motamedi, 2019; Lin et al., 2019; Olatunji and Akanmu, 2015; Sawhney et al., 2020; Rommetveit et al., 2019; Hlady et al., 2018; Khajavi et al.,

2019; Xu et al., 2018; Pan and Zhang, 2021; Boje et al., 2020; Anumba and Roofigari, 2020; Turner et al., 2021).

Application of AI / big data / improved assessment / simulation: Real time data collection provides a database and historical log that can be analyzed through AI, big data and simulations to assess different process variables, discover knowledge to improve design and performance of current and future projects, improve analytics for integrity and regulatory concerns, assess and estimate schedules and costs, assure values and trends are as expected, predict performance, manage safety, risk and quality. Digitalization and intelligence of construction project management is facilitated (Sacks et al., 2020a; Kan and Anumba, 2019; Natephra and Motamedi, 2019; Olatunji and Akanmu, 2015; Sawhney et al., 2020; Rommetveit et al., 2019; Novack, 2019; Kaewunruen and Lian, 2019; Hlady et al., 2018; Xu et al., 2018; Pan and Zhang, 2021; Boje et al., 2020; Turner et al., 2021).

Off-site review / remote access: Remote access enables best work to be done at any time without bureaucratic hassles and moving people, resulting in time and cost savings, efficiency in decision making and project control processes (Olatunji and Akanmu, 2015; Novack, 2019; Hlady et al., 2018; Xu et al., 2018).

Automation: Automation can improve efficiency, supply chain, susceptibility to human errors, simplify data processing, enhance cost and health and safety management (Kan and Anumba, 2019; Olatunji and Akanmu, 2015; Hlady et al., 2018; Xu et al., 2018; Pan and Zhang, 2021; Tetik et al., 2019).

Considering the lean construction principles listed in sections 2 and 3, the interaction of functionalities offered by digital twins that support the application of these principles and lean practices can be seen in Figure 5.3. Bringing virtual and physical world together through sensors, IoT instruments, improved analytics, AI and real-time experiences, DT concept reinvents the way assets are planned, delivered, operated, maintained and managed (Quichen et al., 2019). The interactions between LC and DT show that there is a strong connection between them. Since it is important for all project participants to be aware of important project details and use information adequately to create a learning cycle, lack of information, effective communication and transparency are important barriers in application of LC methods (Alarcon et al., 2005) which also effect the rigorous

planning process causing participants to spend too much time (Viana et al., 2010). Although DT have many benefits and opportunities to offer for LC to overcome these barriers, there are also some costs and risks involved in applications of DT as new digital technologies can disrupt traditional practices through uncertainties and the need of changes in business models (Lavikka et al., 2018).

		<u>Lean Construction Principles</u>														
		Waste reduction	Value increase	Variability reduction	Cycle time reduction	Inventory reduction	Continuous flow and increased flexibility	Increased transparency and visualization	Focus on complete process	Continuous improvement	Benchmarking	Pull system	People	Production control	Safety and quality control	Pre-fabrication
		P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
<u>Digital Twin Functionalities</u>	Visualization F1	X	X	X		X	X	X	X	X		X	X		X	
	Collaboration F2	X	X	X	X		X	X		X		X	X	X		
	Communication F3	X	X	X			X	X		X		X	X	X		
	Prefabrication facilitation F4	X		X	X	X	X									X
	Decision making support F5	X	X	X			X		X	X		X	X			
	Schedule control F6	X	X			X	X		X	X		X		X		
	Enhanced site sensing / Live data F7	X	X	X	X	X	X	X	X	X		X	X	X	X	X
	AI application / Big data / Simulation F8	X	X	X		X	X	X	X	X	X			X	X	
	Off-site review / Remote access F9	X					X						X			X
	Automation F10	X		X			X							X	X	X

Figure 5.3 Lean construction – digital twin interaction

5.8 Application

Smart services enabled by a digital twin can be listed as: enhanced site sensing, automated site progress monitoring, real time data visualization, increased AI application, site safety detection, BIM clash detection simulation and optimized site scheduling and logistics (Boje et al., 2020).

Mayani et al. presented how an oil drilling operator implemented a digital twin system. Digital twin simulated the well and the system contributed to increased safety, efficiency, and early detection of problems (Mayani et al., 2020).

Lu et al. developed a digital twin enabled anomaly detection system that interchanges and interoperates external data related to each BIM object in the digital model to detect anomalies of building assets. The developed system is stated to be

useful in daily operations and management and contributes to automated asset monitoring (Lu et al., 2020b).

Khajavi et al. presented a study that used external sensor network light, temperature and humidity data on a limited digital twin of a façade element and stated that the framework developed could be used to develop a comprehensive digital twin of the building façade and interior (Khajavi et al., 2019).

Ye et al. presented a study where they created digital twins of two bridges in Staffordshire, UK for structural health monitoring. Stated key benefits are efficient query of relevant data, integrated capabilities of data processing and interpretation and collaborative environment (Ye et al., 2019).

Kaewunruen and Lian developed a 6D BIM based digital twin of a railway turnout system which was established over the integrated lifecycle from the planning design to the demolition stage. They stated that the digital twin helped stakeholders to visualize, enable collaboration, improved co-creation of policy and sustainability improvement solutions among stakeholders and promoted cleaner production and maintenance policy (Kaewunruen and Lian, 2019).

Hlady et al. presented a low-cost LiDAR technology application for digital twin creation of a pipeline construction so that any asset's condition at any time can be accurately traced. They mounted a drone platform on a side boom that was constructed on a truck and used LiDAR imagery together with GPS system to create a digital twin of a pipeline during construction. The digital twin is stated to facilitate construction team's job by providing a methodology and to make meeting quality targets and managing costs easier. Time to corrective action was reduced dramatically, operations and integrity were improved, health and safety practices were supported, and efficiency of field inspection was increased (Hlady et al., 2018).

5.9 Benefits, Opportunities, Costs and Risks Associated with Digital Twins

Digital twins give the ability to collect and analyze data on different scales, enabling higher efficiency and safer environment at reduced costs (Kan and Anumba, 2019). Sacks et al. explored digital construction innovations within past 5 years to identify

opportunities and challenges of applications. They set out a range of potential applications and implementation challenges for digital construction innovations (Sacks et al., 2020b). El Jazzer et al. outlined the applications of digital twins in terms of perceived benefits, challenges, and requirements through an extensive literature review. They concluded that although the construction industry is showing an effort to move beyond digital model, digital twin is not fully accomplished yet. Using the knowledge captured in digital twin to improve future construction projects is the long-term benefit of the concept (El Jazzer et al., 2020). Sacks et al. proposed a workflow framework for a datacentric construction management system based on digital twin applied in a lean closed-loop planning and control system. They mentioned certain potential benefits and barriers, benefits mainly arising from better situational awareness and barriers mainly arising from technical issues (Sacks et al., 2020a). Rasheed et al. reviewed current digital twin construction methodologies to show value of digital twin, its enabling technologies and challenges for different stakeholders. They concluded that digital twin concept offers more informed decision-making through data-driven modeling and has technological challenges related to digitalization, big data, security and automation (Rasheed et al., 2020). Bosch-Sijtsema et al. explored the current usage and future trends of digital technologies in construction through literature review and online survey. They discussed the opportunities, barriers and use of these digital technologies for different stakeholders to give a guidance to what measures and capabilities are needed for their implementation in the following 5–10 years (Bosch-Sijtsema et al., 2021).

Digital twins offer the opportunity to produce new knowledge by allowing AI to learn and take decisions, spot trends and anomalies and trigger risk warnings of time, cost, health and safety and performance. Through increased visualization and real time data management can be supported in proactivity and informed decision making which can result in the opportunity to reduce time, cost, space, work and material wastes. Information generated through monitoring and analyzing capabilities of digital twins can be used for reduction of non-value adding activities, optimizing processes and flow, increasing generated value and continuous improvement of the processes. Through the use of the system as a communication, coordination and collaboration tool, increased synergy between teams is possible

leading to improved productivity. System has a potential for transition of certain human expert tasks to digital twin platform, allowing for automation and remote operations (Anumba and Roofigari-Esfahan, 2020; Boje et al., 2020; Hlady et al., 2018; Olatunji and Akanmu, 2015; Turner et al., 2021).

Bringing virtual and physical world together through sensors, IoT instruments, improved analytics, AI and real time experiences could play an important role in creation of smart cities and contribute to well-being, security and solution of natural issues (Augustine, 2020). Increased use of the technology may promote digital twins to serve as management systems that rely on rich real time data, increased visualization of design and processes and that promote proactive management, advanced analysis and effective decision making.

There are also some costs and risks involved in the applications of digital twins. System components consisting of hardware and software, data collection and processing, maintenance of system components, disruption to other critical operations that need computing resources which may be reduced by system's usage and energy supply and consumption are listed as main costs associated with digital twins (Bevilacqua et al., 2020; Hlady et al., 2018; Lu, Parlikad, et al., 2020a; Lu, Xie, et al., 2020; Omer et al., 2019).

Being a cyber physical system, cyber security is an important issue in digital twin systems. Cryptography and blockchain technologies could be used to address security and privacy issues. Interoperability of the integrated systems is another important issue as well as dependability and sustainability which could be enabled by hybrid modelling, communication technologies, artificial intelligence, cloud computing and computational infrastructure. Interaction with the physical system could be improved by augmented and virtual reality (Rasheed et al., 2020).

Being a multi component system, choosing appropriate technologies, system integration, accuracy, quality and storage of collected data are important (Bevilacqua et al., 2020; Hlady et al., 2018; Lu, Parlikad, et al., 2020a; Olatunji and Akanmu, 2015; Omer et al., 2019; Wu et al., 2019). Workforce competency and training can also be challenges faced in the construction industry (Sawhney et al., 2020).

Many studies consider sensing an important ability of a digital twin. The main challenge of using sensors with a digital twin is the sensor dynamics; successful integration, resolution, reading accuracy and frequency and locations (Boje et al., 2020). The data collected by sensors needs semantic enrichment for AI tools and interoperability between systems (Boje et al., 2020). Lack of standards poses a challenge for standardization of data acquired from different resources and their interoperability (Dave et al., 2016; Lu, Parlikad, et al., 2020a).

The digital twin connects the physical world with the virtual, so it should be enriched with real time data and constant update. However, digital twins are unable to support activities that take place exclusively in an analogue medium. The social world should also be considered and not just the link between social and physical but also social and virtual should be understood to open up new perspectives (Bevilacqua et al., 2020; Schrotter and Hürzeler, 2020).

RESEARCH METHODOLOGY

This section explains the research methodology used in this study that is design science research, consisting of problem identification, problem evaluation, requirement identification through benefit, opportunity, cost, risk analysis, design, design evaluation, development, artifact evaluation and contribution steps.

6.1 Design Science Research

Design Science Research is the methodological approach adopted in this study. A major difference between the design science research and traditional research strategies such as action research or case study, is that the main outcome of the design science research is the development of an artefact rather than exploring or describing existing systems. In this research, the proposed artefact is a multi-agent based cyber physical system for lean construction scheduling.

According to Hevner et al., a design science research project searches for a solution to a practice's real-world problem. Vaishnavi and Kuechler state that the defining characteristic of design science research is learning by constructing, that is artifact creation (Hevner et al., 2004; Vaishnavi & Kuechler, 2015). The goal of design science is developing knowledge that the relevant discipline's professionals can use to design solutions for the problems of their field (Van Aken, 2004). Koskela states that assessing construction management as a design science rather than an explanatory science will assist in solving problems that affect this discipline (Koskela, 2008).

In 1990, Takeda et al. developed a method for conducting a research based on design science, which is referred to as design cycle. Five steps of the method are awareness of the problem, suggestion for solving the problem, development of potential solutions, evaluation of the developed artifact and conclusion (Takeda et al., 1990). The research process proposed by Nunamaker et al. consists of constructing a conceptual framework, developing a system architecture, analyzing and designing the system, building the system and evaluating the system (Nunamaker et al., 1990). Method proposed by Peffers et al. for conducting design science research consists of problem identification, definition of expected results,

design and development, demonstration, evaluation and communication (Peppers et al., 2007). According to the model presented by Vaishnavi and Kuechler, which is an adaptation of Takeda et al.'s computable design process model, the first step is the awareness of the problem which may come from multiple sources. The second step is suggestion, which is a creative phase where, based on a new configuration of existing or new elements, a new functionality is proposed. Third step is development where the output of suggestion step that is tentative design is further developed and implemented. The fourth step is evaluation where the developed artifact is evaluated according to evaluation criteria. Finally, the conclusion step is the end of the research cycle and new knowledge production results in knowledge contribution since communication is important in research (Vaishnavi & Kuechler, 2015).

Evaluation is crucial in conducting rigorous Design Science Research. Evaluation in Design Science Research is used to establish the designed artifact's efficacy, effectiveness, efficiency, and ethics. Artificial evaluation which is called experimentation by Nunamaker et al., explores a solution's performance by lab experiments, field experiments, simulations, criteria based analysis, theoretical arguments and mathematical proofs that has the benefit of stronger scientific reliability. Naturalistic evaluation which is called observation by Nunamaker et al., explores a solution's performance in its real environment by case studies, field studies, surveys, ethnography, phenomenology, hermeneutic methods, and action research that has the benefit of stronger internal validity. Ex post evaluation is the evaluation of an instantiated artifact and ex ante is the evaluation of an uninstantiated artifact like a design or model. Ex-ante evaluation is predictive and serves to decide whether to acquire or develop the evaluated artifact or not. What is being evaluated is a design artifact which can either be a process or a product or both (Nunamaker et al., 1990; J. Venable et al., 2016; J. R. Venable et al., 2012).

Sonnenberg and Brocke proposed evaluation activities within a design science research. Evaluation of the problem identification activity ensures a meaningful design science research problem is formulated. The methods that could be applied are: assertion, literature review, practitioner reviews, expert interviews, focus groups or surveys. Evaluation of the design activity is used to show that the artifact to be designed is a solution to the identified problem. The methods that could be

applied are: assertion, mathematical proof, logical reasoning, demonstration, simulation, benchmarking, expert interview and focus group. Evaluation of if and how well the artefact performs could be done by: demonstration with prototype, experiment with prototype, experiment with system, benchmarking, surveys, expert interviews and focus groups. Evaluation of applicability and usefulness in practice of the artefact could be done by: case study, field experiment, survey, expert interview and focus group (Sonnenberg & Vom Brocke, 2011).

Although different methods have been proposed for conducting design science research, some similarities exist between these methods. These similarities are identification of the problem, identification and understanding of requirements of the artifact to be developed, evaluation and contribution. The research method proposed for this study can be seen on Figure 6.1.

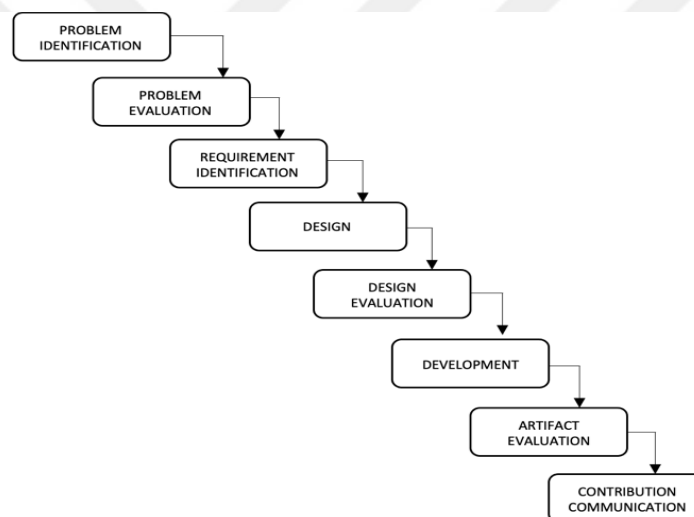


Figure 6.1 Research method

6.2 Problem Identification

An important contributor to success or failure of a project is project planning and control. Lack of monitoring and integrated approach to management of processes are challenges faced by planning and control practices (Jünge et al., 2019). Planning, one of the most important factors in project failures, is an important area to study for improving project management. Making detailed plans and squeezing them into tight control limits will not create effective project control since planning and execution are activities that have a certain degree of uncertainty. Adapting to the uncertainty and relying on expertise to find the best solutions to the problems is a better way to handle the uncertainties. What makes this work is communication

and coordination at lower levels in the planning process regularly before execution of works (Emblemsvag, 2014). Lean planning and control approaches like the Last Planner System and Plan-Do-Check-Act cycle aims to make problems visible at an early stage, assess planning process more holistically, provide decision makers with support, enable proactivity and avoid recurrence of same problems, empowering project control (Jünge et al., 2019).

Lean planning and control approaches focus on achieving targets along the planned path by steering towards targets and when a problem occurs figuring out an alternative solution to achieve them, which is the job of production control. Project controls, aligned with project scope, set cost and schedule targets and monitor progress toward them. These targets are set outside the lean planning and control practices (Ballard and Tommelein, 2016).

Another concern with lean planning and control approaches is poor linkage between different plan levels and sluggish constraint identification and removal reduces planning system's reliability and leads to reactive approach by the site team (Hamzeh et al., 2012). Although information exchange and integration is crucial, site team does not always have access to it or face interoperability issues (Dave et al., 2016). A single platform or system that is able to address all relevant issues rather than different systems that address them individually is needed (Olivieri et al., 2019). To be a quick responder, this system should be able to automate real time management of operations and focus also on dealing with flows and their interdependencies rather than just focus on sequencing activities (Naticchia et al., 2019).

In light of the issues listed above, the problem is identified as a need for an innovative real-time system that facilitates collaboration, data sharing and communication for effective construction project planning and control.

6.3 Problem Evaluation

For problem evaluation, 3 civil engineers and 1 architect with 20+ years' experience in the field were interviewed to identify major obstacles in timely completion of construction projects. The problems, solutions and drawbacks identified in these interviews can be seen on Table 6.1.

Table 6.1 Problems, solutions and drawbacks identified in the interviews

Problem	Solution	Drawback
Unrealistic schedules	*Preparing a preliminary general plan until the crew or subcontractors are determined *Revising the schedule with more detail when crew or subcontractors are determined * Collaborative scheduling	*Preliminary schedule inapplicable and low detailed *Will not be realistic until the teams are determined in terms of discipline or work package *Being able to spare time for collaboration
Poor project control	*Daily data from site - daily reports *Weekly team meeting	*Reliability of data coming from the site *Data from the site needs working on before it can be used on project schedule - use of different languages *Irregular handing in of reports
Poor schedule update	*Monthly evaluation meetings of developments that may cause deviations from the schedule	*Meeting participants unprepared *Inefficient meetings that divert from their purposes, turning into production meetings or people getting defensive etc.
Poor use in analysis	*Man-hour analysis *Physical progress vs financial progress vs temporal progress	*Not used for learning from positive events *Not used for subcontractor cost-efficiency analysis *Not used as reference for proposals or other production programs *Plan reliability not used properly
Employees' inconfidence in the project schedule	*Follow-up and control site with the project schedule and inquire the team through the project schedule	*Although getting the job done, belief or trust in schedule is not obtained *Collaboration gets harder *Segregation between the site and the headquarters"
Not taking or being able to take enough time	*Having a dedicated person/team for the job	*Formation of an understanding that only the planner is responsible for the schedule, leading to the schedule being prepared by someone who is not actually doing the work

The major obstacles were defined as lack of collaboration, need of working on data collected from site, people who perform the work not being able to develop enough proficiency in the project's master schedule and insufficient prospective use of data derived from the schedule. The results from the interview validate the proposed problem.

Also, a bibliographic literature review of lean construction scheduling literature was performed to identify the topics covered, analyze the evolution of research, evolution of studies in years and future direction of research in lean construction scheduling field for evaluating how relevant the problem is.

Scopus and Web of Science were chosen as the main search engines which contain extensive databases in different scientific fields (Li et al., 2019). The workflow for the scientometric analysis is shown in Figure 6.2.

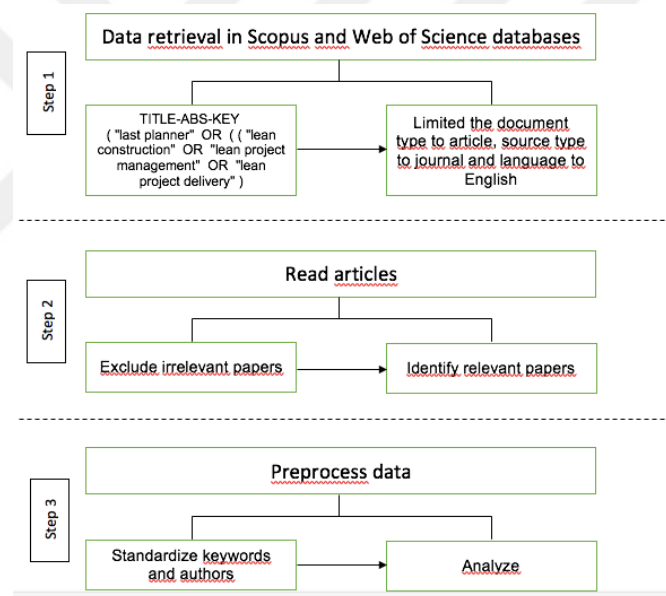


Figure 6.2 Scientometric analysis workflow

At first step journal articles were searched in Scopus up to March 2020 with the source type limited to journals and the language limited to English resulting in 221 articles. Same search was done in Web of Science resulting in 153 articles of which 32 are different from the results of Scopus search. At the second step papers were read to exclude any irrelevant ones and references of articles were checked to find articles that could not be found from the database search, which resulted in 153 related articles. At the third step data such as keywords and author names were preprocessed so they could be all standardized, general words were eliminated and

the data was analyzed. Analysis was done with VOSviewer which is a software for analyzing bibliometric networks.

To analyze the evolution of research trends in lean construction planning, generic terms like lean construction, construction management etc. were removed to obtain a better evaluation of topics. Map of keywords by years can be seen on Figure 6.3.

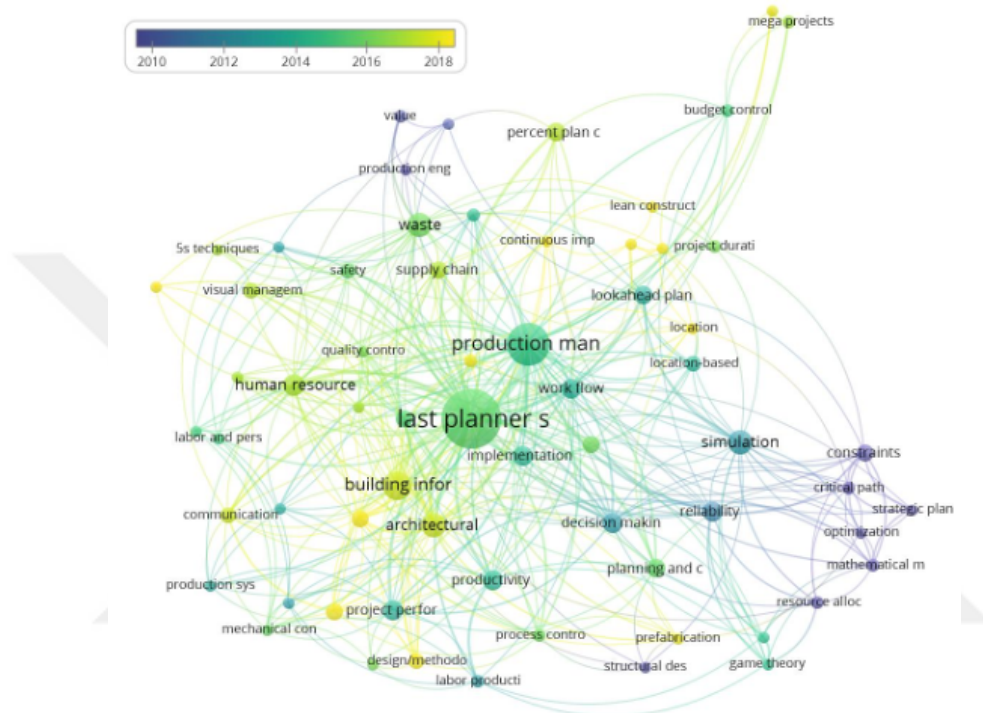


Figure 6.3 Map of keywords by years

As can be seen from the figure, Last Planner system is very dominant in lean construction scheduling field, followed by production management. Recent or emerging relevant topics are building information modelling, social aspects, communication, real time, information theory, prefabrication, design, international projects, supply chains and percent plan complete. Nearly 20% of articles analyze the implementation of the system and its benefits, barriers, effect on performance, duration, cost etc. Again nearly 20% of articles are about developing of a lean construction planning tool or management model, consisting of about 15% of the articles. One of the emerging topics, building information modelling consists around 4% of the articles where all of them were written after 2015. Developing metrics to measure not just plan reliability but also performance has also emerged after 2015. Research based on real time tracking can be seen after 2016. Looking at

the research done so far, there is a trend for developing systems to automate project management and scheduling. The results of the scientometric analysis show that the proposed problem is relevant.

6.4 Requirement Identification

The lean philosophy, which allows the problems to surface avoids repetition by solving them one by one while learning from them. This approach is based on plan-do-check-act (PDCA) cycle taught by Deming. Problems are thoroughly identified and possible solutions are developed at plan stage, plans are put into action at the do stage, target and implementation is compared at the check stage and either success is confirmed or corrective actions are developed at the act stage (Jünge et al., 2019).

Experiences in construction show that construction plans which are prepared by people who are not the ones that actually do the work, tend to be hard to follow by the people who do the work. Disconnection between the schedule and the actual work makes the schedule unrealistic and unfollowable. Last Planner is the most well-known and powerful planning and control system among all lean construction tools (Gao and Low, 2014b). Main steps advocated by the system are to plan in more detail as getting closer to executing the work, to prepare the work plan with those that perform the work, to remove constraints for making work ready and increasing reliability, to make reliable commitments and to learn from failures (F. Hamzeh et al., 2012). However, a deep understanding of the relationship among reallocation of resources and subcontractor crew plan reliability is needed (Rincon et al, 2019).

Visualization is an important part of lean practices. The main aim of a production system visual control is to provide, at an appropriate level, the system's clear visual status for all parties so that necessary actions can be taken. Therefore a visual system should be able to show appropriate measurements, up-to-date information and what is really possible (Ballard and Tommelein, 2014).

Digital Twins represent the state of a system and its development over time (Chevallier et al., 2020; Lu et al., 2020). Although different concepts, as seen on Figure 5.3, adoption of digital twins in lean construction can increase the impact of

lean practices by certain functionalities offered by digital twins that support lean construction. A neutrosophic AHP - benefit, opportunity, cost, risk (BOCR) analysis is performed to better understand the significant obstacles and enablers in digital twin adoption in lean construction, how adoption of digital twin systems enhance lean practices in construction and what factors encourage or discourage its adoption, the significant factors and most influential ones to focus on.

For the BOCR criteria selection, an extensive review of previous work from literature was performed. A Scopus search was performed on literature with search criteria “TITLE-ABS-KEY (({Digital Twin} OR {cyber physical} OR {cyber-physical} OR {cyberphysical})) AND construction)” in engineering subject area with language limited to English and time range up to the end of 2021. Among 664 listed documents, 39 studies presented BOCR of DT applications. After the preliminary review of related studies, 14 benefits criteria, 7 costs criteria, 13 opportunities criteria and 14 risks criteria were identified. These criteria were further explored through expert opinions and finally benefits were grouped under 8, costs were grouped under 6, opportunities were grouped under 8 and risks were grouped under 8 criteria. BOCR criteria can be seen on Table 6.2.

Table 6.2 BOCR criteria

Items	Criteria	Definition	References
Benefits	B1. Visualization	Increased visualization to fully understand design and processes; use of supporting technologies like AR, VR and MR, clash detection between spatial, temporal and 3D objects, resources, equipment, materials, processes etc.	Qiuchen et al., 2020; Corneli et al., 2019; Hlady, 2018; Boje et al., 2020; Golparvar-Fard et al., 2009; Kaewunruen and Xu, 2018; Peng et al., 2020; Anumba and Roofigari, 2020
	B2. Real-time monitoring	Immediate data from the field	Natephra and Motamedi, 2019; Corneli et al., 2019; Hlady, 2018; Boje et al., 2020; Lu et al., 2020; Yuan and Anumba, 2020; Kaewunruen and Xu, 2018; Kan and Anumba, 2019; Sai et al., 2019; Peng et al., 2020; Rasheed et al., 2020; Bosch-Sijtsema et al., 2021; Pan and Zhang, 2021

Table 6.2 BOCR criteria (continued...)

Benefits	B3. Remote access	System can be accessed from anywhere	Hlady, 2018; Boje et al., 2020; Golparvar-Fard et al., 2009; Yuan and Anumba, 2020; Tchana et al., 2019; Omer et al., 2019; Rasheed et al., 2020
	B4. Communication and collaboration	More transparent communication between stakeholders through data transmission and visualization and increased collaboration among different stakeholders and processes by sharing various information created by different parties on the same platform	Hlady, 2018; Lu et al., 2020; Golparvar-Fard et al., 2009; Tchana et al., 2019; Kan and Anumba, 2019; Al-Saeed et al., 2020; Pan and Zhang, 2021
	B5. Improved analysis and decision-making support	Improved analysis of rich real-time data that is integrated with assets and timeline through simulations, predictive modeling, hypothesis testing supports faster and more informed decision-making and identification of cost and progress deviations	Qiuchen et al., 2020; Hlady, 2018; Lu et al., 2020; Yuan and Anumba, 2020; Kan and Anumba, 2019; Lin et al., 2019; Bonci et al., 2019; El Jazzer et al., 2020; Bevilacqua et al., 2020; Bosch-Sijtsema et al., 2021; Pan and Zhang, 2021; Natephra and Motamedi, 2019; Boje et al., 2020; Tchana et al., 2019; Olatunji and Akanmu, 2014; Golparvar-Fard et al., 2009; Pučko et al., 2018; Sai et al., 2019
	B6. Improved efficiency	Improved efficiency through parallel working of man and machine, reduced information loss and increased visibility	Corneli et al., 2019; Hlady, 2018; Bonci et al., 2019; Pan and Zhang, 2021
	B7. Improved quality and health & safety	Health & safety practices supported by and quality improved through increased access to data and visibility and reduced time for corrective action	Hlady, 2018; Kaewunruen and Xu, 2018; Boje et al., 2020; Yuan and Anumba, 2020; Sai et al., 2019; Sacks et al., 2020a
	B8. Proactivity	Advance detection of problems and better insight into processes supporting construction management to be more proactive than reactive	Lin et al., 2019; Hlady, 2018; Tchana et al., 2019; El Jazzer et al., 2020; Sacks et al., 2020a; Pan and Zhang, 2021

Table 6.2 BOCR criteria (continued...)

Costs	C1. System components	Hardware and software	Qiuchen et al., 2020; Hlady, 2018; Lu et al., 2020; Qiuchen et al., 2019; Omer et al., 2019
	C2. Data collection and processing	Cost of computing resources caused by synchronization frequency of data sets	Qiuchen et al., 2020; Qiuchen et al., 2019
	C3. Skilled workforce	Dedicated staff and need for training	Hlady, 2018; Lu et al., 2020; Qiuchen et al., 2019; Omer et al., 2019; Sai et al., 2019
	C4. Maintenance	Large number of devices leads to criticality of maintenance of system components	Yuan and Anumba, 2020; Bevilacqua et al., 2020
	C5. Disruption	System use may cause reduction in computer power causing disruption to other critical operations that need computing resources	Lu et al., 2020
	C6. Energy	Energy supply and consumption related to large number of devices	Bevilacqua et al., 2020
Opportunities	O1. Automation	Transition of certain human expert tasks to DT platform; input for robots or remotely operated machinery; automated site progress monitoring; automated scheduling; automated as built production	Becker et al., 2019; Hlady, 2018; Boje et al., 2020; Olatunji and Akanmu, 2014; Sacks et al., 2020a; Anumba and Roofigari, 2020; Vasey and Menges, 2020
	O2. Continuous learning	Improvement of future generations and future projects through the use of captured historical data	Hlady, 2018; Olatunji and Akanmu, 2014; Dave et al., 2018; Tchana et al., 2019; El Jazzer et al., 2020; Sacks et al., 2020a; Anumba and Roofigari, 2020
	O3. Prevent quality and health & safety risks	Risk warnings by use of real-time data and improved visibility, risk warnings through human activity and field conditions monitoring; zero health and safety risk projects	Hlady, 2018; Boje et al., 2020; Turner et al., 2021; Kaewunruen and Xu, 2018; Kan and Anumba, 2019; Sai et al., 2019; Rasheed et al., 2020; Anumba and Roofigari, 2020

Table 6.2 BOCR criteria (continued...)

Costs	O4. Improved site management and off-site production	Improved site management through operational and strategic insights, work as a child of the DT to monitor off-site components or processes	Turner et al., 2021; Sacks et al., 2020a
	O5. Increased team synergy	Increased synergy in and between teams through the use of system as a tool for communication, collaboration and coordination	Golparvar-Fard et al., 2009; Rasheed et al., 2020
	O6. Innovations in processes and improved optimization	Define new methods for planning and control in both design and production stages, optimize processes, site logistics and scheduling	Sai et al., 2019; Sacks et al., 2020a; Vasey and Menges, 2020; Boje et al., 2020; Kaewunruen and Xu, 2018; Kan and Anumba, 2019; Bevilacqua et al., 2020
	O7. Produce new knowledge	Allowing AI to learn and take decisions; opportunity to spot trends and anomalies; triggering risk warnings of time, cost, health and safety; performance and output suggestions, improved decision-making through use of AI	Qiuchen et al., 2020; Hlady, 2018; Boje et al., 2020; Turner et al., 2021; Peng et al., 2020; Sacks et al., 2020a; Rasheed et al., 2020; Anumba and Roofigari 2020; Bosch-Sijtsema et al., 2021; Olatunji and Akanmu, 2014; Al-Saeed et al., 2020
	O8. Reduced waste	Improved productivity through better performance, efficiency and synergy, reduction in time, cost, space, work and material wastes through better construction progress monitoring, decision-making and identification of mature tasks	Corneli et al., 2019; Boje et al., 2020; Lu et al., 2020; Kan and Anumba, 2019; Sai et al., 2019; Bevilacqua et al., 2020; Sacks et al., 2020a; Rasheed et al., 2020; Pan and Zhang, 2021; Tchana et al., 2019
Risks	R1. Systems and data integration and interoperability	Sensor and network integration, integration of data from autonomous, heterogeneous sources, and different software platforms interoperability, need for linking and matching data among assets and among systems, data standardization need acquired from different technologies in syntactic and semantic formats, semantic enrichment need for optimization tools, search algorithms, other AI tools and interoperability between systems	Natephra and Motamedi, 2019; Corneli et al., 2019; Boje et al., 2020; Lu et al., 2020; Dave et al., 2018; Peng et al., 2020; Vasey and Menges, 2020; Qiuchen et al., 2019; Sacks et al., 2020a; Sacks et al., 2020b; Kaewunruen and Xu, 2018; Bevilacqua et al., 2020

Table 6.2 BOCR criteria (continued...)

Risks	R2. Choosing appropriate technologies	Solutions offered in market not being able to precisely meet industrial needs and specific performance requirements, risk of physical damage to system components like sensors under site conditions	Olatunji and Akanmu, 2014; Bevilacqua et al., 2020; Yuan and Anumba, 2020
	R3. Post processing	Need for data cleaning and post processing for organizing relationships and semantics of collected data, manual review and intervention need for data	Becker et al., 2019; Hlady, 2018; Kaewunruen and Xu, 2018; Omer et al., 2019; Sacks et al., 2020b
	R4. Data storage, quality and accuracy	Challenge of data storage throughout the project life cycle because of data size which is affected by data quality and accuracy, ability of the collected data to meet the requirements of intended use, data accuracy being affected by complex environment and human factor	Natephra and Motamedi, 2019; Olatunji and Akanmu, 2014; Dave et al., 2018; Peng et al., 2020; Bosch-Sijtsema et al., 2021; Becker et al., 2019; Lu et al., 2020; Qiuchen et al., 2019; Omer et al., 2019; Qiuchen et al., 2020; Corneli et al., 2019; Hlady, 2018; Roh et al., 2011; Yuan and Anumba, 2020; Pučko et al., 2018; Bosch-Sijtsema et al., 2021
	R5. Reliance on skilled training	Need for training to incorporate new technologies, lack of AI skills of construction companies', difficulty accepting digital change	Sacks et al., 2020a; Bosch-Sijtsema et al., 2021; Hlady, 2018; Yuan and Anumba, 2020
	R6. Data presentation	Success of DT depending on correct presentation of data and its semantics and in a intuitive way to operate to overcome complexity of data and inability to support activities that take place exclusively in an analogue medium like socio-political issues	Turner et al., 2021; Dave et al., 2018; Bevilacqua et al., 2020; Tchana et al., 2019
	R7. Data security	Balance between data security and system function; threat of cyber-attacks	Yuan and Anumba, 2020; Dave et al., 2018; Peng et al., 2020; Bevilacqua et al., 2020; Bosch-Sijtsema et al., 2021
	R8. Financial risks	Financial risks based on large scale network construction involving many components, investments needing a long-term perspective	Peng et al., 2020; Bosch-Sijtsema et al., 2021

A two-step approach is utilized to develop an assessment model. At the first step BOCR for digital twins are identified through literature review and expert opinions, at the second step dependencies among BOCR for digital twins application in lean construction are determined by neutrosophic AHP. Neutrosophic sets, developed by Smarandache, are a general version of classical, fuzzy and intuitionistic fuzzy sets which reflect uncertainty, inconsistency and real-world problems better by considering truthiness, falsity and indeterminacy (Smarandache, 2002; Abdel-Basset et al., 2017). Neutrosophic sets are used to express experts' judgements to reflect the real-world decision-making problems more effectively. AHP and fuzzy AHP have been used for BOCR analysis to compute priorities of criteria of each BOCR item, however, in a novel manner, neutrosophic AHP is jointly used with BOCR analysis for its better handling of vagueness and uncertainty than AHP and fuzzy AHP (Yucesan and Gul, 2021). Under each BOCR subnet each criterion is compared pairwise by asking which one is more important than the other. Under benefit and opportunity subnets the most beneficial and the highest opportunity criteria get the highest priority, while in cost and risk subnets the most costly or risky criteria get the highest priority. Since it is possible that BOCR items are not equally important, relative weights of each BOCR item should be determined to be able to evaluate their importance according to the goal. To make it easier for experts to make a pairwise comparison of these four items a control hierarchy, which consists of lean construction criteria, is formed so that the experts answer what level of benefit (opportunity, cost or risk) they associate with each lean construction criteria rather than what level of benefit (opportunity, cost or risk) they associate with use of digital twins in lean construction (Lee, 2009). For the lean construction criteria, principles of lean construction are grouped under four main criteria which are reduce waste, increase value, focus on process and flow and continuous improvement. The hierarchy framework can be seen on Figure 6.4.

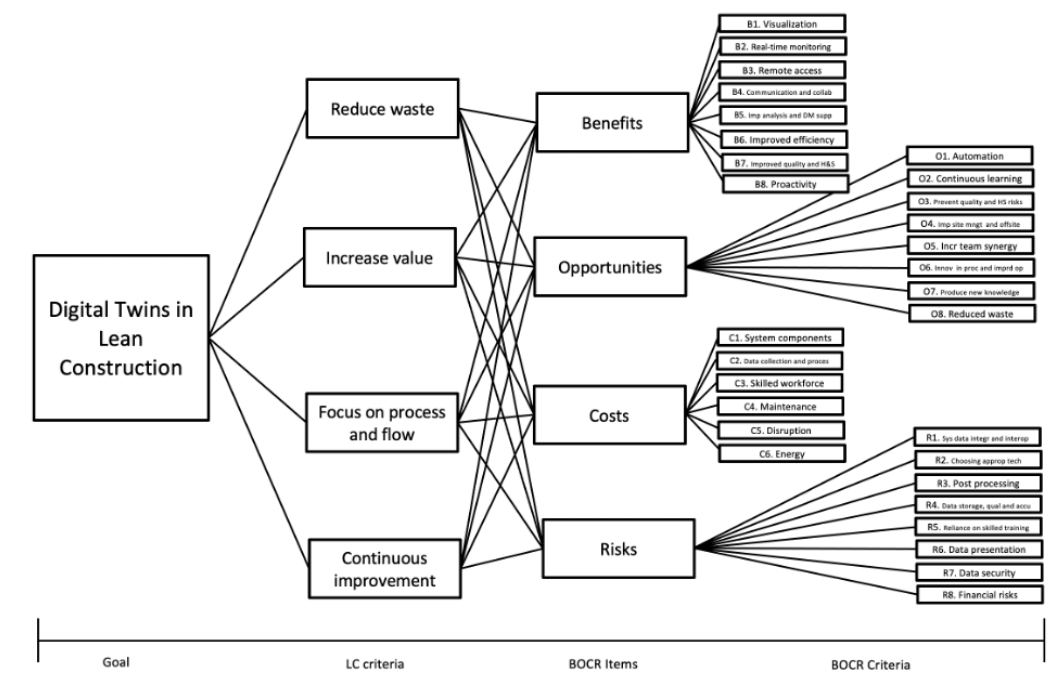


Figure 6.4 Hierarchy framework

BOCR criteria, BOCR items and lean construction criteria are compared pairwise through a 5-point Likert scale questionnaire based on proposed hierarchy structure. The experts are asked to give an importance rating of each strategic criterion with respect to goal, each BOCR item with respect to each strategic criterion and each BOCR criterion on each BOCR item. Preferences are listed as equally, slightly, strongly, very strongly and absolutely significant. To link the verbal expressions to numerical expressions, triangular neutrosophic scale is used which can be seen on Table 6.3 (Abdel-Basset et al., 2018; Nabeeh et al., 2019; Yucesan and Gul, 2021).

For BOCR analysis, 15 experts, selected based on their experience with both digital twins and lean construction, were invited to take part in the developed questionnaire. Since the study requires experience both in lean construction and digital twins, two experts declined to take part in the survey, stating their experience with DT was limited for the study, one expert stated their experience with lean construction was limited for the study and four of the invited experts did not respond at all. Of the 15 invited experts, only 8 responded; all civil engineers, 5 of which are from the industry and 3 of which are from the academia.

Table 6.3 Problems, solutions and drawbacks identified in the interviews

Linguistic scale	Neutrosophic triangular scale
Equally significant	$\tilde{1} = \langle (1, 1, 1); 0.50, 0.50, 0.50 \rangle$
Moderately significant	$\tilde{3} = \langle (2, 3, 4); 0.30, 0.75, 0.70 \rangle$
Strongly significant	$\tilde{5} = \langle (4, 5, 6); 0.80, 0.15, 0.20 \rangle$
Very strongly significant	$\tilde{7} = \langle (6, 7, 8); 0.90, 0.10, 0.10 \rangle$
Absolutely significant	$9 = \langle (9, 9, 9); 1.00, 0.00, 0.00 \rangle$
Sproadic values between scales	$\tilde{2} = \langle (1, 2, 3); 0.40, 0.65, 0.60 \rangle$ $\tilde{4} = \langle (3, 4, 5); 0.60, 0.35, 0.4 \rangle$ $\tilde{6} = \langle (5, 6, 7); 0.70, 0.25, 0.30 \rangle$ $\tilde{8} = \langle (7, 8, 9); 0.85, 0.10, 0.15 \rangle$

The application steps of neutrosophic AHP and their application in this study are:

Step 1 - Model structuring: the benefit, cost, opportunity and risk criteria of digital twin application in construction industry are determined based on an extensive literature review. Principles of lean construction listed in previous studies are grouped under four main items. AHP model structure is formed that includes lean construction criteria, BOCR items and BOCR criteria, which can be seen on Figure 6.4.

Step 2 - Constructing pairwise matrices of the criteria with neutrosophic sets: the experts are asked to make pairwise comparisons of lean construction criteria, pairwise comparison of BOCR items related to each lean construction criterion and cluster comparison of BOCR criteria with respect to items that they belong. Triangular neutrosophic scale shown in Table 6.3 is used for determining the relative preferences. Some important definitions of neutrosophic sets are as follows (Abdel-Basset et al. 2017; Abdel-Basset et al. 2018; Nabeeh et al. 2019):

Step 4 – Consistency check: Consistency measurement is done by Saaty’s method (Saaty, 2006). If the consistency ratio is greater than 0.1, the judgements are inconsistent and the responses are unacceptable. Consistency ratios of all responses were below 0.10 in the study. Estimated weights of BOCR criteria are presented in Figure 6.5.

Among benefits, improved analysis and decision-making support was estimated as having the greatest importance with 16.23%, followed by proactivity with 15.75% and visualization with 14.08%. Among costs, skilled workforce was estimated as having the greatest importance with 33.90%, followed by system components with 19.80% and data collection and processing with 14.82%. Among opportunities, reduced waste was estimated as having the greatest importance with 24.78%, followed by innovations in processes and improved optimization with 12.86% and improved site management and off-site production with 12.39%. Among risks, choosing appropriate technologies was estimated as having the greatest importance with 19.49%, followed by reliance on skilled training with 17.14% and systems and data integration and interoperability with 17.14%.

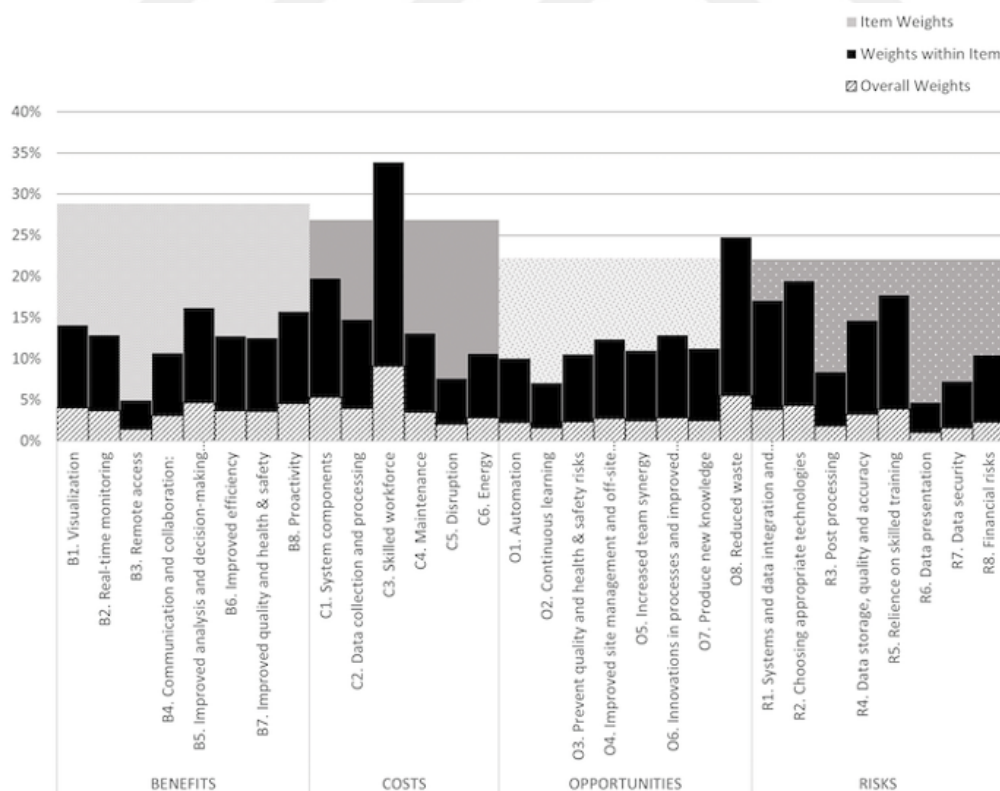


Figure 6.5 Analysis results

Looking at the costs and risks, the obstacles all gather around the system or technology and the people or workforce that is going to make use of it. Besides opportunity to reduce waste, benefit of improved analysis and decision-making support, benefit of proactivity and benefit of visualization are estimated to be the most important enabling factors in adoption of digital twins in lean construction practices. Availability and analysis of real-time data and visualization enables proactivity and informed decision-making which results in opportunity to reduce time, cost, space, work and material wastes as in computer visualization tools and BIM adoption in lean construction (Sacks et al., 2010). Evidently, the results show that digital twins support lean construction practices by reducing waste, supporting informed decision-making and proactivity and improving visualization. Information generated through monitoring and analyzing capabilities of digital twins can be used for reduction of non-value adding activities, optimizing processes and flow, increasing generated value and continuous improvement of the processes.

Requirements of the system are identified by literature review, BOCR analysis and brainstorming as: a visual system that combines lean construction practices and innovative construction progress control technologies, artificial intelligence and digital twin concept. By fulfilling these requirements, the system will be able to provide its users with up-to-date visual information on the status of the project and help in making decisions on project scheduling and resource allocation while supporting lean construction practices.

6.5 Design

Design involves a number of design decisions based on the identified requirements and abstract models of the framework to be developed. Users, workflow and usage patterns are identified.

According to the Construction Extension to the PMBOK the knowledge areas applicable to construction projects are: integration management, scope management, schedule management, cost management, quality management, resource management, communication management, risk management, procurement management, stakeholder management, health safety security environment management, and financial management (Project Management Institute, 2016). Considering these knowledge areas, users of the system are

identified as Planners, Crew Leaders of the Subcontractors, Procurers, Site Inspectors, Project Controllers, QA/QC administrators, HSE administrators.

Workflow consists of 6 processes that use should-can-will-did principle from the Last Planner System as a basis. The processes are operation level plan, assignment level plan, coordinated work plan, production management, worklog and measure and analyze. These processes express the workflow between the users and the system and altogether apply the plan-do-check-act cycle. The system consists of data and digital model, multi agent system and analysis tools. “Plan” phase is realized by forming a digital model for construction plan using the system, “Do” phase is realized by production management using the system, “Check” phase is realized by monitoring resources and performed works via the system and “Act” phase is realized by evaluating the system data and improving the construction plan.

Multi agent system is used for dynamic scheduling, forming, and coordinating work plans of the subcontractors. For being able to respond to unexpected quickly, tools that can automate real time operation management and deal with resources and flows rather than just activity sequencing are needed. Agent based systems which consist of autonomous entities called agents are able to respond to these challenges due to their adaptation, agility and modularization qualities (Naticchia et al., 2019). Agents are able to represent subcontractors in terms of behavior because of their behavior to protect their own interests (Rincon et al., 2019). With their self organization and multi objective planning capabilities, multi agent systems can offer decision making and automatic site management support in real time (Naticchia et al., 2019).

Planners and crew leaders use the system for operation and assignment level planning. The work plan coordination is done by the system and crew leaders use the system for committing to the daily work they are responsible for and recording data concerning their performed tasks. All users use the system to identify resources, constraints, responsibilities, data and documents related to their discipline, follow the project status in real time and produce reports. System is accessible through desktop and mobile devices, so that it is handy for all users.

6.6 Design Evaluation

Number of systems that use lean construction practices, 3D models, augmented reality, digital twin concept, innovative progress control technologies and artificial intelligence systems have been proposed. Design evaluation is done by logical reasoning for effectiveness of the proposed design for being a solution to the identified problem and benchmarking. Comparison of proposed design with similar developed systems can be seen on Table 6.4.

Sriprasert and Dawood (2003) propose a system for reliable plan generation and constraint removal for assignment execution. The system uses 4D visualization but does not show differences between different plan statuses; consider physical, contract, resource and information constraints but does not consider safety and environmental constraints; incorporates project level, operation level and assignment levels of planning but does not support schedule coordination.

Golparvar-Fard et al. (2009) propose a 4 dimensional augmented reality model for automated progress data collection. The model visualizes progress monitoring through superimposition of 4D as planned models over site photographs. They propose that the tool can be used for contractor coordination and communication purposes. The tool is for monitoring purposes does not provide support to the project team with scheduling, constraint removal or resource management issues.

Sacks et al. (2010) propose BIM enabled system based on the Last Planner System that uses Kanban style pull process flow and 3D visualization of process status enabling real time feedback. The system does not show differences between different plan statuses; supplements the Last Planner System but does not support schedule coordination.

Dave et al. (2016) propose IoT enhanced lean construction management system that reports real-time field task status, supports constraint management, process and product visualization and collaboration work negotiation through project team member communication.

Heigermoser et al. (2019) propose a construction management tool that combines 3D visualization with the Last Planner System. The system is based on short-term construction planning and does not consider project or operation level plans. Project scheduling is not implemented in the system.

Song and Fischer (2020) propose a daily planning system that enables a foreman to daily go through the plan do check act cycle. Only six information items are generated which are actual completion date, products built, location, quantity, crew size and performance metric. The system only considers assignment level plans and does not provide support to the project team with scheduling, constraint removal or resource management issues.

Table 6.4 Comparison of proposed design with developed systems

	Application of Lean Principles	Process and Product Visualization	Constraint Tracking	HSE & QA/QC Constraints	Resource Management	Visualize Real-time Production Status	Automated Schedule Coordination	All Levels of Plans	Progress Monitoring	Subcontractor Involvement
LEWIS Sriprasert and Dawood (2003)	X	X	X		X	X		X	X	X
D ⁴ AR Golparvar-Fard et al. (2009)		X				X			X	
KanBIM Sacks et al. (2010)	X	X	X	X	X	X		X	X	X
Visilean Dave et al. (2016)	X	X	X		X	X		X	X	X
BIM based LPS tool Heigermoser et al. (2019)	X	X							X	X
BOMop Song and Fischer (2020)	X	X							X	X
BIM-data mining integrated DT framework Pan and Zhang (2021)		X				X			X	
Proposed Design	X	X	X	X	X	X	X	X	X	X

Pan and Zhang (2021) propose a BIM, IoT and data mining integrated digital twin framework for predicting and optimizing physical construction operations. The model relies on a single monitoring source that is an unmanned aerial vehicle. The system gives feedback about adjusting, developing and predicting project plan but does not consider scheduling, constraint removal or resource management issues.

6.7 Development

In the development stage a framework is developed based on the design criteria. The developed framework is explained in detail in section 7.

6.8 Artifact Evaluation

Artifact evaluation is done by assessing the developed framework for efficacy, validity, consistency, structure and robustness. Evaluation of the developed framework is explained in detail in section 8.

6.9 Contribution

Contribution communication is realized through PhD thesis and journal articles.

In this section, proposed framework for MABIM platform and six processes within the framework are presented.

7.1 Introduction

In construction industry, digital twins are used to manage, plan, predict and demonstrate building, infrastructure or city assets and fast and effective communication between human and the machine is vital (Lu, et al., 2020a; Rasheed et al., 2020). Camponsano et al. state that AEC/FM industry stakeholders rely on metaphors to define digital twin concepts which are listed as a lifecycle representation, a process modeling method, a visualization tool, convergence of the physical and the digital world, an IoT data platform, a shared concern between different communities of practice and a service ecosystem. They also stated that, for the practitioners, representation of systems's process chain view, its change history and decision taken were more important than having high level of detail in graphical representations (Camposano et al., 2021). Construction progress monitoring through cyber physical systems should include data collection, progress monitoring, activity monitoring and reporting (Anumba and Roofigari-Esfahan, 2020). Smart services enabled by a digital twin can be listed as: enhanced site sensing, automated site progress monitoring, real time data visualization, increased AI application, site safety detection, BIM clash detection simulation and optimized site scheduling and logistics (Boje et al., 2020).

Considering lean construction principles, use of innovative technologies and previous studies, a framework for lean construction scheduling, management and control system is proposed that incorporates plan-do-check-act cycle, should-can-will-did view, different levels of planning, schedule coordination, constraint management, progress monitoring, enhanced communication between parties, multi dimensional visualization and improved analysis.

7.2 Proposed Framework

In general, the system is designed to cover two main approaches in lean construction: plan-do-check-act cycle and should-can-will did planning from the Last Planner system. The system framework shown in Figure 7.1, is designed considering these two approaches. The system framework starts with activities that should be done, allows for users to determine what can be done, lets users to commit to their plans so what will be done is determined and finally shows what is done by the feedback from the system users. From the plan-do-check-act cycle perspective, forming a digital model for construction plan using MABIM platform is the plan part, production management using the MABIM platform is the do part, monitoring resources and performed works via MABIM platform is the check part and evaluating MABIM platform data and improving construction plan is the act part.

BIM based digital models and data models which contain geometric and semantic information are transferred into MABIM platform and integrated. In MABIM platform, BIM model, project schedule, planning meetings and data collected from site are combined and analyzed by a multi agent system. All crews in the project team log into the platform and use the platform to both follow planned and realized tasks and put in realized work data. Visualized system facilitates as-built data input so real-time updates of the site work progress is possible, enabling the formation of digital twin of the performed site works for effective schedule control where the project management and site personnel can follow site works in real time.

Master plan and phase schedule are prepared by the planners. Lookahead schedule is prepared by the planners and crew leaders. According to the lookahead schedule, crew leaders detail tasks and prepare weekly workplan. All the workplans from different crews are fed into the MABIM platform, then the platform gives decision support to the planners in coordinating the workplans. Once the workplan is finalized, it is again fed into the platform for all the crews to commit to. Crews follow their daily tasks from the platform and check constraints so they can be removed before a task is started. If there is any problem while performing a task, it is stopped so the problem is solved. If a task is not able to be performed, platform lists alternative tasks from the workable backlog. Crews log into the system both to access info about planned tasks of the day and input data related to realized task they performed via user interface. Site engineers or inspectors log into the system

to follow current status, progress and to confirm finished tasks or call change requests for unconfirmed tasks.

The planning team and the crew are primary actors for being the ones who do something and procurement team, site inspection team, project controllers, QA/QC team and HSE team are secondary actors for responding only after the planning team and the crew team do something. Planning team and the crew who do the work provide the necessary information to the system for coordination of weekly workplan. Other teams use this information to plan their own activities. The crew checks daily tasks to realize the planned works and procurement team makes sure the necessary resources are provided while site inspection team keeps track of the daily tasks. Every time the daily tasks are checked, the system verifies the necessary resources are provided and there are no constraints. If there is a lack of a certain resource or a constraint that prevents a task from being realized, the system lists an alternative task from the workable backlog. When a daily task is completed, the crew inputs necessary information and the work is inspected by the site inspection team for conformity and the system is updated according to new data. If there is a need for a change order it is again listed in the system for the crew to realize.

Platform also provides decision support for procurement activities by resource calendars, provides forecasts and analyses of work performance, team performance, productivity, subcontractor reliability, plan reliability to assist project management team in effective planning and scheduling of the project. Analysis results of the platform can also be used to output daily reports and to follow up and manage a group of projects in different sites and can be integrated into the organizations project management and ERP system which could help in program or portfolio management and scale economy.

7.2.1 Multi Agent System in MABIM

Proposed running process of multiagent system within the MABIM platform can be seen in Figure 7.2. Three main approaches were observed to be used in multi agent planning: centralized planning where planning is done by a delegate agent, plan merging where planning is done separately by each agent and combined by a merger agent and distributed planning where agents coordinate their plans (Wang and Ruan, 2011). Proposed approach for the study is to have subcontractor agents

that form their own plans and then have these plans coordinated by another cooperative planning agent; as in distributed manufacturing systems where a cooperative planning agent arranges the production plan based on information from distributed plants (Kim, 2001). Some important aspects of the MAS working in the proposed system are explored from literature. There are mainly two types of scheduling which are predictive and reactive/dynamic. Reactive/dynamic scheduling will be used in this study since the aim is to coordinate the work schedule according to incurred changes. The system should provide a direct relationship between constraints and schedule change options. The constraints to account for are identified as precedence relationship, material, equipment, crew availability and contract. Engineering and crew work continuity constraints are not considered since the work plans to be coordinated are prepared by the teams who are performing the work. A utility function needs to be identified for utility transfer during negotiation. Coordination can be either central or distributed and a negotiation model should be identified accordingly being either pairwise or multilinked. After the negotiation model is identified, negotiation performatives and expected answers should be listed. Conversation sequence is proposed to be according to the project schedule since the project schedule provides the precedence relationships. Message handling mechanisms should also be determined (Kim, 2001; El-Rayes and Moselhi, 1998; Petrie et al., 1999; Clayton et al., 1998).

The multi agent system is composed of subcontractor agents, planning agent, resource and constraint agent and workable backlog agent. Agents are provided with planned tasks, quantity and precedence of tasks, task status, performance, constraints and reasons for non-realization through the building model that is loaded with 6 week look ahead schedule and real time construction progress data. Subcontractor agents form their weekly work plans based on the lookahead schedule and realized task data. Planning agent merges subcontractor weekly workplans by collecting resource and constraint data from resource and constraint agent and negotiating with subcontractor agents. Weekly workplan formed by the planning agent is fed into the system for the crews/subcontractors to follow. Planning agent also sends lists of tasks to be done to the workable backlog agent in case a planned task cannot be performed so the system can propose a new task instead.

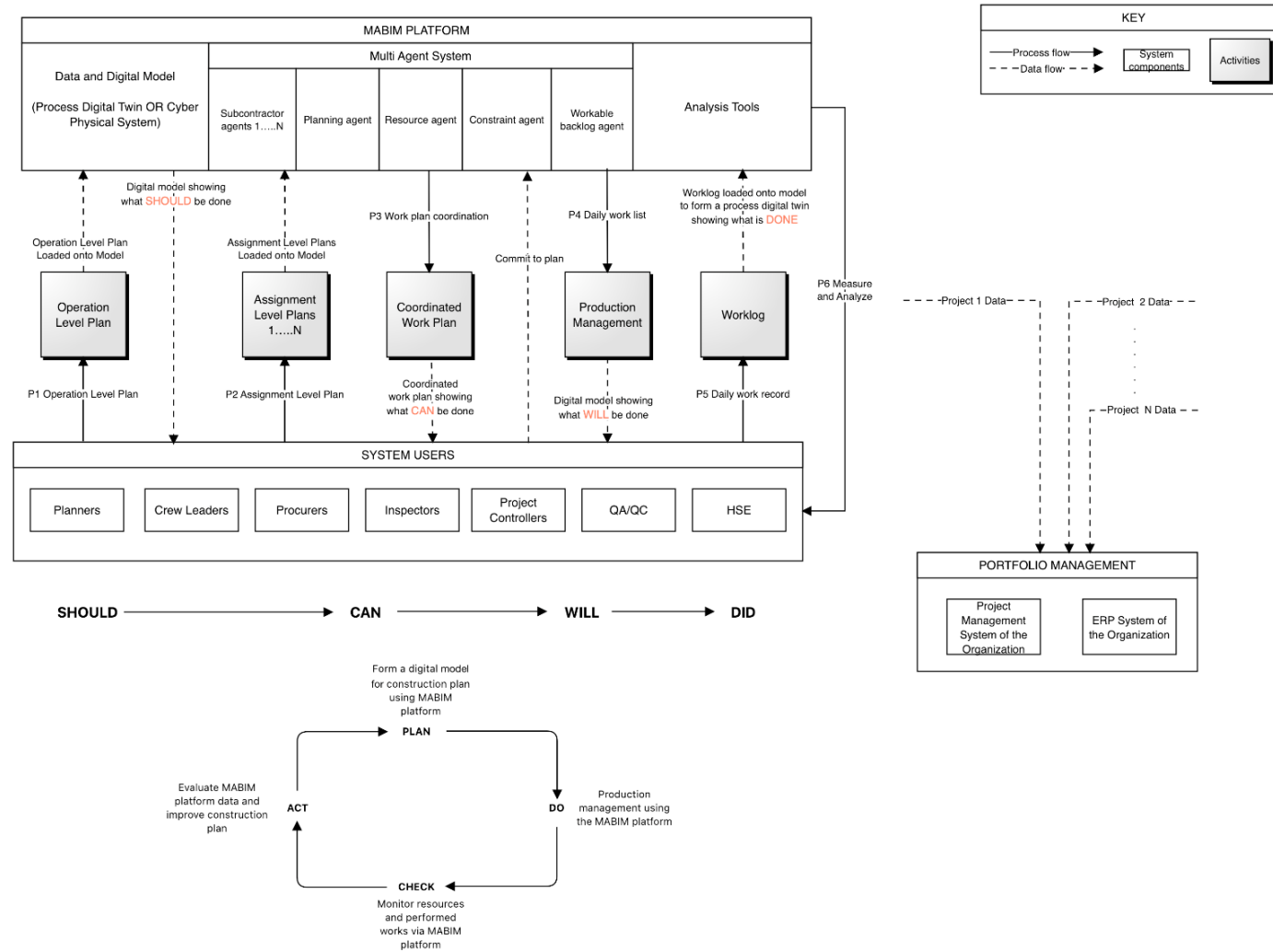


Figure 7.1 System framework

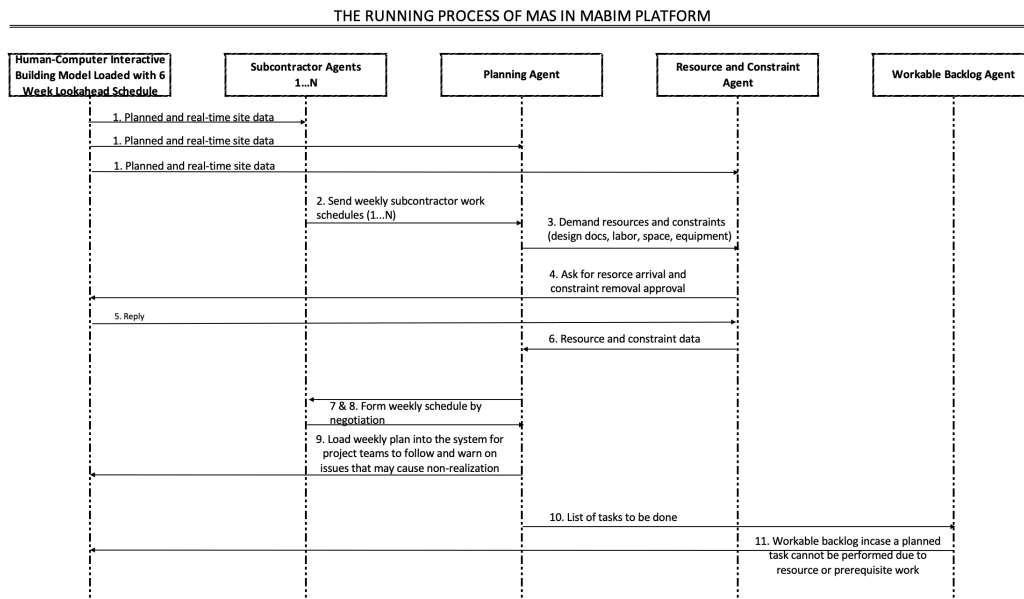


Figure 7.2 The running process of MAS in MABIM

7.2.2 Processes in MABIM

7.2.2.1 Process 1 - Operation Level Plan

In Process 1 (Figure 7.3), planners identify the tasks to be performed for the next 2-6 weeks from the higher level schedule that is integrated in the MABIM platform. Both planner and crew leaders breakdown the tasks as necessary and form relationships between tasks. After the first run studies, the plan is shared with users so that each department identifies constraints, responsibilities, risks and info related to their discipline in order for them to perform their tasks. The formed operational level plan is loaded onto the platform where a digital model with operational level plan is formed which shows the tasks that SHOULD be done. Platform informs users about the constraints and responsibilities for each discipline so that every user removes constraints and allocates resources that is in their responsibility.

7.2.2.2 Process 2 - Assignment Level Plan

In Process 2 (Figure 7.4), planners identify tasks for the week and the workable backlog using the digital model with operational level plan. A weekly task list is formed and crew leaders breakdown these tasks and form relationships if further detail is necessary, then identify specific resources, constraints and requests. Assignment level plans are formed by each subcontractor crew leader is sent for confirmation to the planners for approval and to procurers for deliverability of

resources. After confirmation final assignment level plans are formed for each subcontractor.

7.2.2.3 Process 3 - Work Plan Coordination

In Process 3 (Figure 7.5), assignment level plans of all crews/subcontractors are coordinated through the multi agent system in MABIM platform. Then the system asks each user for confirmation that all required resources are available and all constraints are removed. If all is confirmed then weekly work plan is sent to planners for confirmation and after confirmation digital model with coordinated work plan which shows what CAN be done is formed. If not, then the system asks for new plans and process 2 is repeated.

7.2.2.4 Process 4 - Daily Work List

In Process 4 (Figure 7.6), MABIM platform forms daily work lists for the week with assigned resources and responsibilities. Crew leaders check the daily work lists and commit to the weekly plan. If all crew leaders do not commit then process 3 is repeated. If all crew leaders do commit digital model with daily work lists showing what WILL be done is formed and procurers are notified to ensure just in time delivery of resources according to the plan.

7.2.2.5 Process 5 - Daily Work Record

In Process 5 (Figure 7.7), using the MABIM platform, crew leaders check the daily work to be performed and confirm that the work will be performed. If they cannot perform the daily tasks for some reason the platform lists new tasks from the workable backlog and warns system users so that they take the necessary corrective/preventive actions if needed. If crew leaders can perform the planned daily tasks, they input the task, crew, equipment, material, location information and any needed description through the user interface where the system forms the worklog. The system is updated with the input information and system users are warned to input necessary information about the tasks being performed. After all the information about the daily tasks are collected the digital model with the daily work record showing DID is formed.

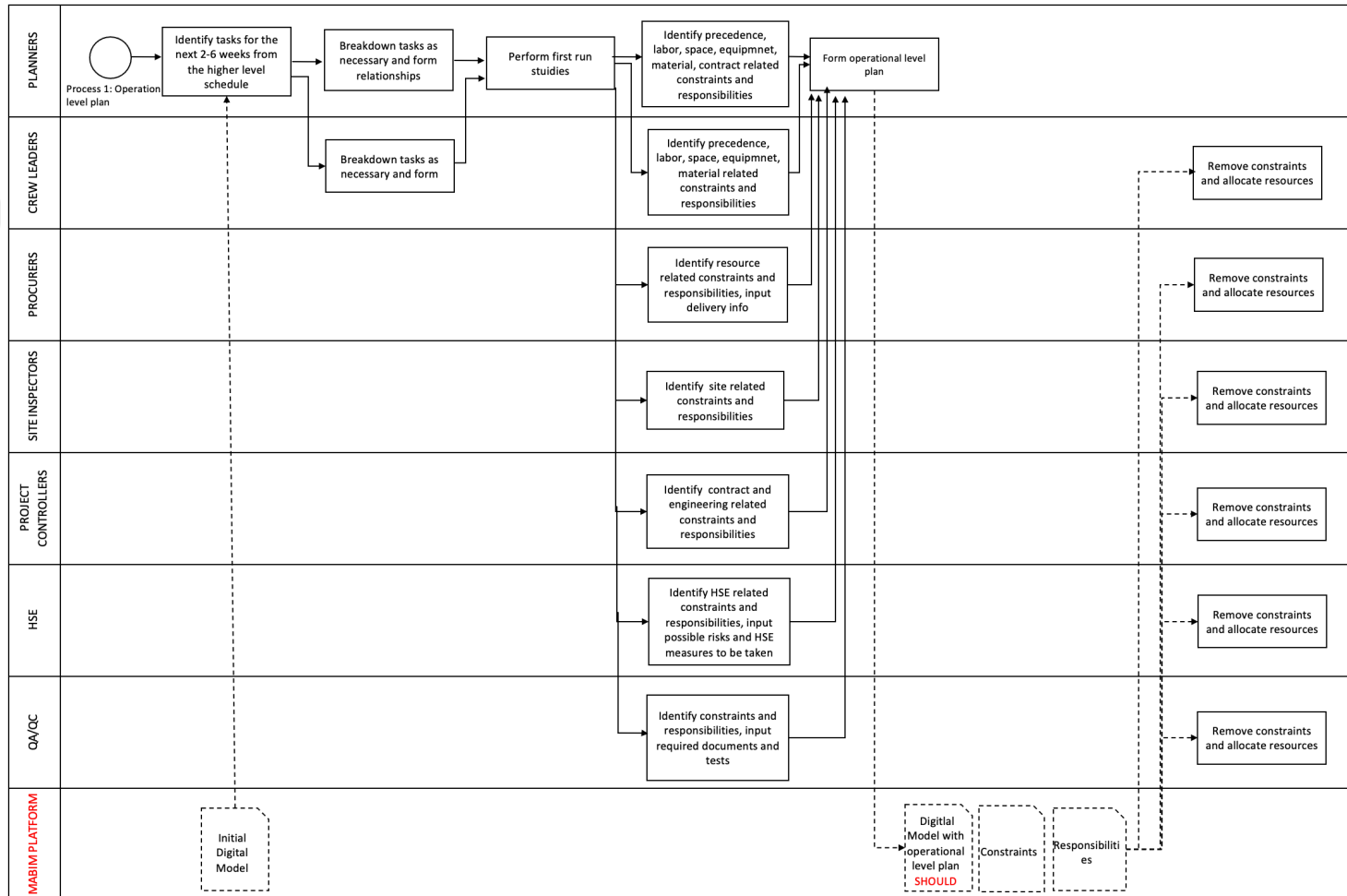


Figure 7.3 Process 1 - Operation level plan

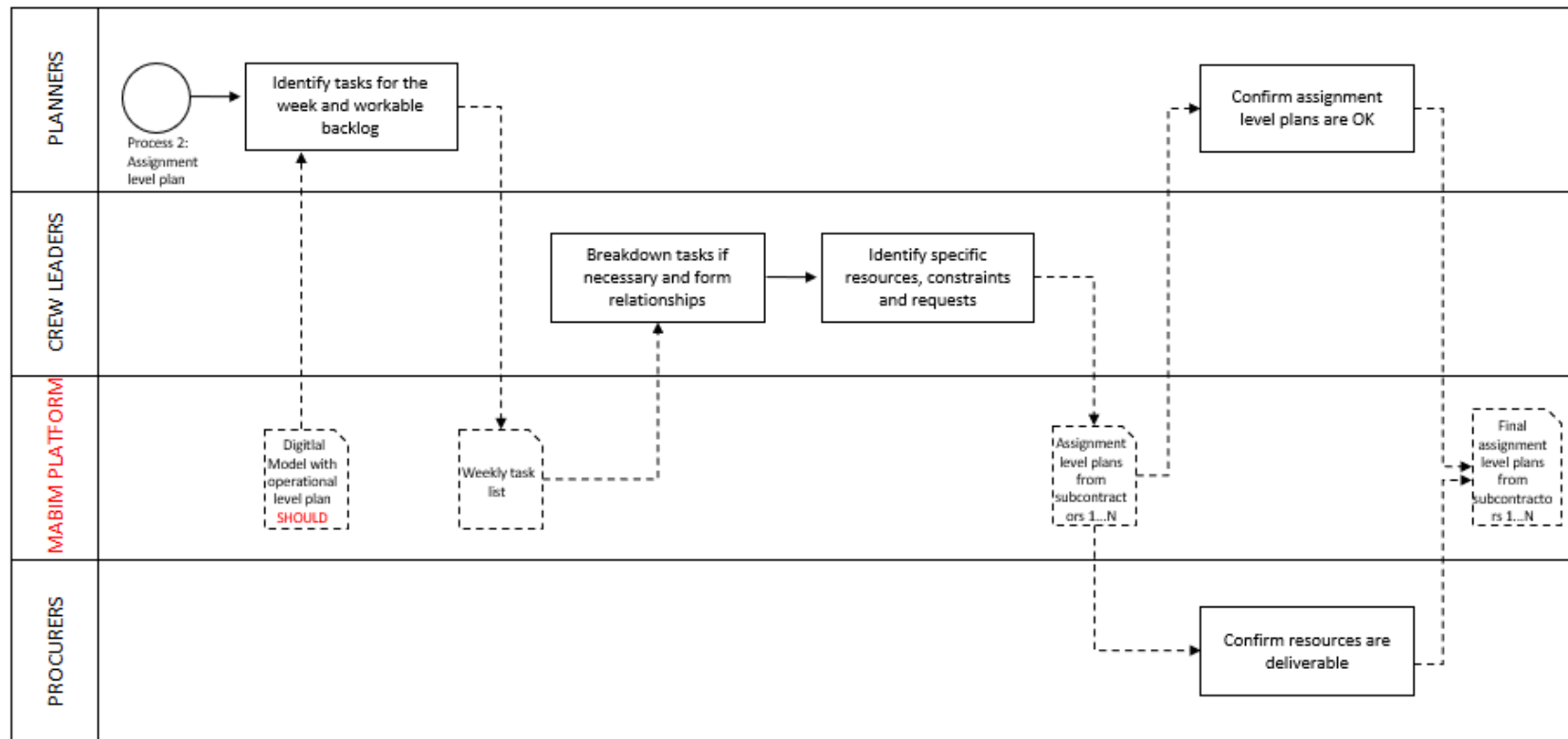


Figure 7.4 Process 2 - Assignment level plan

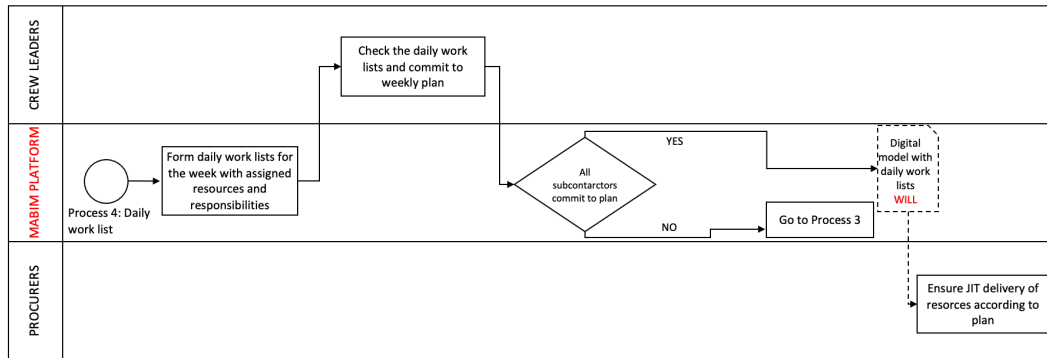


Figure 7.6 Process 4 - Daily work list

7.2.2.6 Process 6 - Measure and Analyze

In Process 6 (Figure 7.8), through the daily work record, a process digital twin of the project is formed by the system. The process digital twin can be used for auto as built schedules, feedback for schedule updates and meetings, percent plan complete report, plan reliability report, constraints and occurrences reports, subcontractor reliability reports, daily reports, productivity reports, resource reports, QA/QC reports, HSE reports, status reports, earned value analysis, forecasts and can be integrated to PM or ERP system of the organization.

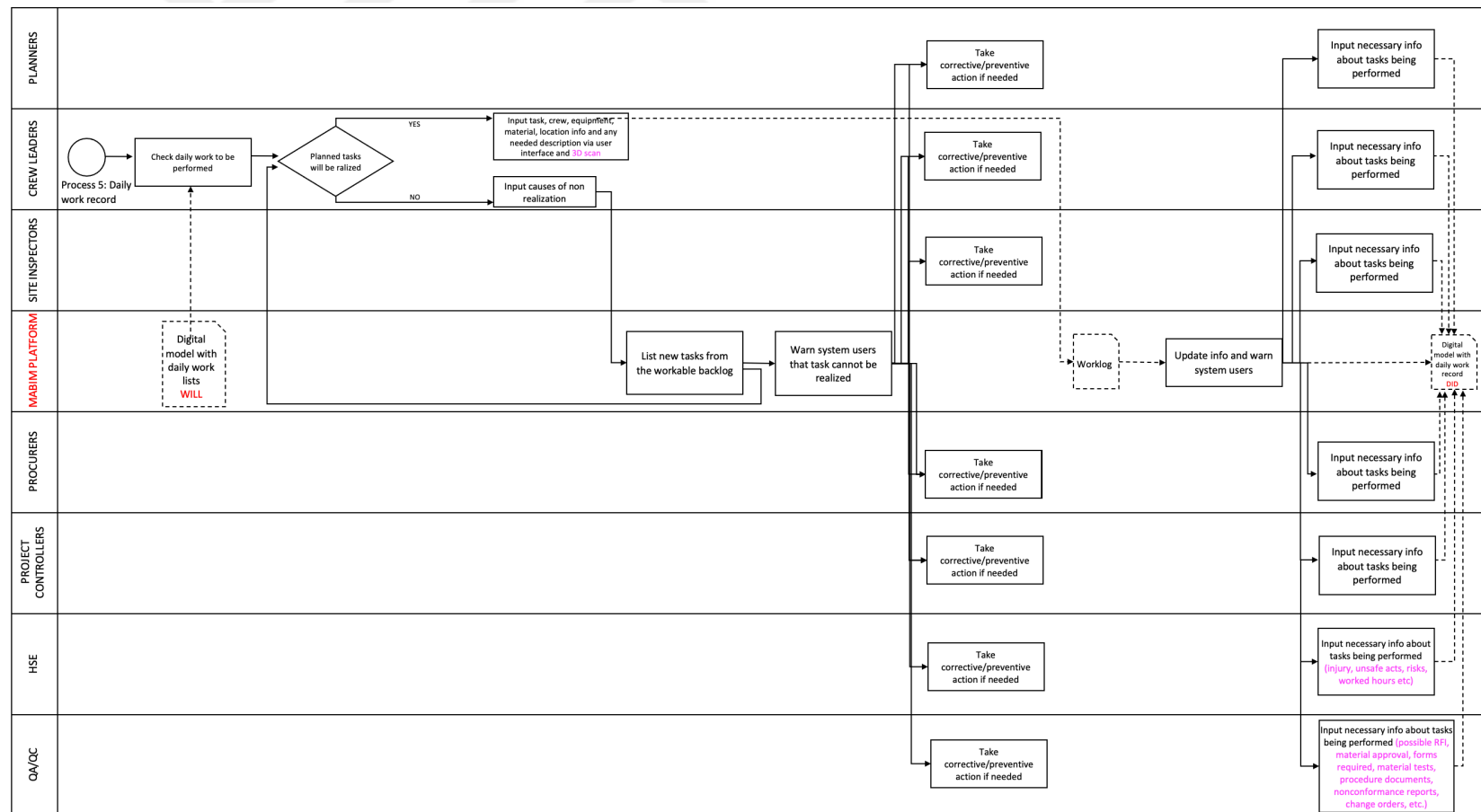


Figure 7.7 Process 5 - Daily work record

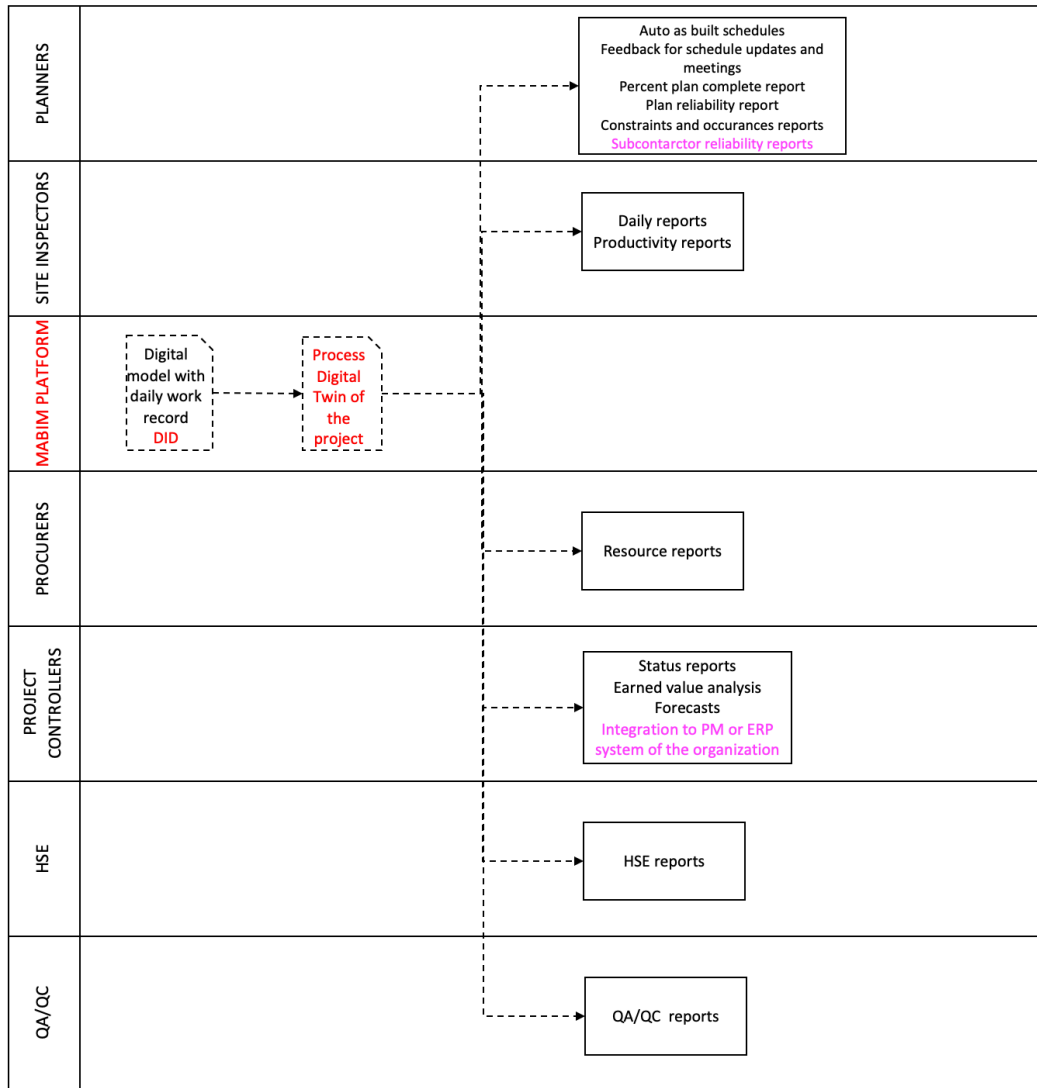


Figure 7.8 Process 6 - Measure and analyze

This section covers the evaluation of the proposed framework by presenting the evaluation criteria and expert interviews.

8.1 Introduction

Building and evaluating are two activities that define design science research and evaluation of the research output is crucial (March and Smith, 1995). Evaluation activities are identified as naturalistic and artificial depending on their nature (Venable et al., 2012). Naturalistic evaluation investigates the performance of a proposed solution by carrying it out in a real environment embracing the complexities of human practice (Venable et al., 2016). Since carried out in a real environment, naturalistic evaluations often have high external validity and they offer different perspectives by involving different stakeholders (Johannesson and Perjons, 2014). Naturalistic ex post evaluation methods for design science research include case studies, field experiments, surveys, expert interviews and focus groups (Sonnenberg and vom Brocke, 2012). Since in depth interviews reach thematic saturation more easily and there is no risk of possible contamination or group bias, expert interviews were conducted to test the validity of the framework proposed in this study (Namey et al., 2016; Hevner and Chatterjee, 2010).

8.2 Evaluation Criteria

Many frameworks and criteria have been proposed for evaluation. Based on literature review following evaluation criteria was proposed for the validation of proposed framework by expert opinion through interviews (Van der Merwe et al, 2020; March and Smith, 1995; Venable et al., 2012; Johannesson and Perjons, 2014; Herselman and Botha, 2015; Kitchenham and Linkman, 2005):

- Utility and efficacy: To what extent is the proposed framework effective for solving the problem it has been proposed?
- Semantic quality (Validity and completeness): Is the framework correct and relevant to the problem? Does it contain all statements about the domain that are correct and relevant?

- Pragmatic quality (Understandability): Is the framework satisfactorily understandable?
- Comparison: How does the framework compare to similar works?
- Side effects: What are the most likely undesirable outcomes?
- Weaknesses: What are the areas for improvement?

8.3 Interviewees

The sample size in interviews depends on theoretical saturation, the point of commonality where little or no new information is produced from the incoming responses. Six to eight participants can uncover 80% of the issues within a system and reach saturation (Guest et al., 2006; Namey et al., 2016). Seven experts were invited to take part in interviews in this study whose descriptive information can be seen on Table 8.1.

Table 8.1 Descriptive information of interviewees

#	Profession	Role	Experience	Experience with LC and DT or BIM	Company Type
1	Civil Engineer	Academic	18 years	7 / 10 years	University
2	Industrial Engineer	Project controls manager	21 years	5 / 8 years	Large scale general contractor
3	Civil Engineer	Founder	16 years	4 / 11 years	Tech startup – cloud based DT platform
4	Software Engineer	Founder and CEO	29 years	4 / 15 years	Software company – project lifecycle tracing through DT
5	Civil Engineer	Academic	24 years	17 / 12 years	University
6	Civil Engineer	BIM Coordinator	15 years	3 / 11 years	Large scale consultant
7	Civil Engineer	Assistant general manager	26 years	6 / 9 years	Large scale general contractor

8.4 Interviews and Evaluation

After generating the framework and its processes, expert interviews were used to evaluate the proposed framework. In this context, seven interviews were conducted with experts who have experience and/or knowledge about LC, DT, BIM and digital technologies in construction to evaluate the proposed based on evaluation criteria listed on section 8.2. Each interview took 1,5 h on average, and framework have been evaluated according to the evaluation criteria by all interviewees.

In terms of pragmatic quality, experts were asked if the framework was satisfactorily understandable. Expert 1 found the framework understandable and stated that the MAS system within the framework has no loopholes and suggested a few improvements such as naming procurer as resource provider so that its scope would be expanded and naming planning agent as scheduling agent because of its role. Expert 2 found the framework satisfactorily understandable and easy to understand since it covers the daily tasks that need to be done on a construction site and has a realistic approach. Expert 3 found the framework clearly understandable for everyone especially with the process flow diagrams. The expert stated that the process digital twin is very clear, but there is uncertainty about whether the digital twin of the project has been created and although the aim of the system is to reveal the digital twin of the process, it is also possible to reveal the digital twin of the project if sensor and 3D capturing technologies are used. Expert 4 found the framework clearly understandable and stated that although the framework uses general terms, it can explain the system in detail. Expert 5 found the framework logical and correctly formed but stated that it may be difficult for someone without a certain degree of knowledge about LC and DT to understand and although it is easy for people who are familiar with the concepts to understand the scope and what is aimed to achieve, more clarity may be needed for people who are not familiar with the concepts. Expert 6 found the framework generally understandable but stated that verbal explanation helps understanding process steps more thoroughly. Expert 7 stated that a non-expert may have difficulty understanding the framework unless explained but found the framework clearly understandable for people who are familiar with the subjects.

In terms of utility and efficacy, experts were asked if the proposed framework was effective for preventing problems that may be encountered during planning and control in lean construction applications, for providing decision-making support and real-time visual project planning and control support. Expert 1 found the framework useful and sufficient for achieving its purpose. The expert stated that the framework allows for unsystematicity and can also provide excellent service to agile production. Expert 2 found the framework to offer improved version of what is currently done on their own sites thus sufficing to achieve its purpose. Expert 3 found the visual support and systems ability to allow participation of entire team in planning to be especially important but stated that qualified workforce, company willingness, and users' dedication of their time are the factors that the framework depends on to serve its purpose. Expert 4 stated that the framework follows a parallel method with the Last Planner, presents the realized process management performance, can solve many of the mentioned problems encountered in lean construction practices and visualization is very clear. The expert also proposed that if the framework can clearly display red flags and automatic warning mechanisms, it will be much more effective. Expert 5 stated that in order for the framework to be adequate and effective, it must have many control points and the flexibility to change for every situation encountered on the way. The expert said that in construction projects happy paths, the scenarios where everything goes well, never work, so it should be confirmed at every stage that everything is okay, feedback should be provided if necessary and as many checkpoints as possible should be placed between actions. Expert 6 stated that the framework is capable of achieving its purpose, but in order for it to be effective, it is necessary to express more clearly that the data in the field can be collected and synchronized digitally and it may be necessary to show the big picture and the coordination of the underlying system. Expert 7 found the framework to be sufficient to achieve its purpose and stated that planning is a difficult process as it requires estimation, but the system supports this issue as it offers reversal options, supports communication and proposed providing feedback for any problems regarding the human factor for correct usage. Expert 8 found the framework successful and effective in achieving its goals and stated that being able to see whether what is planned is realized and providing the opportunity to intervene are important criteria for the effectiveness of the system.

In terms of semantic quality, the experts were asked if the framework accurately covered the full scope of the subject considering lean construction practices and digital twin functionalities. Expert 1 found the framework to accurately cover the scope, especially collaboration and communication but stated that although visualization, advanced field detection and AI are obvious from the framework and flows, they should be shown more clearly. Expert 2 found the framework to cover the scope, especially visualization, collaboration, communication and encouraging everyone's contribution. The expert stated that once the system is developed, designed correctly according to the project and all users have the necessary competence, it is an excellent tool for communication and with its features, it definitely supports lean construction practices. Expert 3 found the framework particularly successful in reducing waste, increasing productivity/efficiency, reducing variability, involving the whole team in planning and stated that the system can be geared towards specific needs with making adjustments according to project needs. Expert 4 stated that digital twin is a living system needing more nourishment and it is important that what is happening is shown more holistically, that it can be followed digitally, and that what is happening can be reported. The expert added that from this point of view, the framework can be improved a little more, but other than that it meets the scope. Expert 5 stated that the framework covers the scope, but focusing on a single point, such as planning, and detailing the framework around this point can ensure that the scope is included more accurately. Expert 6 found the framework to cover the subject correctly and to be very close to digital twin having a virtual-reality cycle. Expert 7 found the framework to be successful in reflecting the scope and containing necessary elements for both process digital twin creation and lean construction planning and providing decision-making support by providing guidance for unrealized work, not just reporting.

In terms of comparison, the experts were asked how the framework compared to similar works. Expert 1 found the framework to offer great contribution compared to similar works. Expert 2 found planning coordination by autonomous agents to be unique and stated that the framework also resembles ERP systems in terms of comprehensiveness but distant at certain points such as process of obtaining accounting and stock data, which may be possible by integration with other systems. Expert 3 stated that having certain common points with previous studies

is a good thing since it is an indication of relevancy of the problem and the solution, however MAS in the framework is unique and the framework represents a system that has a strong applicability. Expert 4 found the framework to be somewhat reminiscent of planning programs but stated that the element that makes the system stand out here is the data entry and feedback flowing into the system which should be very intense. Expert 5 stated that there is no similar work to the framework if the digital twin base is fitted properly. Expert 6 stated that the areas where the information exchange disconnection is most experienced are HSE and QA/QC and the framework fills the gap in literature on this subject; found the framework to be more collaborative than other systems in terms of bringing many different users into the same loop and found the ability to produce user-specific reports to also be an important feature. Expert 7 found the framework's ability to intervene by proposing alternative solutions rather than just keeping track of planned events to be the feature that makes it stand out among others.

In terms of side effects, the experts were asked what the most likely undesirable outcomes could be. Expert 1 stated that because of the structural differences in every project there will be a need for a system arrangement that can adapt to the dynamic structure and since there is no one fits all situation, a solution will need to be produced according to every project, software aspect will be difficult and especially the frontend part will be very busy, in case of commercialization risks will be too high and process digital twin concept that is found in the framework will have to be very clear for the users to fully comprehend. Expert 2 stated that the framework does not represent a one fits all system so that there will be a need for an initial period as a new scenario will be required for each project; found the framework to represent a somewhat complicated system which may require high training leading to problems regarding time and personnel turnover. Expert 3 stated that construction industry's resistance to change may lead to questioning of the system's validity in automation and predictive planning, and effectiveness leading to usage refusal. In this case the expert stated that it will be necessary to conduct a gain-loss analysis comparing the traditional application with the system proposed in this framework and convince potential users. Expert 4 found adaptability for different teams and project types as the biggest problem to be encountered. Expert also stated that the system demands time from team leaders, and it may be necessary

to measure the quality of the input provided by these extremely busy people. Expert 5 stated that it will be difficult to use this system effectively due to the number of people on the construction site, and in this case, the system will have difficulty in providing the full benefit expected from it. Expert 6 stated that subcontractor integration will be painful and the way they will be included in the system and what information will or will not be shared will require systematic permission. The expert also stated that there will be problems arising from human factor and since the inputs will come from people, users should be aware of their impact on the system. Expert 7 stated that the most likely undesirable consequences will be human caused since a deficiency in correct data entry, controlling the system and using it properly will lead to a risk of malfunctioning of the system.

In terms of weaknesses, the experts were asked about the areas for improvement. Expert 1 stated that when the backlog agent proposes a new job, it should suggest it from the critical line and obtain information from the model and master schedule or the last updated work schedule; there should be not only procurer but also a warehouse, accounting may be included, advance user definition can help adapting to dynamic structure of different projects, there is no need to give the planner a say in Process 3 since there is a risk of entering a loop, in Process 5 where the corrective/preventive actions feed should be shown more clearly, and integration to BIM or ERP can prevent multiple data entries. Expert 2 stated that the system is complicated but flexible enough in itself to give the user freedom of movement without forcing the user into a format, however it should also be able to offer this flexibility during the installation phase, adding that the system will work well in an environment where every wheel works very well, but the training cost that will arise for this must also be taken into consideration. The expert also suggested that, the control of plan reliability in the system is left to people and it would be much better if the control of plan reliability could also be provided by the system. Expert 3 stated that autonomization with machine learning, through human control for the workable backlog or an optional feed system, can help prevent the recommendation of jobs with similar constraints such as if a job could not be completed due to weather conditions, the system should not recommend a job to be done outside. The expert also suggested that the planning agent can coordinate the work using certain KPIs while coordinating the plans. Another suggestion by the expert was to create a

digital twin of the entire project by providing automatic input of the productions carried out in the field with sensors without the need for human information input. Expert 4 stated that adaptation can be considered in greater detail by adding more check points while considering variables such as project type, duration, etc. adding resource optimization can also be added to the system. Expert 5 stated that the system is currently very comprehensive, narrowing the scope and creating a more detailed framework will benefit in terms of understandability. Expert 6 stated that before and after processes, which are, design as input and facility management as output, can be included since there will be a lot of available data and it would be useful if this data can be used in the operational phase. Expert 7 stated that features that will be more effective in portfolio management, such as resource management, can be made more effective, making it more suitable for portfolio management in terms of ensuring coordination between projects; system seems to rather work more intensively on a single project.

8.5 Discussion

The proposed framework was evaluated through in depth interviews by 7 experts based on pragmatic quality, utility and efficacy, semantic quality, comparison, side effects and weaknesses. Based on the interview results, the proposed framework was found to achieve visualization of the process, increased communication, coordination and integration between processes by involving whole team, decision making support and waste reduction. Visualization of design, construction platform and processes through integrated models helps stakeholders from different backgrounds visualize the project as a whole and enhances coordination; communication in a rich real-time manner allows for up-to-date real time information sharing, enhanced coordination, and enable collaborative ways of working resulting in waste reduction; collaboration in real time enables qualified engineering, co-creation of sustainable solutions by different stakeholders, integration of various information from different parties which facilitates standardized processes, workflow, transparency, coordination and efficiency; data driven decision making based on robust and accurate data enables performance prediction, accurate estimation of costs and technical issues, ability to sustain same attitude throughout project life and early modifications (Sacks et al., 2020a; Kan

and Anumba, 2019; Natephra and Motamedi, 2019; Lin et al., 2019; Olatunji and Akanmu, 2015; Sawhney et al., 2020; Rommetveit et al., 2019; Novack, 2019; Kaewunruen and Lian, 2019; Hlady et al., 2018; Khajavi et al., 2019; Xu et al., 2018; Pan and Zhang, 2021; Boje et al., 2020; Anumba and Roofigari, 2020; Turner et al., 2021). In line with lean project management's aim to handle decision making by continuous communication and having project team react by a set of methods (Levitt, 2011), collaboration and cooperation between participants and use of information technology for improving integration, facilitates information sharing, access to up-to-date data and ability to make informed decisions (Forbes and Ahmed, 2011). High connectivity between the members of an organization improves performance (Castillo et al., 2018). Combining the collected data collected into a single model that is used by project participants as an information depository (Andújar-Montoya et al., 2020) as in digital twins, enables simulation of different scenarios and performing advanced analysis and serves as a medium to visualize, simulate, manifest, observe and control the physical asset to achieve more efficient, effective, and safer construction projects (Pishdad-Bozorgi et al., 2020).

5 experts found human factor to be important regarding time requirement from the users, quality of data input and users' awareness of their impact on the system, need for training and resistance to change. However, having human in the loop is vital since technological requirements of digital twins at device level include human interaction besides connectivity, data exchange and identifiers (Anumba and Roofigari-Esfahan, 2020). Effective implementation of digital technologies requires significant alterations in the way a construction company works and should engage people in adoption, improve people's skills and understandings, and minimize any potential change resistance (Arayici et al., 2011).

3 experts stated that increased checkpoints and automatic warning mechanisms would help decrease any problems that might arise regarding human factor. Human error is an important factor in system failures (Egwutuoha et al., 2013). Human computer interface design is important factor in preventing human errors. However there are some tradeoffs between qualities that make a user interface usable and safe. Making a user interface extremely usable may allow bypassing of very important safety checks and making a system extremely safe by confirming every action can cause the system to be unusable. Having descriptive messages and

appropriate feedback and guiding the user is important, but the balance between safety and usability should be arranged according to the safety criticality of the system (Shelton, 1999).

3 experts stated that there is no one fits all situation in terms of adaptability to different teams and project types. Construction is a project-based production process where the processes are determined by crews so there is potential for high variability (Forbes and Ahmed, 2011). Construction's products are location based and highly impacted by their environment and require adaptations therefore construction is described as a type of fixed position manufacturing where constructed objects are too large to move through fixed workstations so mobile workstations move through constructed objects (G. Ballard and Tommelein, 2012). In this regard, creating large number of short processes instead of small number of long processes may enhance adaptability.

3 experts proposed improvement in MAS and machine learning integration for more accurate job recommendation and plan reliability control. Digital twin construction incorporates real-time feedback from monitoring technologies, archived information, and machine learning tools. Progress in AI tools, semantic enrichment of BIM models and their accessibility to machine learning tools, and analysis systems are required to bring digital twin into fruition (Sacks et al., 2020a).

2 experts proposed forming the digital twin of the entire project rather than of just the process through sensors and 3D capturing technologies. Three components that make up a digital twin are the physical entity, digital model that accompanies the physical entity throughout its lifetime and the connection that enables exchange of data between the two. It is a specific form of cyber physical system that refers to a near-real time digital replica of a component, product or system, which includes all information that could be useful throughout all lifecycle phases, a dataset representing the state of a system and its development over time. This virtual model of a physical asset, process or a system is dynamic through the involvement of IoT devices and information feedback from people (Boschert and Rosen, 2016; Chevallier et al., 2020; Kan and Anumba, 2019; Lu, Parlikad, et al., 2020b; Rasheed et al., 2020; Tao et al., 2020). Integration of IoT through sensors to monitor the construction progress during construction or to connect the building to various systems to integrate energy and other disciplines after construction, during facility

management has many promising possibilities one of which is the creation of a more realistic virtual representation of components, construction processes and maintenance operations of a building through real time data streams (Aleksandrova et al., 2019; Nykänen et al., 2017; Shahinmoghdam and Motamedi, 2019).

Based on the feedback from the expert interviews system framework, running process of MAS and process 5 are revised. IoT systems are integrated into the framework to create a more comprehensive representation of the components enabling creation of a digital twin of the project. Running process of MAS is revised so that the planning agent is named as plan coordination agent and it is shown that the subcontractor agents, plan coordination agent and resource and coordination agent is provided with worklog information so that agents can learn. Process 5 – Daily work record is revised so that data flow from the sensors and 3D capturing technologies is shown and information about non-realized tasks are also input into the worklog. Revised charts can be seen on Figures 8.1, 8.2 and 8.3.

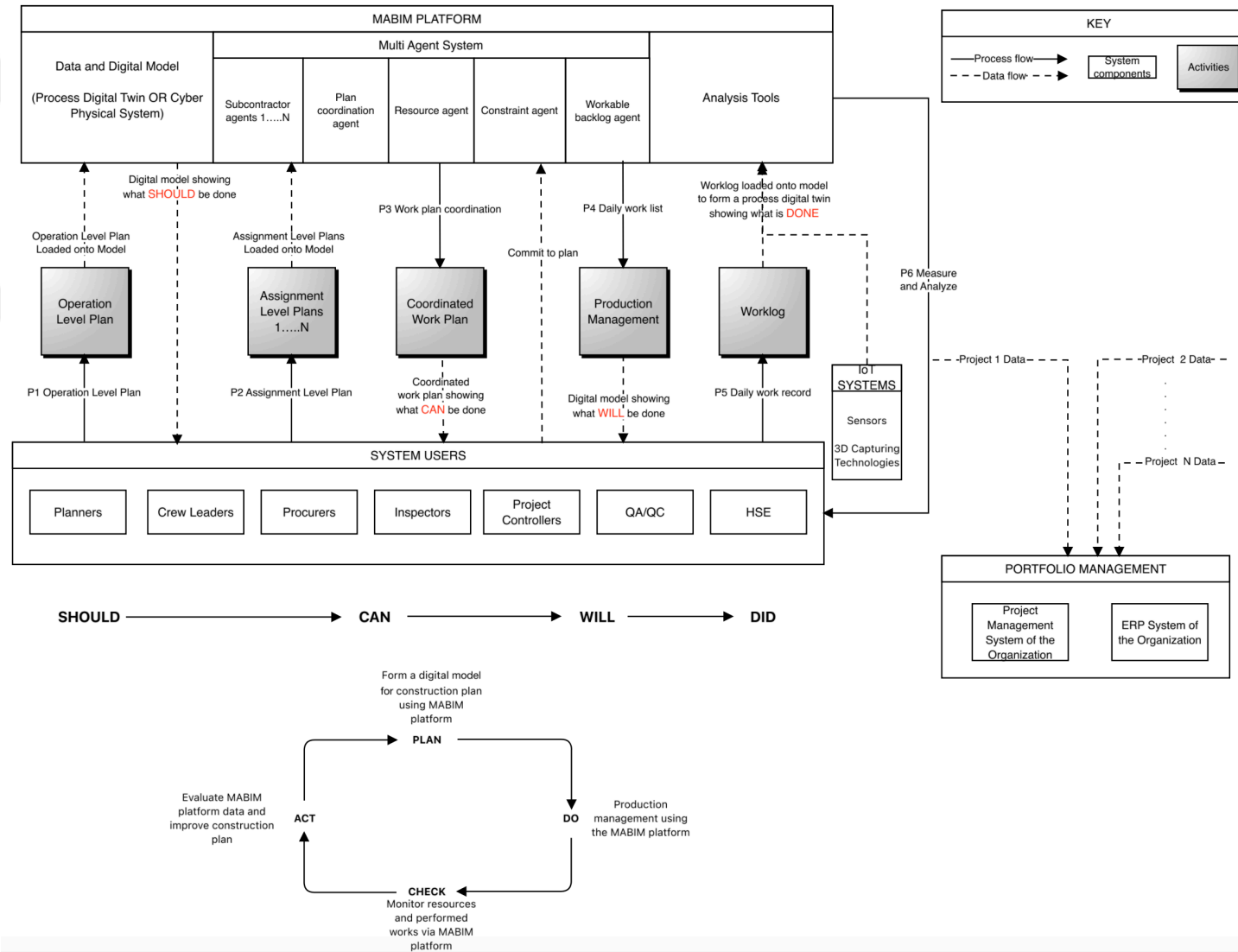


Figure 8.1 System framework revise

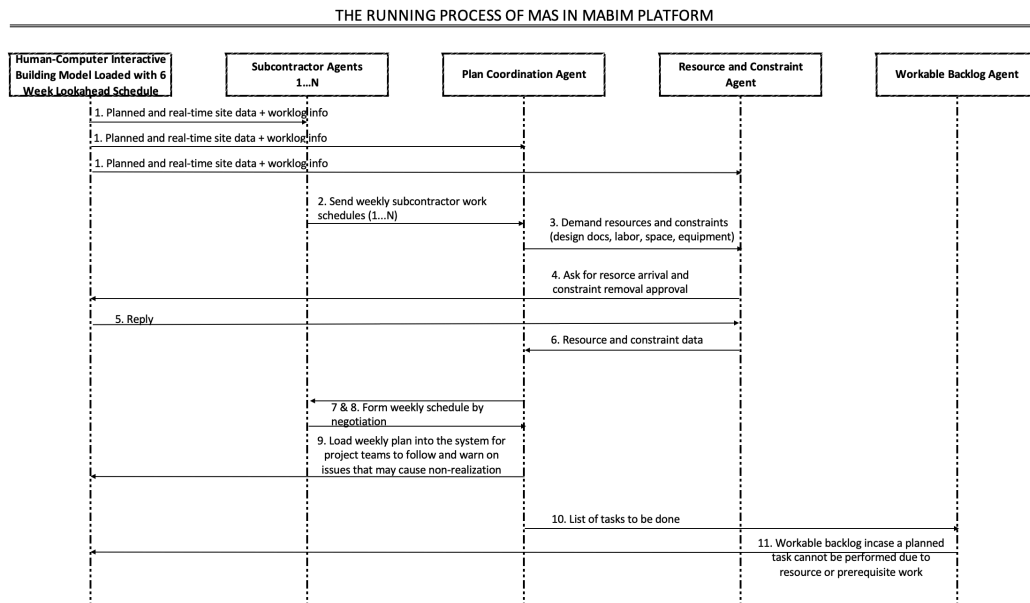


Figure 8.2 The running process of MAS in MABIM revised

9

CONCLUSION

Planning is usually the main focus of the tools used on construction sites for project management and schedules change due to uncertainty in duration and variation as the construction progresses. Field workers prepare their own work plans for adequate production planning and control and lean construction methods are useful in this perspective since they support faster response and reduced uncertainty and constraints. Lean principles have an interdependent relationship with digital technologies in construction, and digital twins, which gather these digital technologies under one roof, improve integration, facilitate information sharing, enable accessing up to date data and support collaboration and coordination and support implementation of lean principles in this sense.

As the time between planning and implementation increases so does the variance and uncertainty. Communication and coordination at lower levels in planning process regularly before execution helps adapting to uncertainties and finding the best solutions to the problems. Lean planning and control approaches aim to make problems visible at an earlier stage. However, linkage between different levels of plans, quick constraint identification and removal and information exchange and integration are vital.

9.1 Conclusion

Aim of this thesis is to develop a framework for visual project progress monitoring and decision support system based on multi agent systems and digital twin for lean project scheduling, that helps minimize waste of materials, time, and effort in order to generate the maximum possible amount of value. Objective is to uncomplicate lean construction scheduling system implementation by organizing it through constraint analysis, sustainable commitment, integration between processes, and stronger understanding by clearer communication and higher connectivity between parties. The proposed system aims to connect planning systems and heterogeneous data. Multi agent system that is integrated in the platform aims to support planners and management in negotiation intensive approaches, like offering decision support on optimal duration, sequencing of tasks etc. The proposed system aims to enable

proactive modelling, tracking and optimization of construction works and their relevant resources, enabling close collaboration between parties and faster reaction so that the project delivery system will be more effective and efficient by improved integration, information sharing, access to up to date data and decision making assistance.

Considering lean construction principles and use of innovative technologies, a framework for lean construction scheduling, management and control system is proposed that incorporates plan do check act cycle, should can will did view, different levels of planning, schedule coordination, constraint management, progress monitoring, enhanced communication between parties, multi dimensional visualization and improved analysis. The workflow in the proposed framework consists of 6 processes that use should-can-will-did principle from the Last Planner System as a basis. The processes are operation level plan, assignment level plan, coordinated work plan, production management, worklog and measure and analyze. These processes express the workflow between the users and the system and altogether apply the plan-do-check-act cycle. The system consists of data and digital model, multi agent system and analysis tools. “Plan” phase is realized by forming a digital model for construction plan using the system, “Do” phase is realized by production management using the system, “Check” phase is realized by monitoring resources and performed works via the system and “Act” phase is realized by evaluating the system data and improving the construction plan. Multi agent system is used for dynamic scheduling, forming, and coordinating work plans of the subcontractors.

The proposed framework is evaluated by 7 experts through in depth interviews based on 6 evaluation criteria which are pragmatic quality, utility and efficacy, semantic quality, comparison, side effects and weaknesses.

All 7 experts found the framework understandable however, 2 of the experts thought the framework could be hard to understand for people without prior knowledge on lean construction and digital twins and 1 of the experts stated that verbal explanation assists clear understanding.

6 of the 7 experts found the framework to have the ability to achieve its purpose. System’s ability to allow for unsystematicity, obtain participation of entire team,

assist communication, provide visualization, presenting realized works and process management performance and provide opportunity intervene were the mentioned properties which were stated to help in effectiveness. 3 of the 7 experts stated that increased checkpoints and automatic warning mechanisms would help decrease any problems that might arise regarding human factor thus increasing utility and efficacy.

5 of the 7 experts found the framework to cover the scope of the subject considering lean construction practices and digital twin functionalities and 2 of the 7 experts stated that although the framework covered the scope, it could be improved. One of them proposed a more holistic approach to show what is happening in a living system, and the other one proposed to focus on a single point such as planning and detailing the framework around it. Collaboration, communication, visualization, virtual-reality cycle and decision making support were the most mentioned factors in regard to framework's semantic quality.

All of the 7 experts found the framework to offer contribution compared to similar works. One of the experts compared the framework to ERP systems and another compared it to planning programs. The features the experts found most standing out were multi agent system within the framework, process digital twin, user inclusiveness especially HSE and QA/QC, and user specific reporting.

In terms of undesirable outcomes, most mentioned factors were human and adaptability. 5 of the experts found human factor to be an important problem regarding time requirement from the users, quality of data input and users' awareness of their impact on the system, need for training and resistance to change. 3 of the expert stated that there is no one fits all situation and adaptability to different teams and project types will be the biggest problem encountered. One expert mentioned the systematic permission regarding information sharing to be an issue.

The most mentioned areas for improvement were automatization and flexibility. 3 of the experts proposed improvement in MAS and machine learning integration for more accurate job recommendation in case of non-realization of planned works and plan reliability control. 3 of the experts stated adaptation to different projects could be improved by considering different variables such as project type, duration etc.

and adding more check points. Increased integration was proposed by 2 experts such as warehouse data, accounting data, design management and facility management. 2 of the experts found the system complicated and stated that the training cost could be high. 2 of the experts proposed considering resource management and optimization which could also help in portfolio management. 2 of the experts proposed forming the digital twin of the entire project rather than of just the process through sensors and 3D capturing technologies.

Based on the evaluation of the experts through in depth interviews, the proposed framework was found to achieve visualization of the process, increased communication, coordination and integration between processes by involving whole team, decision making support and waste reduction. These results showed that the proposed framework was able to fulfill its aim.

In line with the feedback from the expert interviews system framework is improved in terms of automatic data collection and machine learning by revising Process 5 – Daily work record, running process of MAS, and main system framework. IoT systems are integrated into the framework so that data flow from the sensors and 3D capturing technologies enable a more comprehensive representation of the components enabling creation of a digital twin of the project.

9.2 Prospective studies

Prospective studies include further developing the proposed framework by minimizing human factor by including more checkpoints and red flag and warning mechanisms as the experts proposed and detailing the integration of digital data collection technologies like sensors and 3D capturing enabling the emergence of the digital twin of not just the process but the whole project. Since the proposed artefact is a theoretical framework, running process, planning and merging algorithms and negotiation processes of the multi agent system within the framework will have to be elaborated and developed for being able to develop the system the framework represents. Besides the multiagent system, visualization of the tasks and reevaluation of the user identification will have to be worked on in detail so the system is able to show every task in a way every user can understand and able to support every user, especially in terms of crews, when developed.

REFERENCES

- Abdel-Basset, M., Mohamed, M., Zhou, Y. and Hezam, I. (2017). Multi-criteria group decision-making based on neutrosophic AHP. *J Intell Fuzzy Syst*, 33(6):4055–4066.
- Abdel-Basset M., Mohamed M. and Smarandache F. (2018). An Extension of Neutrosophic AHP–SWOT Analysis for Strategic-Planning and Decision-Making. *Symmetry*, 10(4):116.
- Afsari, K., Eastman, C., and Shelden, D. (2017). Building information modeling data interoperability for cloud-based collaboration: Limitations and opportunities. *International Journal of Architectural Computing*, 15(3), 187–202.
- Agyekum, K., Ayarkwa, J., and Adjei-Kumi, T. (2013). Minimizing Materials Wastage in Construction: a Lean Construction Approach. *Journal of Engineering and Applied Sciences*, 5(1), 125–146.
- Ahuja, R., Sawhney, A., and Arif, M. (2018). Developing organizational capabilities to deliver lean and green project outcomes using BIM. *Engineering, Construction and Architectural Management*, 25(10), 1255–1276.
- Al-Aomar, R. (2012). A lean construction framework with Six Sigma rating. *International Journal of Lean Six Sigma*, 3(4), 299–314.
- Al-Saeed, Y., Edwards, D. J., and Scaysbrook, S. (2020). Automating construction manufacturing procedures using BIM digital objects (BDOs): Case study of knowledge transfer partnership project in UK. *Construction Innovation*.
- Al Hattab, M., and Hamzeh, F. (2015). Using social network theory and simulation to compare traditional versus BIM-lean practice for design error management. *Automation in Construction*, 52, 59–69.
- Alarcón, L. F., Diethelm, S., Rojo, O., and Calderón, R. (2008). Assessing the impacts of implementing lean construction. *Revista Ingenieria de Construcción*, 23(1), 26–33.
- Aleksandrova, E., Vinogradova, V., and Tokunova, G. (2019). Integration of digital technologies in the field of construction in the Russian Federation. *Engineering Management in Production and Services*, 11(3), 38–47.
- Alsehaimi, A. O., Fazenda, P. T., and Koskela, L. (2014). Improving construction management practice with the Last Planner System: A case study. *Engineering, Construction and Architectural Management*, 21(1), 51–64.
- Alves, T. da C. L., and Tsao, C. C. Y. (2007). Lean construction – 2000 to 2006. *Lean Construction Journal*, 3(1), 46–70.
- Amoah, E. K., and Nguyen, T. V. (2019). Optimizing the usage of Building Information Model (BIM) interoperability focusing on data not tools. *Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019*.
- Andújar-Montoya, M. D., Galiano-Garrigós, A., Echarri-Iribarren, V., and Rizo-Maestre, C. (2020). BIM-LEAN as a methodology to save execution costs in

- building construction-An experience under the spanish framework. *Applied Sciences (Switzerland)*, 10(1913).
- Ansah, R. H., and Sorooshian, S. (2017). Effect of lean tools to control external environment risks of construction projects. *Sustainable Cities and Society*, 32, 348–356.
- Anumba, C. J., and Roofigari-Esfahan, N. (2020). *Cyber-Physical Systems in the Built Environment*. Springer.
- Anumba, C. J., and Roofigari, N. (Eds.). (2020). *Cyber-Physical Systems in the Built Environment*. Springer International Publishing.
- Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C., and O'Reilly, K. (2011). Technology adoption in the BIM implementation for lean architectural practice. *Automation in Construction*, 20, 189–195.
- Augustine, P. (2020). The industry use cases for the Digital Twin idea. In *Advances in Computers* (Vol. 117, Issue 1). Elsevier Inc.
- Babalola, O., Ibem, E. O., and Ezema, I. C. (2019). Implementation of lean practices in the construction industry: A systematic review. *Building and Environment*, 148, 34–43.
- Ballard, G. (2008). The Lean Project Delivery System: An Update. *Lean Construction Journal*, 1–19.
- Ballard, G., and Tommelein, I. (2012). Lean Management Methods for Complex Projects. *Engineering Project Organization Journal*, 2, 85–96.
- Ballard, G., and Tommelein, I. (2014). Current Process Benchmark for the Last Planner System. *Lean Construction Journal*, 57–89.
- Ballard, H. G. (2000). *The Last Planner System of Production Control* (Issue May).
- Banawi, A., and Bilec, M. M. (2014). A framework to improve construction processes: Integrating Lean, Green and Six Sigma. *International Journal of Construction Management*, 14(1), 45–55.
- Bataglin, F. S., Viana, D. D., Formoso, C. T., and Bulhões, I. R. (2020). Model for planning and controlling the delivery and assembly of engineer-to-order prefabricated building systems: Exploring synergies between lean and BIM. *Canadian Journal of Civil Engineering*, 47, 165–177.
- Bataw, A., Kirkham, R., and Lou, E. (2016). The Issues and Considerations Associated with BIM Integration. *MATEC Web of Conferences*.
- Belsky, M., Sacks, R., and Brilakis, I. (2016). Semantic Enrichment for Building Information Modeling. *Computer-Aided Civil and Infrastructure Engineering*, 31, 261–274.
- Bevilacqua, M., Bottani, E., Ciarapica, F. E., Costantino, F., Donato, L. Di, Ferraro, A., Mazzuto, G., Monteriù, A., Nardini, G., Ortenzi, M., Paroncini, M., Pirozzi, M., Prist, M., Quatrini, E., Tronci, M., and Vignali, G. (2020). Digital twin reference model development to prevent operators' risk in process plants. *Sustainability (Switzerland)*, 12(3), 1–17.
- Björnfot, A., and Jongeling, R. (2007). Application of line-of-balance and 4D CAD for lean planning. *Construction Innovation*, 7(2), 200–211.

- Boje, C., Guerriero, A., Kubicki, S., and Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. *Automation in Construction*, 114.
- Bolton, A., Butler, L., Dabson, I., Enzer, M., Evans, M., Fenemore, T., Harradence, F., Keaney, E., Kemp, A., Luck, A., Pawsey, N., Saville, S., Schooling, J., Sharp, M., Smith, T., Tennison, J., Whyte, J., Wilson, A., and Makri, C. (2018). The Gemini Principles. In *CDBB_REP_006*.
- Bonci, A., Carbonari, A., Cucchiarelli, A., Messi, L., Pirani, M., and Vaccarini, M. (2019). A cyber-physical system approach for building efficiency monitoring. *Automation in Construction*, 102, 68–85.
- Bortolini, R., Formoso, C. T., and Viana, D. D. (2019a). Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling. *Automation in Construction*, 98, 248–264.
- Bortolini, R., Formoso, C. T., and Viana, D. D. (2019b). Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling. *Automation in Construction*, 98(November 2018), 248–264.
- Boschert, S., and Rosen, R. (2016). Digital Twin-The Simulation Aspect. In *Mechatronic Futures* (pp. 59–74).
- Brilakis, I., and Haas, C. (2020). *Infrastructure computer vision*. Butterworth-Heinemann.
- Camposano, J. C., Smolander, K., and Ruippo, T. (2021). Seven metaphors to understand digital twins of built assets. *IEEE Access*, 9.
- Castillo, T., Alarcón, L. F., and Salvatierra, J. L. (2018). Effects of Last Planner System Practices on Social Networks and the Performance of Construction Projects. *Journal of Construction Engineering and Management*, 144(3).
- Cesarotti, V., Gubinelli, S., and Introna, V. (2019). The evolution of Project Management (PM): How Agile, Lean and Six Sigma are changing PM. *The Journal of Modern Project Management*, 7(3).
- Chevallier, Z., Finance, B., and Boulakia, B. C. (2020). A reference architecture for smart building digital twin. *CEUR Workshop Proceedings*, 2615, 1–12.
- Choo, H. J., Hammond, J., Tommelein, I. D., Austin, S. A., and Ballard, G. (2004). DePlan: A tool for integrated design management. *Automation in Construction*, 13(3), 313–326.
- Choo, H. J., Tommelein, I. D., Ballard, G., and Zabelle, T. R. (1999). WorkPlan: Constraint-Based Database for Work Package Scheduling. *Journal of Construction Engineering and Management*, 125(3), 151–161.
- Chua, D. K. H., and Shen, L. J. (2005). Key Constraints Analysis with Integrated Production Scheduler D. *Journal of Construction Engineering and Management*, 131(7), 753–764.
- Chua, D. K. H., Shen, L. J., and Bok, S. H. (2003). Constraint-based planning with integrated production scheduler over internet. *Journal of Construction Engineering and Management*, 129(3), 293–301.
- Clayton, M., Kunz, J. and Fischer, M. (1998). The charrette test method. *CIFE Technical Rep*, 120.

- Corneli, A., Naticchia, B., Carbonari, A., and Bosch , F. (2019). Augmented reality and deep learning towards the management of secondary building assets. *Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019*.
- Costa, G., and Madrazo, L. (2015). Connecting building component catalogues with BIM models using semantic technologies: An application for precast concrete components. *Automation in Construction*, 57, 239–248.
- Court, P. F., Pasquire, C., and Gibb, A. (2009). A lean and agile construction system as a set of countermeasures to improve health, safety and productivity in mechanical and electrical construction. *Lean Construction Journal*, 2009, 61–76.
- Daniel, E. I., Pasquire, C., Dickens, G., and Ballard, H. G. (2017). The relationship between the last planner system and collaborative planning practice in UK construction. *Engineering, Construction and Architectural Management*, 24(3), 407–425.
- Dave, B., Hamalainen, J.-P., Kemmer, S., Koskela, L., and Koskenvesa, A. (2015). Suggestions to Improve Lean Construction Planning. *Proceedings of the 23rd Annual Conference of the International Group for Lean Construction*, 193–202.
- Dave, B., Koskela, L., and Kiviniemi, A. (2013). *Implementing Lean in construction - Lean construction and BIM*. CIRIA.
- Dave, B., Kubler, S., Fr mbling, K., and Koskela, L. (2016). Opportunities for enhanced lean construction management using Internet of Things standards. *Automation in Construction*, 61, 86–97.
- Dawood, N., and Sriprasert, E. (2006). Construction scheduling using multi-constraint and genetic algorithms approach. *Construction Management and Economics*, 24(1), 19–30.
- Deng, Y., Gan, V. J. L., Das, M., Cheng, J. C. P., and Anumba, C. (2019). Integrating 4D BIM and GIS for Construction Supply Chain Management. *Journal of Construction Engineering and Management*, 145(4), 1–14.
- Eastman, C. M., Jeong, Y. S., Sacks, R., and Kaner, I. (2010). Exchange model and exchange object concepts for implementation of national BIM standards. *Journal of Computing in Civil Engineering*, 24(1), 25–34.
- Egwutuoha, I. P., Levy, D., Selic, B., and Chen, S. (2013). A survey of fault tolerance mechanisms and checkpoint/restart implementations for high performance computing systems. *The Journal of Supercomputing*, 65, 1302–1326.
- El-Rayes, K. and Moselhi, O. (1998). Resource-driven scheduling of repetitive activities. *Construction management & economics*, 16(4), 433–446.
- El-Sabek, L. M., and McCabe, B. Y. (2018). Framework for Managing Integration Challenges of Last Planner System in IMPs. *Journal of Construction Engineering and Management*, 144(5), 1–14.
- Emblemsvag, J. (2014). Lean Project Planning: Using Lean Principles in Project Planning. *International Journal of Construction Project Management*, 6(2), 185–207.

- Erol, H., Dikmen, I., and Birgonul, M. T. (2017). Measuring the impact of lean construction practices on project duration and variability: A simulation-based study on residential buildings. *Journal of Civil Engineering and Management*, 23(2), 241–251.
- Fayek, A. R., and Peng, J. (2013). Adaptation of WorkFace Planning for construction contexts. *Canadian Journal of Civil Engineering*, 40(10), 980–987.
- Florescu, A. and Barabas, S. (2022), Development trends of production systems through the integration of lean management and industry 4.0, *Applied Sciences*, Vol. 12, p. 4885.
- Forbes, L. H., and Ahmed, S. M. (2011). *Modern Construction Lean Project Delivery and Integrated Practices*. CRC Press.
- Franz, B., and Messner, J. (2019). Evaluating the Impact of Building Information Modeling on Project Performance. *Journal of Computing in Civil Engineering*, 33(3), 1–9.
- Gambatese, J. A., Pestana, C., and Lee, H. W. (2017). Alignment between Lean Principles and Practices and Worker Safety Behavior. *Journal of Construction Engineering and Management*, 143(1).
- Gao, S., and Low, S. P. (2014a). *Lean Construction Management The Toyota Way*. Springer Science+Business Media Singapore.
- Gao, S., and Low, S. P. (2014b). The Last Planner System in China's construction industry - A SWOT analysis on implementation. *International Journal of Project Management*, 32(7), 1260–1272. h
- Gbadamosi, A. Q., Mahamadu, A. M., Oyedele, L. O., Akinade, O. O., Manu, P., Mahdjoubi, L., and Aigbavboa, C. (2019). Offsite construction: Developing a BIM-Based optimizer for assembly. *Journal of Cleaner Production*, 215, 1180–1190.
- Ghosh, S., and Burghart, J. (2019). Lean Construction: Experience of US Contractors. *International Journal of Construction Education and Research*, 00(00), 1–21.
- Ghosh, S., Dickerson, D. E., and Mills, T. (2019). Effect of the Last Planner System® on Social Interactions among Project Participants. *International Journal of Construction Education and Research*, 15(2), 100–117.
- Golparvar-Fard, M., Peña-Mora, F., and Savarese, S. (2009). D4AR-A 4-dimensional augmented reality model for automating construction progress monitoring data collection, processing and communication. *Journal of Information Technology in Construction*, 14, 129–153.
- González, V. A., Orozco, F., Senior, B., Ingle, J., Forcael, E., and Alarcón, L. F. (2015). LEBSO: Lean-Based Simulation Game for Construction Management Classrooms. *Journal of Professional Issues in Engineering Education and Practice*, 141(4).
- González, V., Alarcón, L. F., Maturana, S., Mundaca, F., and Bustamante, J. (2010). Improving planning reliability and project performance using the reliable commitment model. *Journal of Construction Engineering and Management*, 136(10), 1129–1139.

- Gonzalez, V., Alarcon, L. F., and Mundaca, F. (2008). Investigating the relationship between planning reliability and project performance. *Production Planning and Control*, 19(5), 461–474.
- Guest, G., Bunce, A., and Johnson, L. (2006). How many interviews are enough? An experiment with data saturation and variability. *Field methods*, 18(1), 59–82.
- Gurevich, U., and Sacks, R. (2014). Examination of the effects of a KanBIM production control system on subcontractors' task selections in interior works. *Automation in Construction*, 37, 81–87.
- Hamzeh, F., Ballard, G., and Tommelein, I. D. (2012). Rethinking Lookahead Planning to Optimize Construction Workflow. *Lean Construction Journal* 2012 pp 15-34 www.LeanConstructionJournal.com, 15–34.
- Hamzeh, F. R., Saab, I., Tommelein, I. D., and Ballard, G. (2015). Understanding the role of “tasks anticipated” in lookahead planning through simulation. *Automation in Construction*, 49(PA), 18–26.
- Hassan Ibrahim, N. (2013). Reviewing the evidence: USE of digital collaboration technologies in major building and infrastructure projects. *Journal of Information Technology in Construction*, 18, 40–63.
- Heigermoser, D., García de Soto, B., Abbott, E. L. S., and Chua, D. K. H. (2019). BIM-based Last Planner System tool for improving construction project management. *Automation in Construction*, 104(June 2018), 246–254.
- Heravi, G., and Rashid, M. (2018). Developing an Approach to Develop and Validate a Lean Construction Plan Using Performance Evaluation of Repetitive Subprojects. *Journal of Architectural Engineering*, 24(1).
- Herselman, M., and Botha, A. (2015). Evaluating an artifact in design science research. *Proceedings of the 2015 Annual Research Conference on South African Institute of Computer Scientists and Information Technologists*.
- Hevner, A., and Chatterjee, S. (2010). *Design Research in Information Systems: Theory and Practice*. Springer Science Business Media LLC.
- Hines, P., Holwe, M., and Rich, N. (2004). Learning to evolve: A review of contemporary lean thinking. *International Journal of Operations and Production Management*, 24(10), 994–1011.
- Hlady, J., Glanzer, M., and Fugate, L. (2018). Automated creation of the pipeline digital twin during construction - Improvement to construction quality and pipeline integrity. *Proceedings of the Biennial International Pipeline Conference, IPC*.
- Hopp, W. J. (2018). Positive lean: merging the science of efficiency with the psychology of work. *International Journal of Production Research*, 56(1–2), 398–413.
- Hopp, W. J., and Spearman, M. L. (2004). To pull or not to pull: What is the question? *Manufacturing and Service Operations Management*, 6(2), 133–148.
- Horman, M. J., and Thomas, H. R. (2005). Role of Inventory Buffers in Construction Labor Performance. *Journal of Construction Engineering and Management*, 131(7), 834–843.

- Hosseini, S. A. A., Nikakhtar, A., Wong, K. Y., and Zavichi, A. (2012). Implementing Lean Construction Theory to Construction Processes' Waste Management. *ICSDC 2011: Integrating Sustainability Practices in the Construction Industry - Proceedings of the International Conference on Sustainable Design and Construction 2011, January*, 414–420.
- Howell, G. A. (1999). What is lean construction. *Proceedings IGLC-7*.
- Howell, G., and Ballard, G. (1998). Implementing Lean Construction: Understanding and Action. *Proceedings IGLC '98*.
- Howell, G., Ballard, G., and Demirkesen, S. (2017). Why Lean Projects Are Safer. *25th Annual Conference of the International Group for Lean Construction, II*, 895–901.
- Howell, S., Rezgui, Y., and Beach, T. (2017). Integrating building and urban semantics to empower smart water solutions. *Automation in Construction*, 81.
- Hu, Z. Z., Zhang, X. Y., Wang, H. W., and Kassem, M. (2016). Improving interoperability between architectural and structural design models: An industry foundation classes-based approach with web-based tools. *Automation in Construction*, 66, 29–42.
- Jang, S., and Lee, G. (2018). Impact of organizational factors on delays in bim-based coordination from a decision-making view: A case study. *Journal of Civil Engineering and Management*, 24(1), 19–30.
- Jin, R., Zou, Y., Gidado, K., Ashton, P., and Painting, N. (2019). Scientometric analysis of BIM-based research in construction engineering and management. *Engineering, Construction and Architectural Management*, 26(8), 1750–1776.
- Johannesson, P. and Perjons, E. (2014). *An Introduction to Design Science*. Springer International Publishing.
- Johansen, E., and Walter, L. (2007). Lean construction: Prospects for the German construction industry. *Lean Construction Journal*, 3(1), 19–32.
- Jones, D., Snider, C., Nassehi, A., Yon, J., and Hicks, B. (2020). Characterising the Digital Twin: A systematic literature review. *CIRP Journal of Manufacturing Science and Technology*, 29, 36–52.
- Jünge, G. H., Alfnes, E., Kjersem, K., & Andersen, B. (2019). Lean project planning and control: empirical investigation of ETO projects. *International Journal of Managing Projects in Business*, 12(4), 1120–1145.
- Kaewunruen, S., and Lian, Q. (2019). Digital twin aided sustainability-based lifecycle management for railway turnout systems. *Journal of Cleaner Production*, 228, 1537–1551.
- Kan, C., and Anumba, C. (2019). Digital Twins as the Next Phase of Cyber-Physical Systems in Construction. *The 2019 ASCE International Conference on Computing in Civil Engineering*.
- Karan, E. P., and Irizarry, J. (2015). Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services. *Automation in Construction*, 53, 1–12.
- Khajavi, S. H., Motlagh, N. H., Jaribion, A., Werner, L. C., and Holmstrom, J. (2019). Digital Twin: Vision, benefits, boundaries, and creation for buildings.

IEEE Access, 7, 147406–147419.

- Khanh, H. D., and Kim, S. Y. (2016). A Survey on Production Planning System in Construction Projects Based on Last Planner System. *KSCE Journal of Civil Engineering*, 20, 1–11.
- Kim, K. (2001). *Distributed coordination of project schedule changes: An agent-based compensatory negotiation approach*. Diss. Stanford University
- Kim, S. C., and Kim, Y. W. (2014). Computerized integrated project management system for a material pull strategy. *Journal of Civil Engineering and Management*, 20(6), 849–863.
- Kitchenham, B., and Linkman, S. (2005). Experiences of using an evaluation framework. *Information and Software Technology*.
- Klinc, R., and Turk, Ž. (2019). Construction 4.0 – Digital Transformation of One of the Oldest Industries. *Economic and Business Review*, 21(3), 393–410.
- Koseoglu, O., Sakin, M., and Arayici, Y. (2018). Exploring the BIM and lean synergies in the Istanbul Grand Airport construction project. *Engineering, Construction and Architectural Management*, 25(10), 1339–1354.
- Koskela, L. (1992). *Application of the new production philosophy to construction* (Vol. 72).
- Koskela, L. (1993). Lean Production in Construction. *1993 Proceedings of the 10th ISARC, Houston, USA*, 47–54.
- Koskela, L., Ferrantelli, A., Niiranen, J., Pikas, E., and Dave, B. (2019). Epistemological Explanation of Lean Construction. *Journal of Construction Engineering and Management*, 145(2), 1–10.
- Kovvuri, P. R. R., Sawhney, A., Ahuja, R., and Sreekumar, A. (2016). Efficient Project Delivery Using Lean Principles - An Indian Case Study. *Journal of The Institution of Engineers (India): Series A*, 97(1), 19–26.
- Lai, H., and Deng, X. (2018). Interoperability analysis of ifc-based data exchange between heterogeneous BIM software. *Journal of Civil Engineering and Management*, 24(7), 537–555.
- Lavikka, R., Kallio, J., Casey, T. and Airaksinen, M. (2018), “Digital disruption of the AEC industry: technology-oriented scenarios for possible future development paths”, *Construction Management and Economics*, Vol. 36 No. 11, pp. 635-650.
- Lee, A. (2009). A fuzzy AHP evaluation model for buyer–supplier relationships with the consideration of benefits, opportunities, costs and risks. *Int.l Journal of Production Research*, vol.47, pp.4255-4280.
- Lee, J., Bagheri, B., and Kao, H.A. (2015). A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems. *Manufacturing Letters*, 3, 18–23.
- Lee, S. K., Kim, K. R., and Yu, J. H. (2014). BIM and ontology-based approach for building cost estimation. *Automation in Construction*, 41, 96–105.
- Levitt, R. E. (2011). Towards project management 2.0. *Engineering Project Organization Journal*, 1(3), 197–210.

- Li, L., Li, Z. , Li, X., and Wu, G. (2019). A review of global lean construction during the past two decades: analysis and visualization, *Eng. Constr. Archit. Manag.*, vol. 26, no. 6, pp. 1192–1216, 2019.
- Li, X., Wu, P., Shen, G. Q., Wang, X., and Teng, Y. (2017). Mapping the knowledge domains of Building Information Modeling (BIM): A bibliometric approach. *Automation in Construction*, 84, 195–206.
- Li, Z., and He, D. (2013). Discuss a Method of Collaborative Construction Project Information Management Based on BIM. *ICCREM 2013: Construction and Operation in the Context of Sustainability*.
- Liker, J. K. (2004). *The Toyota Way: 14 Management Principles from the World's Greatest Manufacturer*. McGraw-Hill.
- Lin, Z. Y., Petzold, F., and Ma, Z. L. (2019). A real-time 4D augmented reality system for modular construction progress monitoring. *Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019*.
- Lindhard, S., and Wandahl, S. (2015). Exploration of correct LPS practices in scheduling of large, complex, and constrained construction projects. *International Journal of Project Organisation and Management*, 7(1), 56–71.
- Liu, H., Lu, M., and Al-Hussein, M. (2016). Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry. *Advanced Engineering Informatics*, 30, 190–207.
- Liu, M., Ballard, G., and Ibbs, W. (2011). Work flow variation and labor productivity: Case study. *Journal of Management in Engineering*, 27(4), 236–242.
- Lokshina, I. V., Greguš, M., and Thomas, W. L. (2019). Application of integrated building information modeling, iot and. *Procedia Computer Science*, 160, 497–502.
- Lu, Q., Parlikad, A. K., Woodall, P., Don Ranasinghe, G., Xie, X., Liang, Z., Konstantinou, E., Heaton, J., and Schooling, J. (2020a). Developing a Digital Twin at Building and City Levels: Case Study of West Cambridge Campus. *Journal of Management in Engineering*, 36(3), 05020004.
- Lu, Q., Xie, X., Parlikad, A. K., and Schooling, J. M. (2020b). Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance. *Automation in Construction*, 118.
- Lyons, A. C., Vidamour, K., Jain, R., and Sutherland, M. (2013). Developing an understanding of lean thinking in process industries. *Production Planning and Control*, 24(6), 475–494.
- Ma, X., Chan, A. P. C., Wu, H., Xiong, F., and Dong, N. (2018). Achieving leanness with BIM-based integrated data management in a built environment project. *Construction Innovation*, 18(4), 469–487.
- Magnani, F., Carbone, V., and Moatti, V. (2019). The human dimension of lean: a literature review. *Supply Chain Forum*, 20(2), 132–144.
- Mahalingam, A., Yadav, A. K., and Varaprasad, J. (2015). Investigating the role of lean practices in enabling BIM adoption: Evidence from two Indian cases.

- Journal of Construction Engineering and Management*, 141(7), 1–11.
- Mahmood, A., and Abrishami, S. (2020). BIM for lean building surveying services. *Construction Innovation*, 20(3), 447–470.
- Mäki, T., Kerosuo, H., and Koskenvesa, A. (2020). This has been a real uphill battle — Three organisations for the adoption of last planner system. *Canadian Journal of Civil Engineering*, 47(2), 109–117.
- March, S.T., and Smith, G.F. (1995). Design and natural science research on information technology. *Decision Support Systems*, vol. 15, pp. 251–266.
- Mayani, M. G., Baybolov, T., Rommetveit, R., Ødegaard, S. I., Koryabkin, V., and Lakhtionov, S. (2020). Optimizing drilling wells and increasing the operation efficiency using digital twin technology. *SPE/IADC Drilling Conference, Proceedings*.
- Mehany, M. S. H. M. (2015). Lean Construction Principles Past and Present – A Business Model Consistency. *51st ASC Annual International Conference Proceedings*, 371–377.
- Mitropoulos, P., and Nichita, T. (2010). Critical concerns of production control system on projects with labor constraints: Lessons from a residential case study. *Journal of Management in Engineering*, 26(3), 153–159.
- Mossman, A. (2009). Creating value: A sufficient way to eliminate waste in lean design and lean production. *Lean Construction Journal*, 2009, 13–23.
- Nabeeh, N. A., Abdel-Basset, M., El-Ghareeb, H. A., and Aboelfetouh, A. (2019). Neutrosophic multi-criteria decision making approach for iot-based enterprises. *IEEE Access*, 7, 59559–59574.
- Namey, E., Guest, G., McKenna, K., and Chen, M. (2016). Evaluating bang for the buck: a cost-effectiveness comparison between individual interviews and focus groups based on thematic saturation levels. *American Journal of Evaluation*, 37(3), 425–440.
- Nascimento, D., Caiado, R., Tortorella, G., Ivson, P., and Meiriño, M. (2018). Digital Obeya Room: exploring the synergies between BIM and lean for visual construction management. *Innovative Infrastructure Solutions*, 3(19).
- Natephra, W., and Motamedi, A. (2019). Live data visualization of IoT sensors using augmented reality (AR) and BIM. *Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019*.
- Nath, T., Attarzadeh, M., Tiong, R. L. K., Chidambaram, C., and Yu, Z. (2015). Productivity improvement of precast shop drawings generation through BIM-based process re-engineering. *Automation in Construction*, 54, 54–68.
- Naticchia, B., Carbonari, A., Vaccarini, M., and Giorgi, R. (2019). Holonic execution system for real-time construction management. *Automation in Construction*, 104, 179–196.
- Nawari, N. O., and Ravindran, S. (2019). Blockchain and Building Information Modeling (BIM): Review and applications in post-disaster recovery. In *Buildings* (Vol. 9).
- Nguyen, P., and Akhavian, R. (2019). Synergistic Effect of Integrated Project Delivery, Lean Construction, and Building Information Modeling on Project

- Performance Measures: A Quantitative and Qualitative Analysis. *Advances in Civil Engineering*, 2019.
- Niknam, M., and Karshenas, S. (2017). A shared ontology approach to semantic representation of BIM data. *Automation in Construction*, 80, 22–36.
- Novack, J. (2019). Digital twins and industry 4.0: Videogamers will staff and manage industrial projects in the near future. *Society of Petroleum Engineers - Abu Dhabi International Petroleum Exhibition and Conference 2019, ADIP 2019*.
- Nykänen, E., Reda, F., and Pinto-Seppä, I. (2017). Impacts and future challenges of European research for a smart built environment. *2017 International Conference on Engineering, Technology and Innovation: Engineering, Technology and Innovation Management Beyond 2020: New Challenges, New Approaches, ICE/ITMC 2017 - Proceedings*.
- O'Connor, R., and Swain, B. (2013). *Implementing Lean in construction: Lean tools and techniques – an introduction*. CIRIA.
- Ochoa, J. J. (2014). Reducing plan variations in delivering sustainable building projects. *Journal of Cleaner Production*, 85, 276–288.
- Ohno, T. (1988). *Toyota Production System Beyond Large Scale Production*. Productivity Press.
- Olatunji, O. A., and Akanmu, A. A. (2015). An adaptive cyber-physical system's approach to construction progress monitoring and control. *Building Information Modeling: Applications and Practices*, 269, 195–221.
- Olivieri, H., Seppänen, O., Alves, T. D. C. L., Scala, N. M., Schiavone, V., Liu, M., and Granja, A. D. (2019). Survey Comparing Critical Path Method, Last Planner System, and Location-Based Techniques. *Journal of Construction Engineering and Management*, 145(12).
- Omer, M., Margetts, L., Hadi Mosleh, M., Hewitt, S., and Parwaiz, M. (2019). Use of gaming technology to bring bridge inspection to the office. *Structure and Infrastructure Engineering*, 15(10), 1292–1307.
- Pan, Y., and Zhang, L. (2021). A BIM-data mining integrated digital twin framework for advanced project management. *Automation in Construction*, 124(July 2020).
- Pauwels, P., Zhang, S., and Lee, Y. C. (2017). Semantic web technologies in AEC industry: A literature overview. *Automation in Construction*, 73, 145–165.
- Petrie, C., Goldmann, S. and Raquet, A. (1999). Agent-based project management. *Artificial intelligence today*. Springer, Berlin, Heidelberg.
- Pishdad-Bozorgi, P., Gao, X., and Shelden, D. (2020). Introduction to cyber-physical systems in the built environment. In A. Sawhney, M. Riley, and J. Irizarry (Eds.), *Construction 4.0 An Innovation Platform for the Built Environment* (Issue February, pp. 23–41).
- Priven, V., and Sacks, R. (2015). Effects of the Last Planner System on Social Networks among. *Journal of Construction Engineering and Management*, 141(6).
- Project Management Institute (2016). *Construction Extension to the PMBOK*

Guide. Project Management Institute, Incorporated

- Pučko, Z., Šuman, N., and Rebolj, D. (2018). Automated continuous construction progress monitoring using multiple workplace real time 3D scans. *Advanced Engineering Informatics*, 38, 27–40.
- Qiuchen Lu, V., Parlikad, A.K., Woodall, P., Ranasinghe, G.D. and Heaton, J. (2019), “Developing a dynamic digital twin at a building level: using Cambridge campus as case study”, *ICSIC 2019 Driving data-informed decision-making*, pp. 67-75.
- Rakib, F. H., Howlader, S., Rahman, M., and Bhuiyan, A. Y. (2019). Application of BIM based interoperability-a case study. *Journal of System and Management Sciences*, 6, 106–114.
- Rasheed, A., San, O., and Kvamsdal, T. (2020). Digital twin: Values, challenges and enablers from a modeling perspective. *IEEE Access*, 8, 21980–22012.
- Ratajczak, J., Riedl, M., and Matt, D. T. (2019). BIM-based and AR application combined with location-based management system for the improvement of the construction performance. *Buildings*, 9(118).
- Rincón, J. L., Fernández-Solís, J. L., Lavy, S., and Du, J. (2019). Effect of Autonomous Agents on Last Planner System Performance in Texas. *Journal of Management in Engineering*, 35(1), 1–11.
- Rommetveit, R., Mayani, M. G., Nabavi, J., Helgeland, S., Hammer, R., and Råen, J. (2019). Automatic realtime monitoring of drilling using digital twin technologies enhance safety and reduce costs. *Society of Petroleum Engineers - Abu Dhabi International Petroleum Exhibition and Conference 2019, ADIP 2019*.
- Russell, M. M., Liu, M., Howell, G., and Hsiang, S. M. (2015). Case studies of the allocation and reduction of time buffer through use of the last planner system. *Journal of Construction Engineering and Management*, 141(2).
- Saaty, T.R. (2006). *Decision Making with the Analytic Network Process*, Springer.
- Sacks, R., Brilakis, I., Pikas, E., Xie, H. S., and Girolami, M. (2020a). Construction with digital twin information systems. *Data-Centric Engineering*, 1.
- Sacks, R., Girolami, M. and Brilakis, I. (2020b), “Building information modelling, artificial intelligence and construction tech”, *Developments in the Built Environment*, Vol. 4, 100011.
- Sacks, R., Eastman, C., Lee, G., and Teicholz, P. (2018). *BIM Handbook: a guide to building information modeling for owners, designers, engineers, contractors, and facility managers* (Third). John Wiley & Sons.
- Sacks, R., Esquenazi, A., and Goldin, M. (2007). LEAPCON: Simulation of lean construction of high-rise apartment buildings. *Journal of Construction Engineering and Management*, 133(7), 529–539.
- Sacks, R., and Goldin, M. (2007). Lean Management Model for Construction of High-Rise Apartment Buildings. *Journal of Construction Engineering and Management*, 133(5), 374–384.
- Sacks, R., Gurevich, U., and Shrestha, P. (2016). A review of Building Information Modeling protocols, guides and standards for Large construction clients.

- Journal of Information Technology in Construction*, 21, 479–503.
- Sacks, R., and Harel, M. (2006). An economic game theory model of subcontractor resource allocation behaviour. *Construction Management and Economics*, 24(8), 869–881.
- Sacks, R., Koskela, L., Dave, B. A., and Owen, R. (2010a). Interaction of lean and building information modeling in construction. *Journal of Construction Engineering and Management*, 136(9), 968–980.
- Sacks, R., Koskela, L., Dave, B. A., and Owen, R. (2010b). Interaction of lean and building information modeling in construction. *Journal of Construction Engineering and Management*, 136(9), 968–980.
- Sacks, R., Ma, L., Yosef, R., Borrmann, A., Daum, S., and Kattel, U. (2017). Semantic Enrichment for Building Information Modeling: Procedure for Compiling Inference Rules and Operators for Complex Geometry. *Journal of Computing in Civil Engineering*, 31(6).
- Sacks, R., Radosavljevic, M., and Barak, R. (2010). Requirements for building information modeling based lean production management systems for construction. *Automation in Construction*, 19(5), 641–655.
- Saieg, P., Sotelino, E. D., Nascimento, D., and Caiado, R. G. G. (2018). Interactions of Building Information Modeling, Lean and Sustainability on the Architectural, Engineering and Construction industry: A systematic review. *Journal of Cleaner Production*, 174, 788–806.
- Salem, O. M., Salem, O., Asce, M., Solomon, J., Genaidy, A., Minkarah, I., and Asce, M. (2015). *Lean Construction : From Theory to Implementation Lean Construction : From Theory to Implementation*. 4(October 2006), 61–67.
- Salem, O., Solomon, J., Genaidy, A., and Luegring, M. (2005). Site implementation and assessment of lean construction techniques. *Lean Construction Journal*, 2(2), 1–21.
- Santorella, G. (2017). *Lean Culture for the Construction Industry Building Responsible and Committed Project Teams*. CRC Press.
- Sarhan, J. G., Xia, B., Fawzia, S., and Karim, A. (2017). Lean construction implementation in the Saudi Arabian construction industry. *Construction Economics and Building*, 17(1), 46–69.
- Sattler, L., Lamouri, S., Pellerin, R., Deneux, D., Larabi, M., and Maigne, T. (2019). Multi-domain BIM interoperability: queries as data-exchange vectors. *Proceedings of the 2019 International Conference on Industrial Engineering and Systems Management, IESM 2019*.
- Sattler, L., Lamouri, S., Pellerin, R., and Maigne, T. (2019). Interoperability aims in building information modeling exchanges: A literature review. *IFAC-PapersOnLine*, 52(13), 271–276.
- Sawhney, A., Riley, M., and Irizarry, J. (2020). *CONSTRUCTION 4.0 An Innovation Platform for the Built Environment*. Routledge.
- Schimanski, C. P., Marcher, C., Monizza, G. P., and Matt, D. T. (2020). The last planner® system and building information modeling in construction execution: From an integrative review to a conceptual model for integration. *Applied*

Sciences (Switzerland), 10(821).

- Schimanski, C. P., Monizza, G. P., Marcher, C., and Matt, D. T. (2019). Pushing digital automation of configure-to-order services in small and medium enterprises of the construction equipment industry: A design science research approach. *Applied Sciences (Switzerland)*, 9.
- Schrotter, G., and Hürzeler, C. (2020). The Digital Twin of the City of Zurich for Urban Planning. *PFG - Journal of Photogrammetry, Remote Sensing and Geoinformation Science*, 88, 99–112.
- Sepasgozar, S.M.E., Hui, F.K.P., Shirowzhan, S., Foroozanfar, M., Yang, L. and Aye, L. (2021), Lean practices using building information modeling (BIM) and digital twinning for sustainable construction, *Sustainability*, Vol. 13, p. 161.
- Seppänen, O., Ballard, G., and Pesonen, S. (2010). The combination of last planner system and location-based management system. *Lean Construction Journal*, 2010(January), 43–54.
- Shah, R., and Ward, P. T. (2007). Defining and developing measures of lean production. *Journal of Operations Management*, 25(4), 785–805.
- Shahinmoghadam, M., and Motamedi, A. (2019). Review of BIM-centred IoT deployment: State of the art, opportunities, and challenges. *Proceedings of the 36th International Symposium on Automation and Robotics in Construction, ISARC 2019*.
- Shelton, C. P. (1999). Human interface / human error. *Online: www.users.ece.cmu.edu* (01.12.2023).
- Shetty, P., and Rao, B. P. (2019). Importance of Lean Concepts and its Need in Construction Projects. *International Journal of Recent Technology and Engineering*, 8(2), 2534–2541.
- Shin, T. S. (2017). Building information modeling (BIM) collaboration from the structural engineering perspective. *International Journal of Steel Structures*, 17(1), 205–214.
- Sivaganesh, P., and Ratnayake, R. M. C. (2019). Application of Last Planner® System in Product Concept Development Phase: Use of Lean Concepts in Academic Project Work. *IEEE International Conference on Industrial Engineering and Engineering Management*, 351–355.
- Slivon, C. A., Howell, G. A., Koskela, L., and Rooke, J. (2010). Social construction: Understanding construction in a human context. *Lean Construction Journal*, 66–75.
- Smarandache F. (2002). Neutrosophy and neutrosophic logic. *First International Conference on Neutrosophy, Neutrosophic Logic, Set, Probability, and Statistics*, Uni. of New Mexico, NM, Vol 87301, pp. 338–353.
- Song, M. A. and Fischer, M. (2020). Daily plan-do-check-act (PDCA) cycles with level of development (LOD) 400 objects for foremen. *Advanced Engineering Informatics*, Volume 44.
- Song, L., and Liang, D. (2011). Lean construction implementation and its implication on sustainability: A contractor's case study. *Canadian Journal of Civil Engineering*, 38(3), 350–359.

- Sonnenberg, C., and vom Brocke, J. (2012). Evaluation Patterns for Design Science Research Artefacts. In M. Helfert & B. Donnellan (Eds.), *Proceedings of the European Design Science Symposium (EDSS) 2011* (Vol. 286, pp. 71-83). Dublin, Ireland: Springer Berlin/Heidelberg.
- Sriprasert, E., and Dawood, N. (2002). Next generation of construction planning and control system: the LEWIS approach. *Proceedings IGLC-10*.
- Sriprasert, E., and Dawood, N. (2003). Multi-constraint information management and visualisation for collaborative planning and control in construction. *Electronic Journal of Information Technology in Construction*, 8(March), 341–366.
- Steel, J., Drogemuller, R., and Toth, B. (2012). Model interoperability in building information modelling. *Software and Systems Modeling*, 11, 99–109.
- Stern, T. V. (2017). *Lean and Agile Project Management How to Make Any Project Better, Faster, and More Cost Effective*. CRC Press.
- Stevens, M. (2014). Increasing Adoption of Lean Construction by Contractors. *Proceedings IGLC-22*, 377–388.
- Tao, F., Liu, A., Hu, T., and Nee, A. Y. C. (2020). Digital Twin Driven Smart Design. In *Journal of Chemical Information and Modeling* (Vol. 53, Issue 9). Academic Press.
- Taylor, A., Taylor, M., and McSweeney, A. (2013). Towards greater understanding of success and survival of lean systems. *International Journal of Production Research*, 51(22), 6607–6630.
- Terreno, S., Asadi, S. and Anumba, C. (2019). An exploration of synergies between lean concepts and BIM in FM: a review and directions for future research. *Buildings*, Vol. 9, p. 147.
- Tetik, M., Peltokorpi, A., Seppänen, O., and Holmström, J. (2019). Direct digital construction: Technology-based operations management practice for continuous improvement of construction industry performance. *Automation in Construction*, 107.
- Tezel, A., and Aziz, Z. (2017). From conventional to it based visual management: A conceptual discussion for lean construction. *Journal of Information Technology in Construction*, 22, 220–246.
- Tezel, A., Koskela, L., and Aziz, Z. (2018). Lean thinking in the highways construction sector: motivation, implementation and barriers. *Production Planning and Control*, 29(3), 247–269.
- Tezel, A., and Nielsen, Y. (2013). Lean Construction Conformance among Construction Contractors in Turkey. *Journal of Management in Engineering*, 29(3), 236–250.
- Tezel, A., Taggart, M., Koskela, L., Tzortzopoulos, P., Hanahoe, J., and Kelly, M. (2020). Lean construction and BIM in small and medium-sized enterprises (SMEs) in construction: a systematic literature review. *Canadian Journal of Civil Engineering*, 47, 186–201.
- Thürer, M., Tomašević, I., and Stevenson, M. (2017). On the meaning of ‘Waste’: review and definition. *Production Planning and Control*, 28(3), 244–255.

- Tommelein, I. D. (1998). *Pull Driven Scheduling for Pipe-Spool Installation: Simulation of Lean Construction Technique*. 124, 279–288.
- Tommelein, I. D. (2008). “Poka Yoke” or Quality by Mistake Proofing Design and Construction Systems. *Proceedings for the 16th Annual Conference of the International Group for Lean Construction*.
- Tommelein, I. D. (2015). Journey toward Lean Construction: Pursuing a Paradigm Shift in the AEC Industry. *Journal of Construction Engineering and Management*, 141(6), 1–12.
- Tserng, H. P., Yin, S. Y. L., and Ngo, T. L. (2013). A lean prebid planning model for construction contractors: A case study in Vietnam. *Journal of Marine Science and Technology (Taiwan)*, 21(4), 430–441.
- Turner, C. J., Oyekan, J., Stergioulas, L., and Griffin, D. (2021). Utilizing Industry 4.0 on the Construction Site: Challenges and Opportunities. *IEEE Transactions on Industrial Informatics*, 17(2), 746–756.
- Van der Merwe, A., Gerber, A., and Smuts, H. (2020). Guidelines for Conducting Design Science Research in Information Systems. In: Tait, B., Kroeze, J., Gruner, S. (eds) *ICT Education. SACLA 2019. Communications in Computer and Information Science*, vol 1136. Springer, Cham.
- Venable, J., Pries-Heje, J., and Baskerville, R. (2012). A Comprehensive Framework for Evaluation in Design Science Research. In K. Peffers, M. Rothenberger & B. Kuechler (Eds.), *Design Science Research in Information Systems. Advances in Theory and Practice* (Vol. 7286, pp. 423–438). Berlin / Heidelberg: Springer.
- Venable, J., Pries-Heje, J. and Baskerville, R. (2016). FEDS: A framework for evaluation in design science research. *European Journal of Information Systems*.
- Venugopal, M., Eastman, C. M., Sacks, R., and Teizer, J. (2012). Semantics of model views for information exchanges using the industry foundation class schema. *Advanced Engineering Informatics*, 26(2), 411–428.
- Viana, D.D., Mota, B., Formoso, C.T., Echeveste, M., Peixoto, M. and Rodrigues, C.L. (2010), “A survey on the Last planner system: impacts and difficulties for implementation in Brazilian companies”, *Proc., IGLC*.
- Viana, D. D., Formoso, C. T., and Isatto, E. L. (2011). Modelling the network of commitments in the last planner system. *Lean Construction Journal*, 2011(Special Issue), 55–67.
- Viana, D. D., Formoso, C. T., and Isatto, E. L. (2017). Understanding the theory behind the Last Planner System using the Language-Action Perspective: two case studies. *Production Planning and Control*, 28(3), 177–189.
- Wambeke, B. W., Liu, M., and Hsiang, S. M. (2012). Using last planner and a risk assessment matrix to reduce variation in mechanical related construction tasks. *Journal of Construction Engineering and Management*, 138(4), 491–498.
- Wang, C. and Ruan, S.Y. (2011). Agent-Based Collaborative Decision-Making Processes For Dynamic Scheduling. *2011 IEEE International Summer Conference of Asia Pacific Business Innovation and Technology Management*.

- What is Lean?* (n.d.). Lean Enterprise Institute. Retrieved February 13, 2020, from <https://www.lean.org/WhatsLean/>
- Winch, G. M., and Kelsey, J. (2005). What do construction project planners do? *International Journal of Project Management*, 23(2), 141–149.
- Womack, J. P., and Jones, D. T. (2003). *Lean Thinking Banish Waste and Create Wealth in Your Corporation*. Free Press.
- Womack, J. P., Jones, D. T., and Roos, D. (1990). *The Machine that Changed the World*. Maxwell Macmillan International.
- Wong, J. K. W., Ge, J., and He, S. X. (2018). Digitisation in facilities management: A literature review and future research directions. *Automation in Construction*, 92, 312–326.
- Wu, X., Yuan, H., Wang, G., Li, S., and Wu, G. (2019). Impacts of lean construction on safety systems: A system dynamics approach. *International Journal of Environmental Research and Public Health*, 16(2).
- Xu, Y., Bondaletova, N. F., Kovalev, V. I., and Komrakov, A. V. (2018). Digital Twin Concept in Managing Industrial Capital Construction Projects Life Cycle. *Proceedings of 2018 11th International Conference; Management of Large-Scale System Development, MLSD 2018*.
- Ye, C., Butler, L., Calka, B., Iangurazov, M., Lu, Q., Gregory, A., Girolami, M., and Middleton, C. (2019). A digital twin of bridges for structural health monitoring. *Proceedings of the 12th International Workshop on Structural Health Monitoring*.
- Yucesan, M. and Gul, M.(2021). Failure modes and effects analysis based on neutrosophic analytic hierarchy process: method and application. *Soft Computing* 25, 11035–1105
- Zegarra, O., and Alarcón, L. F. (2017). Variability propagation in the production planning and control mechanism of construction projects. *Production Planning and Control*, 28(9), 707–726.
- Zhang, L., and Chen, X. (2016). Role of Lean Tools in Supporting Knowledge Creation and Performance in Lean Construction. *Procedia Engineering*, 145, 1267–1274.
- Zhang, X., Azhar, S., Nadeem, A., and Khalfan, M. (2018). Using Building Information Modelling to achieve Lean principles by improving efficiency of work teams. *International Journal of Construction Management*, 18(4), 293–300.
- Zhou, B. (2016). Lean principles, practices, and impacts: a study on small and medium-sized enterprises (SMEs). *Annals of Operations Research*, 241(1–2), 457–474.

PUBLICATIONS FROM THE THESIS

Conference Papers

1. Altan, E., and Işık, Z. (2020). Lean construction scheduling. In A. Damcı, C. Budayan and S. Ulubeyli (Eds.), *6th International Project and Construction Management Conference Proceedings* (pp. 1386-1396).

Papers

1. Altan, E., and Işık, Z. (2023). Digital twins in lean construction: a neutrosophic AHP–BOCR analysis approach. *Engineering, Construction and Architectural Management*.

