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The Ontology of Lean Construction 4.0 in the Construction Industry

Wassim Al Balkhi

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Wassim Al Balkhi. The Ontology of Lean Construction 4.0 in the Construction Industry. Civil Engineering. Centrale Lille Institut, 2023. English. NNT : 2023CLIL0022 . tel-04474366

HAL Id: tel-04474366

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CENTRALE LILLE

THESE

présentée en vue
d'obtenir le grade de

DOCTEUR

En

Spécialité : Génie Civil

Par

Wassim AL BALKHY

DOCTORAT délivré par CENTRALE LILLE

Title of the Thesis

The Ontology of Lean Construction 4.0 in the Construction Industry

L'ontologie du Lean Construction 4.0 dans l'industrie de la construction

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Thèse de doctorat préparée au Laboratoire de Mécanique Multi physique et Multi échelle
- LAMcube – CNRS - UMR 9013 - Ecole Doctorale ENGSYS 632

DEDICATION

I dedicate this thesis to:

My beloved parents (Abdul Kareem and Azzah): Your unconditional support and endless love have always been my strength in overcoming difficulties and challenges. Thank you for making me the person I am today.

My precious diamond; my lifelong best friend, and my life partner (My Salam): You taught me the true meaning of love and transformed my life for the better. You keep bringing happiness to my heart every time I see you. Thank you for being my soul mate and for making me feel loved.

My loving and supportive siblings (Waad, Wesam, Shhenaz, and Mohammad): Your incredible love and unwavering enthusiasm always inspired me to strive for success. Thank you for making me the proudest brother in the world.

My angle, my future, and my life (My Salma). I want you to know how deeply loved you are from the earliest moments of your life.

My dear extended family; my greatest army of believers and supporters (Mariam, Hanan, Haitham, Randa, Ahmad, Motaz, Fardos, Amna, Eman, Athar, Ghassan, Inas, Laith, Kais, Adam, Amir, and all my great family). Thank you for being so important in my life.

Free Syrian people: I dedicate this thesis with hopes for a brighter future, free from the unimaginable suffering and pain you have endured.

ACKNOWLEDGEMENTS

As an important chapter in my life draws to a close, I find it essential to express my heartfelt gratitude to all those who played a role in this milestone:

I would like to start by thanking my dear teacher and exceptional supervisor; **Prof. Dr. Zoubeir LAFHAJ**. Thank you for your continuous support and guidance since I knew you. Your kindness, wisdom, and generosity have made me feel incredibly fortunate.

I extend my gratitude to my dear co-supervisor **Prof. Dr. Ivanka IORDANOVA**. Thank you for your understanding, trust, innovative ideas, and guidance.

I am also grateful to the **French Ministry for Europe and Foreign Affairs, Campus France**, and the **Embassy of France in Jordan** for supporting this life-changing opportunity and helping me go through this journey. Special thanks to **Mme. Caterina SABBATINI-CLEC'H, Mme. Hind MALKAWI, Mme. Marie-Astrid BERTHELOT**, and **Mme. Rawan ALHOMAIMAT**.

Thanks to our significant industrial partner at **COEFF Lean Management Consulting** for the great levels of kindness and exceptional collaborative spirit. Special thanks to **Mr. Vincent MORAEL** and **Mme. Eva CHAIZE**.

I would also like to express my appreciation to the jury members of this thesis for their dedicated time and effort. I refer to **Prof. Tamara AL-BITTAR, Dr. HDR. Karim BEDDIAR, Prof. Lauri KOSKELA, Prof. Mirosław SKIBNIEWSKI, Prof. Martin FISCHER, Dr. Zofia RYBKOWSKI, Prof. Mohamed AL-HUSSEIN**, and **Mr. Vincent MORAEL**.

Many thanks to all my colleagues and friends at Centrale Lille Institut and the team of Prof. LAFHAJ. Throughout this journey, I have had the privilege of working with numerous researchers, doctoral candidates, engineers, interns, and students who have joined our team. Your presence and collaboration have enriched my experience. Special Thanks to dears: **Dorra KARMAOUI, Slim REBAI, Samer BU-HAMDAN, Yassine BOUABDALLAOUI, Soufiane EL MOUSSAOUI, Fatima ABAAOUCH, and Salam ALHOMSI**.

I also thank my colleagues at the French Lean Construction Institut (IFCL). Special thanks to **Dr. Béatrice ROUZÉ**.

I would like to express my sincere appreciation and gratitude to **Prof. Rateb SWEIS** and **Prof. Ghaleb SWEIS** for their unwavering support during my stay in Jordan. Your support helped me improve my research skills, expand my knowledge, and remain motivated to complete my academic studies.

I am thankful to all the co-authors of the published papers during the work on this thesis. I extend special thanks to **Mr. Alan MOSSMAN** and **Prof. Dr-Ing. Thomas LINNER**.

Finally, I am indebted to all my friends who have been a constant source of support throughout my Ph.D. journey. Your encouragement and friendship have meant the world to me.

ABSTRACT

This research focuses on improving the construction industry; with a focus on the French construction sector, especially in the context of issues such as low profitability levels, high cost of materials, and high rates of workplace accidents. To do this, it explores the integration of two concepts: Lean Construction and Construction 4.0. The main idea behind Lean Construction is to generate value, eliminate waste, and improve overall efficiency, while Construction 4.0 involves the use of advanced technologies to enhance construction operations. The potential benefits of these two concepts, such as innovation, sustainability, cost and time savings, and improved safety and quality, are widely recognized. However, adopting these concepts faces several challenges. Therefore, the research aims to bridge the gaps by examining opportunities and ways to create integration between Lean and Industry 4.0 in construction.

The thesis is composed of six chapters, each exploring a specific aspect of Lean Construction and Construction 4.0. **The first chapter** reviews the principles of Lean and Construction 4.0 and identifies opportunities and barriers to the adoption of Lean Construction 4.0. **The second chapter** examines the relationship between Lean Construction and the Internet of Things (IoT), showing how IoT can support the implementation of Lean Construction and contribute to improving flow, value creation, problem-solving, continuous improvement, and collaboration between partners. **The third chapter** explores the relationship between Lean Construction and the integration and collaboration of digital tools in the design phase. Using two French cases demonstrates how this integration can improve design performance, meet deadlines, enhance

collaboration, and satisfy the client. **The fourth chapter** presents the concept of a digital twin in construction and its integration into Lean Construction. Despite the challenges, adopting the digital twin is expected to improve the performance of the construction sector and solve various issues related to safety, loss of productivity, and poor environmental performance. **The fifth chapter** studies the integration of Lean Construction and 3D printing, showing how these two concepts can work together to improve performance, reduce levels of waste and carbon impact, and enhance efficiency. **The sixth chapter** compares Lean Construction with the Advanced Work Packaging (AWP) method, two construction project management methods. The findings demonstrate that their integration can promote collaboration, efficiency, and continuous improvement, although additional studies are needed to confirm these findings. This comparison helps to understand and integrate these two concepts to improve the construction environment.

The contributions of this thesis include proposing frameworks to support the implementation of Lean Construction 4.0 along the main phases of the construction project lifecycle, explaining the nature of the relationship between Lean Construction and Construction 4.0, and finally studying the current levels of implementation of Construction 4.0 in France.

Keywords: Lean Construction 4.0, Lean Construction, Construction 4.0, Industry 4.0, Construction, Internet of Things (IoT), Digital Twin (DT), Building Information Modeling (BIM), Three-Dimensional Printing (3D Printing), Advanced Work Packaging (AWP), France.

RÉSUMÉ

Cette recherche se concentre sur l'amélioration de l'industrie de la construction ; avec un accent sur le secteur français de la construction, en particulier dans le contexte de problèmes comme les faibles niveaux de rentabilité, le coût élevé des matériaux, et les taux élevés d'accidents du travail. Pour ce faire, elle explore l'intégration de deux concepts : la Construction Lean et la construction 4.0.

L'idée principale derrière la Construction Lean est d'éliminer les gaspillages et d'améliorer l'efficacité globale, tandis que la construction 4.0 implique l'utilisation de technologies avancées pour améliorer les opérations de construction. Les avantages potentiels de ces deux concepts, tels que l'innovation, la durabilité, l'économie de coûts et de temps, l'amélioration de la sécurité et de la qualité, sont largement reconnus. Cependant, leur adoption se heurte à plusieurs défis. La recherche vise donc à combler les lacunes en examinant les opportunités et les moyens de créer une intégration entre le Lean et l'industrie 4.0 dans la construction.

La thèse se divise en six chapitres, chacun explorant des aspects spécifiques et des interactions potentielles entre la Construction Lean et de la construction 4.0.

Le premier chapitre présente une revue des principes du Lean et de la Construction 4.0 et identifie les opportunités et les obstacles à l'adoption de la Lean Construction 4.0.

Le deuxième chapitre examine la relation entre la Construction Lean et l'Internet des Objets (IoT), en montrant comment l'IoT peut soutenir la mise en œuvre de la Construction Lean et contribuer à améliorer le flux, la génération de valeur, la résolution de problèmes, l'amélioration continue et la collaboration entre les partenaires.

Le troisième chapitre explore la relation entre la Construction Lean et l'intégration et la collaboration des outils numériques dans la phase de conception. À partir de deux cas français, il démontre comment cette intégration peut améliorer les performances de la conception, aider à respecter les délais, améliorer la collaboration et satisfaire le client.

Le quatrième chapitre présente le concept de jumeau numérique dans la construction et son intégration dans la Construction Lean. Malgré les défis, l'adoption du jumeau numérique a le potentiel d'améliorer les performances du secteur de la construction et résoudre divers problèmes liés à la sécurité, à la perte de productivité et à la mauvaise performance environnementale.

Le cinquième chapitre étudie l'intégration de la Construction Lean et de l'impression 3D, en montrant comment ces deux concepts peuvent fonctionner ensemble pour améliorer les performances, réduire les niveaux de gaspillage et l'impact carbone, et améliorer l'efficacité.

Le sixième chapitre compare la Construction Lean avec la méthode Advanced Work Packaging (AWP), deux méthodes de gestion de projets de construction. Les résultats démontrent que leur intégration peut promouvoir collaboration, efficacité et amélioration continue, bien que des études supplémentaires soient nécessaires pour confirmer ces résultats. Cette comparaison aide à comprendre et à intégrer ces deux concepts pour améliorer l'environnement de la construction.

Les contributions de cette thèse comprennent la proposition d'un cadre conceptuel pour soutenir la mise en œuvre du Lean Construction 4.0 le long des principales phases du cycle de vie du projet de construction, l'explication de la nature de la relation entre la

Construction Lean et la Construction 4.0, et enfin l'étude des niveaux de mise en œuvre actuels de la Construction 4.0 en France.

Mots-clés : Lean Construction 4.0, Lean Construction, Construction 4.0, Industrie 4.0, Construction, Internet des objets (IoT), jumeau numérique, modélisation des informations du bâtiment (BIM), Advanced Work Packaging (AWP), France.

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LIST OF ABBREVIATIONS

Abbreviation	Stand for
3D printing	Three-Dimensional Printing
AEC	Architecture, Engineering, and Construction
AECO	Architecture, Engineering, Construction, and Operation
AECOFM	Architecture, Engineering, Construction, Operation, and Facility Management
AI	Artificial Intelligence
AM	Additive Manufacturing
AR	Augmented Reality
ASTM	American Society for Testing and Materials
AWP	Advanced Work Packaging
BAS	Building Automation Systems
BE	Built Environment
BIM	Building Information Modeling
BLE	Bluetooth Low Energy
BOT	Build-operate-transfer
C&D W	Construction and Demolition Waste
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CDM	Collaborative Design Management
CII	Construction Industry Institute
CO₂	Carbon dioxide
COAA	Construction Owners Association of Alberta
CoT	Cloud of Things
CPM	Critical Path Methods
CPS	Cyber-Physical System
CR	Cost Reporting
CWP	Construction Work Package
DSM	Design Structure Matrix
DT	Digital Twin
EWP	Engineering Work Package
FEA	Finite Element Analysis
FIEC	European Construction Industry Federation

GDP	Gross Domestic Product
GHG	Greenhouse Gases
GIS	Geographic Information System
GMP	Guaranteed Maximum Price
GPS	Global Positioning System
HVAC	Heating, Ventilation, And Air-Cooling
ICT	Information Communication Technology
IdF	Industrie du Futur
IEC	International Electrotechnical Commission
IGLC	Annual Conference of the International Group for Lean Construction
IoT	Internet of Things
IPD	Integrated Project Delivery
ISARC	International Symposium on Automation and Robotics in Construction
ISO	International Organization for Standardization
IT	Information Technology
IWP	Installation Work Package
JIT	Just-In-Time
KPI	Key Performance Indicator
LBMS	Location-Based Management System
LCI	Lean Construction Institute
LoRa	LongRang
LPS	Last Planner System
M2M	Machine to Machine
MBOM	Manufacturing Bill of Materials
MDPI	Multidisciplinary Digital Publishing Institute
ML	Machine Learning
MR	Mixed Reality
NFC	Near-Field Communication
NVA	Non-Value-Adding
OM	Operation and Maintenance
OSC	Offsite Construction
PDCA	Plan-Do-Check-Act
PMI	Project Management Institute
POC	Path of Construction
PPC	Planned-Percent-Completed

PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QA	Quality Assurance
QC	Quality Control
RA	Root-cause Analysis
RFID	Radio Frequency Identification
RS	Reason Summary for non-competition
SLR	Systematic Literature Review
SME	Small and Mid-Sized Enterprise
SOA	Service-oriented architecture
SSL	Secure Sockets Layer
SV	Schedule Variation
TFV	Transformation-Flow-Value theory
TPM	Total Productive Maintenance
TPS	Toyota Production Systems
TQM	Total Quality Management
TVD	Target Value Design/Delivery
UWB	Ultra-wideband
VA	Value-Adding
VDC	Virtual Design and Construction
VM	Visual Management
VR	Virtual Reality
VSM	Value Stream Mapping
WBS	Work Breakdown Structure
WEF	World Economic Forum
WFP	Workface Planning
WIP	Work-In-Progress
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WoT	Web of Things
WPAN	Wireless Personal Area Network
WSN	Wireless Sensors Network
WWAN	Wireless wide area network
WWP	Weekly work plan
XR	Extended Reality

GENERAL INTRODUCTION

The Concept of Lean Construction 4.0

This thesis presents the concept of Lean Construction 4.0 and its implementation in different phases in the building life cycle. Lean Construction 4.0 refers to the integration between the practices and technologies of Construction 4.0 and the principles and tools of Lean Construction philosophy.

Lean Construction originated from the application of Lean thinking in the construction industry. Over the years, there has been no agreement on a specific definition for Lean Construction. One of the definitions that were raised following studying a list of existing literature about Lean Construction was “a philosophy that aims to improve the collaboration between all project stakeholders to maximize value for all of them in general and the customer in particular, in addition to eliminating all kind of wastes, achieving continuous improvement, improving flow, reducing cost and enhancing safety and quality” (Albalkhy & Sweis, 2021). Another definition was presented by Lean Construction Institute which explained Lean as a “Culture of respect and continuous improvement aimed at creating more value for the customer while identifying and eliminating waste” (Lean Construction Institute, 2023).

In turn, Construction 4.0 refers to applying a broader concept (Industry 4.0 or the fourth industrial revolution) in the construction industry to enable the digital transformation and utilization of technology to respond to the industry's challenges. Similar to Lean, there is no agreement on a specific definition for Construction 4.0, but in general, it can be understood based on the use of various technologies, methods, and principles to make the production system more autonomous, dynamic, flexible, and precise (Hines et al., 2023). Examples of these technologies and methods include Building Information Modeling (BIM), industrial and modular construction, digital twin

(DT), the internet of things (IoT) and cyber-physical systems (CPSs), additive manufacturing (AM) or three-dimensional printing (3D Printing), big data, artificial intelligence (AI), digital monitoring for supply chain, cloud computing, blockchain, and others (Yali Chen et al., 2022; Sacks et al., 2020). Sawhney (2020) defined Construction 4.0 based on three main transformational trends:

- 1- Industrial production and construction: This includes the methods and technologies that support the industrialization processes in construction such as 3D printing, modularization and prefabrication, and automation.
- 2- Cyber-physical systems: in which sensors and IoT systems are used to sense important information from the physical layers and actuators to make physical actions.
- 3- Digital technologies: which include the technologies that are used to create and use digital information under specific data standards and interoperability such as BIM, clouding, AI, cybersecurity, reality capture (e.g. Virtual Reality; VR, Augmented Reality; AR, Extended Reality; XR; Mixed Reality; MR), blockchain, and others.

The integration between Lean Construction and Construction 4.0 is covered in this thesis in three main ways suggested in the literature (González et al., 2022a; Hines et al., 2023) (as shown in **Figure 1**): Lean Construction as an enabler for Construction 4.0, Construction 4.0 as an enabler for Lean Construction, and the correlation between Lean Construction and Construction 4.0. To study these three forms of integration, this thesis uses different methods to discuss theoretical bases about the integration between Lean and methods and technologies of Construction 4.0 and covers examples and cases of Lean Construction 4.0 implementation.

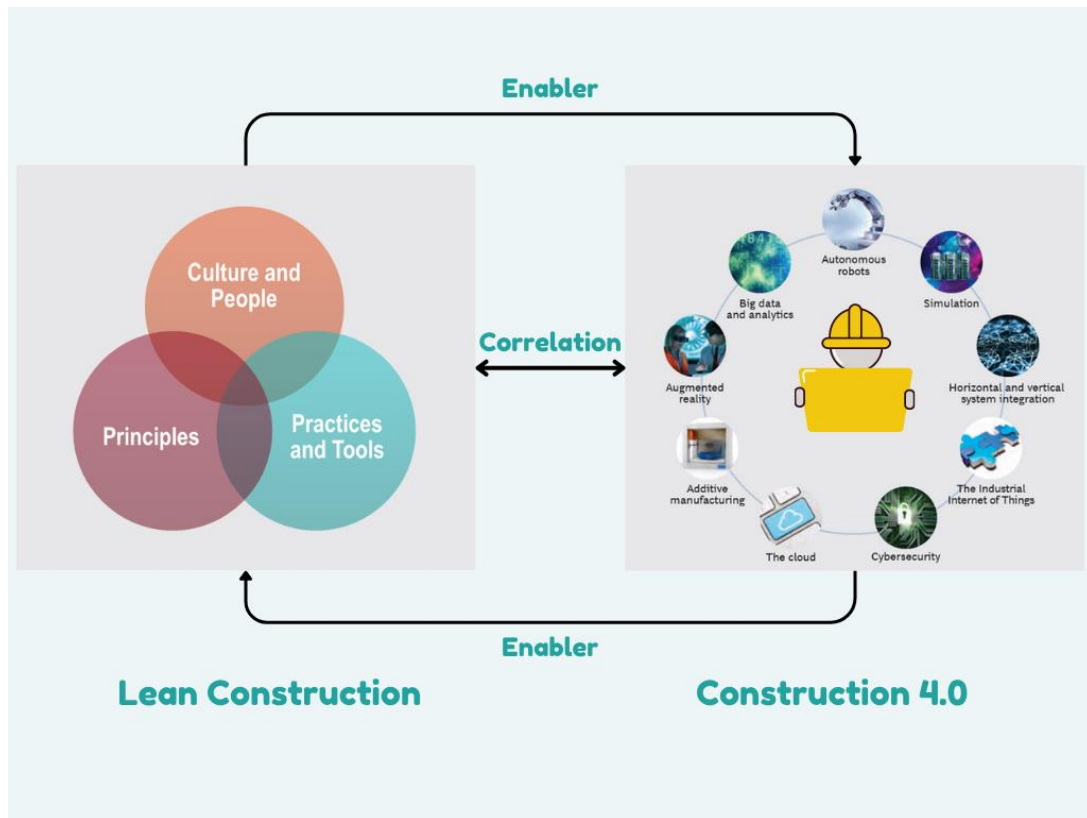


Figure 1. The relationship between Lean Construction and Construction 4.0

Motivations

The current state of the global and French construction sector

The construction industry is a main player in improving the quality of life and a key pillar in the global and national economies. The industry accounted for 13% of the global gross domestic product (GDP) in 2020 with expectations to reach 13.5% in 2030 (Oxford Economics, 2021). The construction market size was 7.28\$ trillion in 2021 with the ability to employ more than 180 million people around the world (Business Wire, 2022; McKinsey, 2020).

Due to the importance of the construction industry, there have been countless investigations to evaluate its performance on the global regional, and national levels in many places around the globe (Egan, 1998; European Commission, 2022; McKinsey, 2020; Oxford Economics, 2021; WEF,

2016). Despite the different locations of these investigations and reports, most studies agree that the construction industry is still unable to show major improvement and its performance is still underperforming. According to Sawhney et al (2020), studies and investigations about the performance of the construction industry agree on a set of key challenges that face this industry, which is:

- Low levels of research, development, innovation, and technology adoption
- Lack of skilled and sufficient workforce
- Low levels of standardization and high levels of fragmentation
- Absence of improvement culture and limited collaboration
- Poor productivity, predictability, and profitability
- Deficient procurement systems
- Poor knowledge management and absence of learning
- Resistance to change

Despite having one of the largest construction markets in which the total investment reached Euro 324 billion and the number of enterprises working in the sector was more than 725 hundred thousand enterprises in 2021 (European Commission, 2022; FIEC, 2021), France has not been immune to experiencing these challenges. Studies about the French construction sector have shown numerous problems that can be summarized as follows:

- Economic-related problems: the margin rates for construction works in France (in 2016 the margin for structural work was 3.1%, for finishing work was 1.8%, and for public work was 2.5%) are less than those in other countries (e.g. the average margin rate in the US is around 4.4%) (Michel & Rivaton, 2021). The low levels of profitability are accompanied by increased cost of materials especially after the pandemic of COVID-19 and the war in

Ukraine. A recent study showed that 84% of the members of Capeb Vosges (Confédération de l'Artisanat et des Petites Entreprises du Bâtiment: Confederation of Crafts and Small Businesses in the Building Industry) suffered from a rise in the prices of the materials between the time the quote was drawn up and the end of the project; 55% of them failed to pass the rise to their customers (Batiactu.com, 2022). In addition to the high cost of labor hours in France (around 40-50% of the cost of construction activities; while it is 14-18% in the French automobile sector) (Michel & Rivaton, 2021). As a result, high pressure continues to be created on the construction companies due to financial constraints. Statistics showed that company deaths in the construction sector in France in 2019 were more than 28,000 (European Commission, 2022) and the number of companies that experienced financial difficulties in March 2022 was doubled when compared to March 2021 (Batiactu.com, 2022).

- Delays, poor quality, and disputes: in 2018, 29% of home buyers in France suffered from an average of 5.4 months of delays in the delivery of their houses and 47% were not satisfied with the quality of the work (Michel & Rivaton, 2021). As a result, the sector is witnessing an increased number of disputes and claims (one out of four disputes resulting from delays) (Michel & Rivaton, 2021).
- Safety-related issues: according to L'Assurance Maladie (2023), the construction and public work sector is considered among the most dangerous sectors in France. Statistics on their website (ameli.fr) show that the construction sector experiences 56 occupational accidents for every 1000 employees (the average for all sectors is 34 accidents) with a rate of one accident every two minutes. According to the same source, in 2018, 6 million working days were lost due to accidents at work in the sector. As a result, the sector witnesses early retirement of existing labor and resistance to entering the construction industry by the

young workforce (Arndt et al., 2005; Bock, 2015; W. Lee et al., 2017; Ci Jyun Liang et al., 2020).

- Environmental-related problems: the French construction sector is responsible for 20-25% of the total greenhouse gas emissions (GHG) in the country (Michel & Rivaton, 2021). It is also characterized by high energy consumption. According to an evaluation of the energy efficiency for different sectors in France, the construction sector had one of the lowest records (30 out of 100) (Michel & Rivaton, 2021). Moreover, in 2020, the French construction sector was responsible for more than 240 million tons of construction and demolition waste (C&D W), out of them, 2.61% are hazardous wastes (Eurostat, 2023; Statista Research Department, 2022).
- Low levels of investment in research and development (R&D): it was found that only 38 companies belonging to the construction sector are among the 1000 most-spending companies on R&D in Europe and less than 1% of the French companies' turnover is spent on R&D activities (the percentage is 6% in the automobile sector) (Michel & Rivaton, 2021).

Benefits of both concepts

Despite the insufficient levels of adoption on the global and national scale, it can be said that the interest in Lean Construction is increasing. This is due to the expected benefits from its adoption. According to Jorgensen and Emmitt (2008), Lean implementation results were labeled by many researchers as “revolutionary” despite the lack of documentation in some cases. These results included improvements in cost saving, project duration reduction, higher safety awareness and fewer accident rates, sustainability, errors and rework reduction, waste reduction, better inventory management, higher predictability of work, higher labor productivity, and increased customer

satisfaction (Conte & Gransberg, 2001; Farrar et al., 2004; Ko, 2010; Koerckel & Ballard, 2005; Mohan & Iyer, 2005; Mossman, 2009; Nahmens et al., 2012; Yahya & Mohamad, 2011).

In turn, the last few years have witnessed several studies that aimed to identify the potential benefits of Construction 4.0 in the construction sector. According to Sawhney et al (2020), these benefits can be in enabling innovation, improving sustainability, improving the image of the construction industry by transforming the work, workers, and workplace, cost and time saving, improving safety conditions, improving quality, enhancing predictability, and achieving customer satisfaction.

The need to link the two concepts

While Lean Construction and Construction 4.0 have the potential to revolutionize the construction industry, their adoption still faces several challenges and barriers (Albalkhy et al., 2021; Albalkhy & Sweis, 2021; Bolpagni et al., 2022; González et al., 2022a; Sawhney et al., 2020). Additionally, the integration of Lean Construction and Construction 4.0 is a need not only to maximize the benefits of the two concepts but also to mitigate the impact of their false implementation. On one hand, when looking at the organizational triad, which is supported by Lean thinking and includes process, people, and technology, it is widely conceived that whenever there is a technology-based solution, companies may overemphasize the technology and its implementation and neglect the integration of the people and the efforts to present improvements in the process. Which in turn can disempower people and cause failures to achieve better performance and productivity (Dave et al., 2008). On the other hand, Lean has been seen by some researchers as a low-tech approach that supports standardization and simplicity, which causes losses of opportunities to use high-tech tools that help to respond to the complex nature of projects and capture all needed information (Heidenberg & Porres, 2010; Hines et al., 2023). While this argument may not be so accurate as it does not agree with the goals of achieving better capturing, visualization, and control of flow and

waste, achieving continuous improvement, and supporting the principle of autonomation (one of the main practices in Toyota Production Systems (TPS); automation with human touches), it can be said that the sole dependence on Lean is not enough; especially with the rapid advancement of technology (Hines et al., 2023).

Therefore, despite the different natures of Lean Construction and Construction 4.0, there is room to benefit from their integration to create a more flexible system. In such a system, information is collected, analyzed, and used in transparent and efficient ways to ensure the continuous improvement of the process and the integration of people (González et al., 2022b). As a result, it ensures that processes are done correctly, on time, and with the best decision-making approaches (McHugh, Dave, & Koskela, 2022a).

Research Gaps and Objectives

The integration between Lean and Industry 4.0 is still in its infancy and there is a need to make more efforts to investigate the opportunities and ways to create this integration. However, while the last few years have witnessed some reviews about Lean and Industry 4.0 in different fields including the construction sector (Fioravanti et al., 2018; Hines et al., 2023; Müller & Birkel, 2020; Rosin et al., 2020; Sanders et al., 2016; Santos et al., 2021; Sony, 2018; Valamede & Akkari, 2020), only a limited number of reviews focused on the link between Lean Construction and specific Industry 4.0/Construction 4.0 technologies and methods in the construction environment (apart from BIM) (Dakhli et al., 2019; Tezel et al., 2022a). Accordingly, the first objective of this thesis is:

Objective 1: To review the synergies between Lean Construction and Construction 4.0 technologies.

The number of studies on Lean Construction implementation in the French construction sector is still low (Dakhli et al., 2016, 2017; Dakhli & Lafhaj, 2018) and the knowledge about the integration between Lean Construction and Construction 4.0 is still limited. By shedding light on some cases from France, this thesis aims to achieve:

Objective 2: To investigate the link between Lean Construction and Construction 4.0 practices in France.

Additionally, as Lean Construction 4.0 is still a new concept, there is an insufficient number of cases about its adoption and implementation along the different phases of the building life cycle. Accordingly, the third and fourth objectives of this thesis are:

Objective 3: To propose frameworks to integrate Lean Construction and Construction 4.0 technologies.

Objective 4: To examine the implementation of Lean Construction 4.0 along different phases of the building life cycle.

The final objective aims to study the relationship between Lean Construction and new project management methods. This relationship has received a lot of attention for many years and the relationship between Lean Construction and the project management theory was well investigated (Koskela et al., 2002; Koskela & Howell, 2002). Nevertheless, some new methods are gaining popularity in practices and research but received less attention concerning their relation with Lean. A clear example of these methods is the Advanced Work Packaging (AWP). Therefore, the fifth research objective is:

Objective 5: To analyze similarities and differences between Lean Construction and AWP and the future opportunities of their integration.

Research Questions

Based on the above-mentioned objectives, this thesis tries to answer the following research questions (RQs):

- **RQ1:** What are the links between Lean Construction and Construction 4.0 technologies?
- **RQ2:** How can Lean Construction and Construction 4.0 be integrated into different phases of the building life cycle?
- **RQ3:** What are the perspectives of the French construction sectors regarding the integration of Lean and Construction 4.0 integration?
- **RQ4:** What are the similarities and differences between Lean Construction and AWP? And What are the opportunities for their integration?
- **RQ5:** Why Lean Construction 4.0 is needed in the construction industry?

Structure of the Thesis

To achieve the objectives of the study, this thesis presents six case studies and four literature reviews organized in six chapters as follows (as shown in **Figure 2**):

GENERAL INTRODUCTION: it aims to present a research background and discusses the motivations, gaps, and objectives of this thesis.

Chapter 1. LITERATURE REVIEW: this chapter aims to present a general overview of Lean philosophy and Construction 4.0.

Chapter 2. LEAN CONSTRUCTION AND IOT: This chapter explains the relationship between Lean Construction and IoT (a cyber-physical system technology as mentioned above). The chapter is built on the results of three works:

- The first one (**Review 1**) is a systematic literature review about the synergies between Lean Construction and IoT (**objective 1**).
- The second one (**Case 1**) is based on the application of IoT to improve workflow in the phase of materials produced in a brick factory in France (**Objective 2 and Objective 4**).
- The third work (**Case 2**) is based on a proposed model to improve flow synchronization between the offsite fabrication and onsite assembly in industrialized production systems (**Objective 3**).

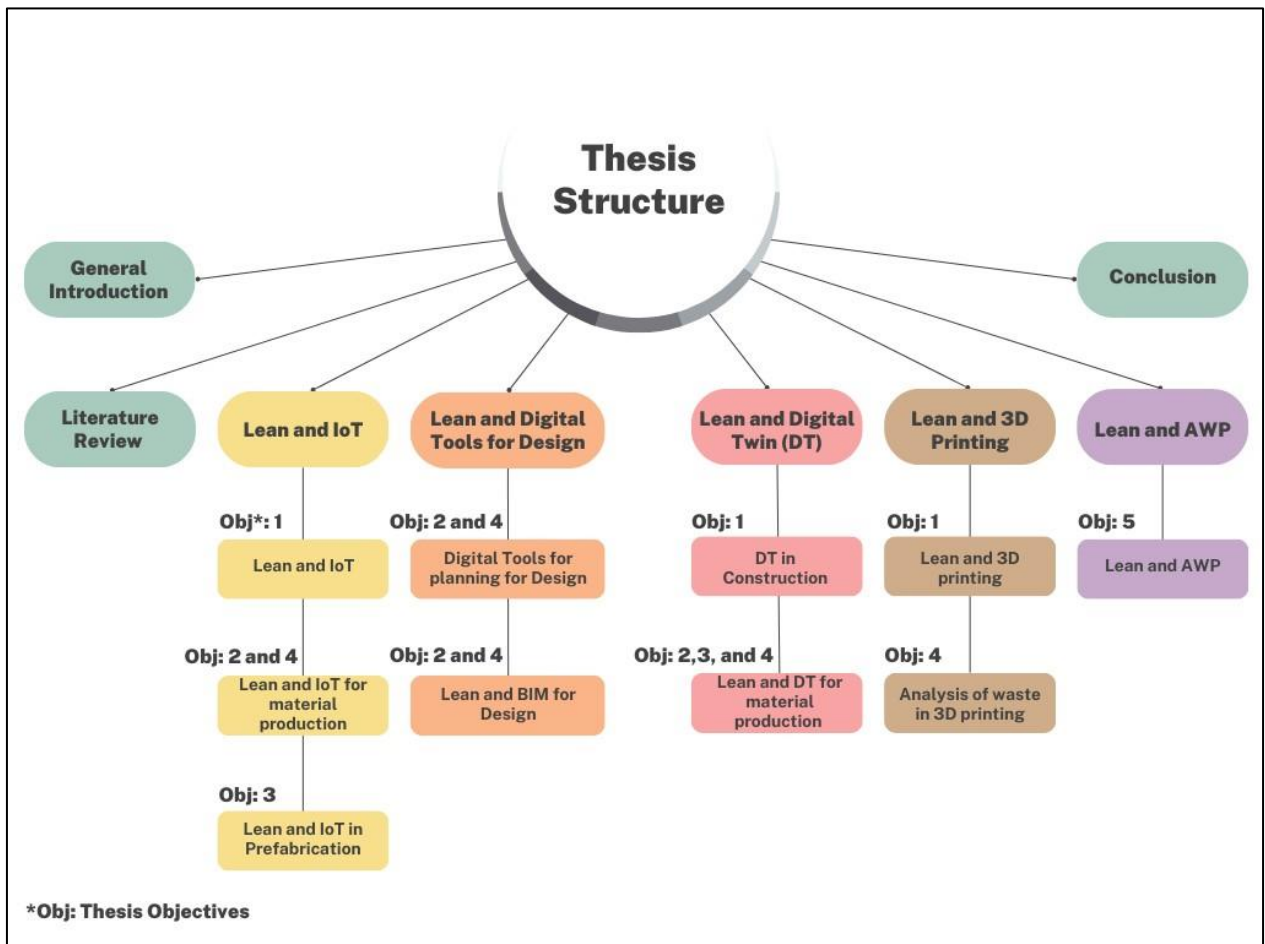


Figure 2. Thesis Structure

Chapter 3. LEAN CONSTRUCTION AND INTEGRATION AND COLLABORATION TOOLS

FOR DESIGN MANAGEMENT: this chapter was built over two works about the integration of Lean and digital technologies in the design phase:

- The first work (**Case 3**) is about the use of Lean and digital tools during the COVID-19 pandemic to improve planning for design activities in France (**Objective 2 and Objective 4**).
- The second work (**Case 4**) is based on the perspectives of the design professionals in France regarding the integration between Lean and BIM and its impact on design performance (**Objective 2 and Objective 4**).

Chapter 4. LEAN CONSTRUCTION AND DIGITAL TWIN: this chapter aims to present links between Lean and digital twin as a Construction 4.0 digital technology. The chapter is based on two works:

- The first one (**Review 2**) is a review of the use of digital twin in the construction sector and its links with Lean Construction (**Objective 1**).
- The second work (**Case 5**) is based on the application of digital twin-based value stream mapping (VSM) in the materials production phase in a brick factory in France (**Objective 2 and Objective 4**).

Chapter 5. LEAN CONSTRUCTION AND 3D PRINTING: this chapter aims to present the relationship between Lean Construction and 3D Printing technology as an industrial construction and production technology. This chapter is based on two works:

- The first work (**Review 3**) is a review of the synergies between Lean and 3D Printing (**Objective 1**).

- The second work (**Case 6**) is built over the application of Lean principles as an enabler to improve 3D Printing processes (**Objective 4**).

Chapter 6. LEAN CONSTRUCTION AND NEW PROJECT MANAGEMENT METHODS: THE CASE OF ADVANCED WORK PACKAGING (AWP): this chapter aims to achieve **Objective 5** by presenting the results of a review (**Review 4**) of the similarities and differences between Lean and AWP and the possible opportunities of their integration.

GENERAL CONCLUSIONS: This section presents the overall conclusions of the thesis, in addition to the implications, limitations, and future directions for research works.

Scientific Valorization

During the work on this thesis, the author participated in **22** publications with his research team.

The results of these publications are organized as follows:

Chapter 1

AlBalkhy, W., Sweis, R., & Lafhaj, Z. (2021). Barriers to adopting Lean Construction in the construction industry—The case of Jordan. *Buildings*, 11(6), 222.

Chapter 2

AlBalkhy, W., Rankohi, S., Lafhaj, Z., Iordanova, I., Ramirez Velasquez, J.M., Bourgault, M., & Pellerin, R. (2023). Lean and IoT integration to improve flow in construction prefabrication: a proposed framework. *Proc. 31st Annual Conference of the International Group for Lean Construction (IGLC)*. 836-845. <http://doi.org/10.24928/2023/0260>

Karmaoui, D., **AlBalkhy, W.**, Danel, T., Jullien, A., Lafhaj, Z., & Chapiseau, C. (2022). IoT-based architecture to improve workflow in bricks manufacturing. *Modular and Offsite Construction (MOC) Summit Proceedings*, 42–49.

Mossman, A., Talssi, M., **AlBalkhy, W.**, Karmaoui, D., & Lafhaj, Z. (2022). Pourquoi faire aujourd’hui le choix de la construction modulaire? - HORS SITE. *Hors Site, PRINTEMPS*(17), 73–80. <https://hors-site.com/pourquoi-faire-aujourd'hui-le-choix-de-la-construction-modulaire/>

Dardouri, S., BuHamdan, S., **AlBalkhy, W.**, Dakhli, Z., Danel, T., & Lafhaj, Z. (2022). RFID platform for construction materials management. *International Journal of Construction*

Management, ahead of p(ahead of print). <https://doi.org/10.1080/15623599.2022.2073085>

Murugaiyan, K., **Albalkhy, W.**, Lafhaj, Z., & Font, F. (2022a). Supply Chain Management in Construction: State of The Arte. *The Twelfth International Conference on Construction in the 21st Century (CITC-12)*, 437–444.

Albalkhy, W., Lafhaj, Z., Jai, H., Sweis, R. The Integration of Lean Construction and IoT: a Systematic Literature Review. *In Progress*

Chapter 3

Albalkhy, W., Chaize, E., Morael, V., & Lafhaj, Z. (2023). Lean Construction and Building Information Modeling (BIM) in design management: survey results from French companies. *Proc. 31st Annual Conference of the International Group for Lean Construction (IGLC)*. 220-229. <https://doi.org/10.24928/2023/0257>

Chaize, E., **Albalkhy, W.**, Morael, V., & Lafhaj, Z. (2022). Impact of Lean Practices in the Planning of Design Tasks: Evidence From Two Projects in France. *Proc. 30th Annual Conference of the International Group for Lean Construction (IGLC)*, 492–503. <https://doi.org/10.24928/2022/0154>

Murugaiyan, K., **Albalkhy, W.**, Lafhaj, Z., & Font, F. (2022a). Supply Chain Management in Construction: State of The Arte. *The Twelfth International Conference on Construction in the 21st Century (CITC-12)*, 437–444.

Chapter 4

Karmaoui, D., **Albalkhy, W.**, Lafhaj, Z., & Chapiseau, C. (2023). Lean and Industry 4.0 in brick manufacturing: a digital twin-based value stream mapping proposed framework. *Proc. 31st Annual Conference of the International Group for Lean Construction (IGLC)*. <https://doi.org/10.24928/2023/0259>

AlBalkhy, W., Karmaoui, D., Ducoulombier, L., Lafhaj, Z., Linner, T. Digital Twin in the Built Environment: a Systematic Literature Review. *In Progress*

Chapter 5

Lafhaj, Z., **Albalkhy, W.**, & Karmaoui, D. (2022). Identification of Lean Waste in Construction 3D Printing Processes. *The International Inorganic-Bonded Fiber Composite Conference (IIBCC)*.

Albalkhy, W., Bing, S., El-Babidi, S., Lafhaj, Z., Ducoulombier, L. (2023). The Analysis of Lean Wastes in Construction 3D Printing: A Case Study. *In ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*. Chennai, India, July 3–9, 2023 (Vol. 40, pp. 621-628).

Chapter 6

Lafhaj, Z., Rebai, S., **Albalkhy, W.**, Hamdi, O., Mossman, A., & Alves Da Costa, A. (2023). Understanding Complexity in Construction Projects: Literature Review. *In Progress*.

Rebai, S., **Albalkhy, W.**, Hamdi, O., & Lafhaj, Z. (2023). Lean Construction and AWP: similarities, differences, and Opportunities. *Proc. 31st Annual Conference of the International Group for Lean Construction (IGLC)*. 1428-1439. <http://doi.org/10.24928/2023/0258>

Other research works

Albuainain, N., Sweis, G., **AlBalkhy, W.**, Sweis, R., & Lafhaj, Z. (2021). Factors affecting occupants' satisfaction in governmental buildings: The case of the Kingdom of Bahrain. *Buildings*, 11(6), 231.

Lafhaj, Z., **Al Balkhy, W.**, & Linner, T. S. (2022). Teaching Construction Robotics for Higher Education Students:" Imagine and Make". In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction* (Vol. 39, pp. 47-54). IAARC Publications.

Lafhaj, Z., **Al Balkhy, W.**, & Linner, T. (2022). "Imagine and Make": Teaching Construction Robotics for Higher Education Students. *Construction Robotics*, 6 (2), 207.

Schmailzl, M., Spitzhirn, M., Eder, F., Krüll, G., Obergrießer, M., Linner, T., **AlBalkhy, W.**, & Lafhaj, Z. (2023). Towards interfacing human-centered design processes with the AEC industry by leveraging BIM-based planning methodologies. In *40th International Symposium on Automation and Robotics in Construction (ISARC 2023)*: Chennai, India, July 3–9, 2023

Lafhaj, Z., Chikhi, E., Mossman, A., **Albalkhy, W.**, Thepaut, A. (2023). Integrated project delivery, source d'inspiration pour transformer le secteur de la construction. *Hors Site, Mars 2023*, 66–70. <https://hors-site.com/integrated-project-delivery-source-dinspiration-pour-transformer-le-secteur-de-la-construction/>

Karmaoui, D., Abaaouch, F., **AlBalkhy, W.**, Julien, A., Lafhaj, Z. (2023). Investigating geopolymer brick mix design properties using recycled brick waste, granulated blast furnace slag, and metakaolin. *In Progress*.

CHAPTER 1. LITERATURE REVIEW

Chapter 1. Literature Review

This chapter aims to support the understanding of the concept of Lean Construction 4.0. To do so, the chapter presents a review of the related literature to define Lean Construction, its origins, principles, and tools. It also illustrates the concept of Construction 4.0 and its applications in the construction industry.

1.1 Lean Construction

1.1.1 Lean thinking

The word "Lean" was coined in 1988 by John Krafcik in his paper "The Triumph of the Lean Production System", which aimed to explain the Toyota Production System (TPS) (Krafcik, 1988). Thanks to the famous Japanese engineer, Taiichi Ohno, TPS was developed as a response to the numerous challenges that faced Toyota after World War II. Among these challenges are low levels of productivity in the Japanese factories in comparison to the factories in the US, diversity in the demand of the Japanese customer, and lack of raw materials supply and spaces for inventory (Ohno, 1988; Womack et al., 1990; Womack & Jones, 1996). These challenges created needs for 1) optimize the process and reduce cycle time and machine setup time to avoid loss in productivity, 2) transition toward benefiting from the advantages of craft production and mass production at the same time without being affected by the high cost of the former and the rigidity of the latter, 3) work to achieve zero inventory and avoid the loss of materials (Diekmann et al., 2004; Innella et al., 2019; Womack et al., 1990).

Aiming at enhancing the full production operation, Ohno studied the experience of the US car manufacturer, Ford. But unlike Ford, where there has been a huge focus on standardization, Ohno identified meeting the customer needs, achieving continuous improvement, and eliminating all

types of waste as the fundamentals of TPS (Howell, 1999). The term waste refers to all activities that consume resources but do not add any value for the customer. Initially, Ohno (1988) defined seven types of waste in the production process, which are defects, overproduction, waiting, transportation, waste of excessive inventory, unnecessary movement (motion), and excessive processing. After that, other researchers defined other types of waste such as the failure to benefit from crises and the non-utilized talents (Dakhli & Lafhaj, 2018; El Jazzer & Nassereddine, 2021) (as shown in **Figure 1.1**).

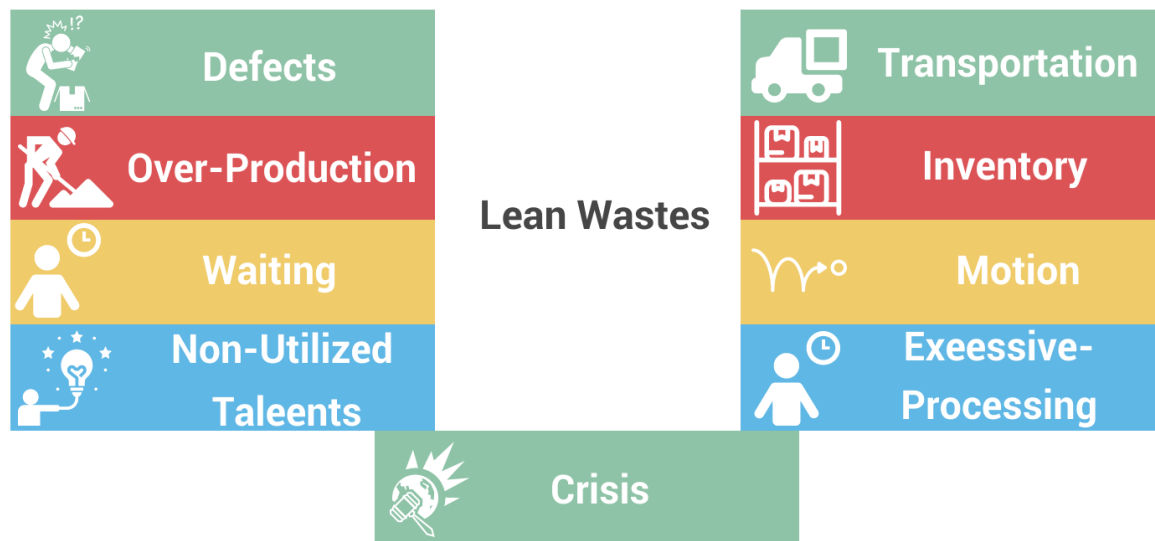


Figure 1.1. Types of waste in Lean thinking (Lafhaj & Albalkhy, 2023)

In addition, Ohno identified respect for people as a core concept and Just-in-time (JIT) and automation as the pillars of TPS. JIT implies that materials will be delivered at the right time, to the right location, with the right quantity and will be brought to their location immediately before the installation without any delays caused by storage in a laydown or staging area (Tommelein & Weissenberger, 1999). In turn, automation (Jidoka in Japanese) refers to automation with a human touch (Ohno, 1988). **Table 1.1** shows a comparison between automation and automation. In turn, Monden (1983) identified JIT, Automation, workforce flexibility, and creativity as the

main pillars of TPS and quality control, quality assurance, and respect for humanity as the main goals of it.

Table 1.1. Automation and autonomation (Boakye-adjei et al., 2015)

Category	Automation	Autonomation
People	Manual processes become easier but still needs human supervision	Supervisors can multi-task and productivity improves
Machines	Machines complete cycle until stop button is activated	Machine detection of errors and correction is autonomous
Quality	Defects can be produced in mass quantities due to machine malfunction	Machine crashes are prevented by auto-stop, hence defects are avoided
Error and Diagnosis	Errors are discovered later and root cause analysis is long term	Errors are discovered and corrected quicker

The development of TPS helped Toyota to achieve remarkable success not only in Japan but also in the global market. Since then, there have been many works that aimed to describe TPS and the principles and theory of Lean. One of the most famous works was done by Womack, Jones, and Ross who were among the earliest researchers who studied the experience of Toyota and published the book “The Machine that Changed the World” and the review “Beyond Toyota: How to Root out waste and pursue perfection” (Womack et al., 1990; Womack & Jones, 1996). In their work, Lean principles were defined as 1) customer value, 2) value stream mapping (VSM), 3) creating flow and eliminating waste, 4) establishing pull, and 5) achieving continuous improvement.

Another significant work was by Jeffery Liker in his book “The Toyota Way”, in which he presented 14 principles for Lean thinking distributed in four groups (4P): philosophy, process, people and partner, and problem-solving (Liker, 2004).

1.1.2 Lean thinking in construction

Transformation-Flow-Value (TFV) Theory

Since the early 1990s following the success of Lean principles in Toyota, and then in manufacturing and other fields, several researchers and practitioners have contributed to the presentation of the Lean philosophy in the construction industry. The earliest work was the presentation of the “new production philosophy to construction” by Lauri Koskela (1992), which was then followed by the Transformation-Flow-Value theory (TFV) in 2000 (Koskela, 2000).

TFV theory has three central concepts. The first (Transformation) is transforming the inputs into outputs by decomposing the work into tasks, then minimizing the cost of these undertakings to realize the efficiency of the added-value activities. The second concept (Flow) is the flow of materials and information that includes, in addition to transformation, inspection, moving, and waiting. The main aim of flow design and improvement is minimizing the waste of non-added value activities. The third concept (Value) is the value generated from the customer’s point of view by ensuring an understanding of the needs of the customer and fulfillment of these needs. According to Koskela (2000), TFV theory has to be applied in the design, control, and improvement of the production system in construction.

Bertelsen and Koskela (2004) asserted that most project managers focus on managing transformation to gain higher productivity, which is necessary for all projects. Nevertheless, managing flow is usually ignored. Koskela (2000) affirmed that the sequential method of project realization, the absence of quality thought, segmental control, and critical path networks violate the principles of the flow process and lead to non-optimal flow and expansion of non-value-adding activities. Bertelsen and Koskela (2004) confirmed that supply chain management and collaboration between different parties of the project improve the management of flow activities.

In turn, managing value generation is the most challenging concept, as it is a learning process that involves the client and design professionals, in which designers understand the client's needs, and the client realizes the design.

As illustrated in **Table 1.2**, understanding production based on TFV raises the attention toward balancing the three views combined. It can be said that TFV supposes that in practice, there should be three areas of management; task management (transformation), flow management, and value management.

Table 1.2. TFV theory viewpoints (Koskela et al., 2002)

Viewpoint	Transformation	Flow	Value
Concept	Transformation of inputs to outputs	The flow of material and information from its initial state to the final product	Generation of value to the customer
Function	Making individual tasks efficient	Minimizing waste	Minimizing value loss (Ensuring customer requirements are met)
Application	Task Management	Flow Management	Value Management
Evaluation	The "input" and "output" of each internal process on its own	The flow between the different processes	The product (intermediate and final) vs. customer

Last Planner System® (LPS)

Another important work was the presentation of the most famous Lean Construction tool, which is the Last Planner System® (LPS) by Glenn Ballard. While studying the planning activities in construction projects, Ballard noticed the following deficiencies in traditional planning (Ballard, 2000; Ballard & Howell, 1994):

- Management focuses on controlling bad changes rather than causing good changes or "breakthroughs".

- Planning is done by a sole planner (or a team of planners) and understood based on the skills and talents of the planners rather than being understood as a systematic and collaborative approach.
- Planning neglects crew-level planning and focuses only on a schedule. It also neglects the match between what should be done, and what will be done, with the constraint: of what can be done.
- Performance is usually not measured.
- There is no work done to identify failure causes or to learn how to act on these causes.

In addition, the tasks are usually not achieved as planned, because planning and execution in construction are based on project control rather than production control, and usually, there is a lack of collaboration and involvement of stakeholders in the planning process (Ballard & Howell, 1994).

Accordingly, LPS was introduced as a production planning and control tool for construction that aims to enhance the collaboration between the stakeholders. The term “last planner” refers to the person or the team responsible for producing an individual construction assignment on site (e.g. foremen) (Ballard, 2000). The goal of LPS is to create a social process based on discussion between planning and site staff to have a reliable workflow (Gao & Low, 2014). Further, LPS is a transition from controlling workers to controlling the flow that links the workers together (Aziz & Hafez, 2013).

According to Ballard et al. (2009) the principles that guide thinking and actions in LPS are as follows:

1. The closer to executing the task, the higher need for more detailed plans.
2. Planning tasks should include those who are performing these tasks.

3. The team is accountable for identifying and removing constraints on planned tasks.
4. Promises should be secure and reliable.
5. Learn from failures.

LPS has generally different levels of planning and control and incorporates the pull concept and plan based on what “CAN” be done instead of the push mechanism that is based only on what “SHOULD” be done. This planning structure (illustrated in **Figure 1.2**) identifies constraints to be removed, develops performance measures such as Planned-Percent-Completed (PPC), and integrates the learning process based on the principles of continuous improvement and non-compliance to plan analysis (Porwal et al., 2010). The main planning and control levels in LPS are (LCI Congress, 2016):

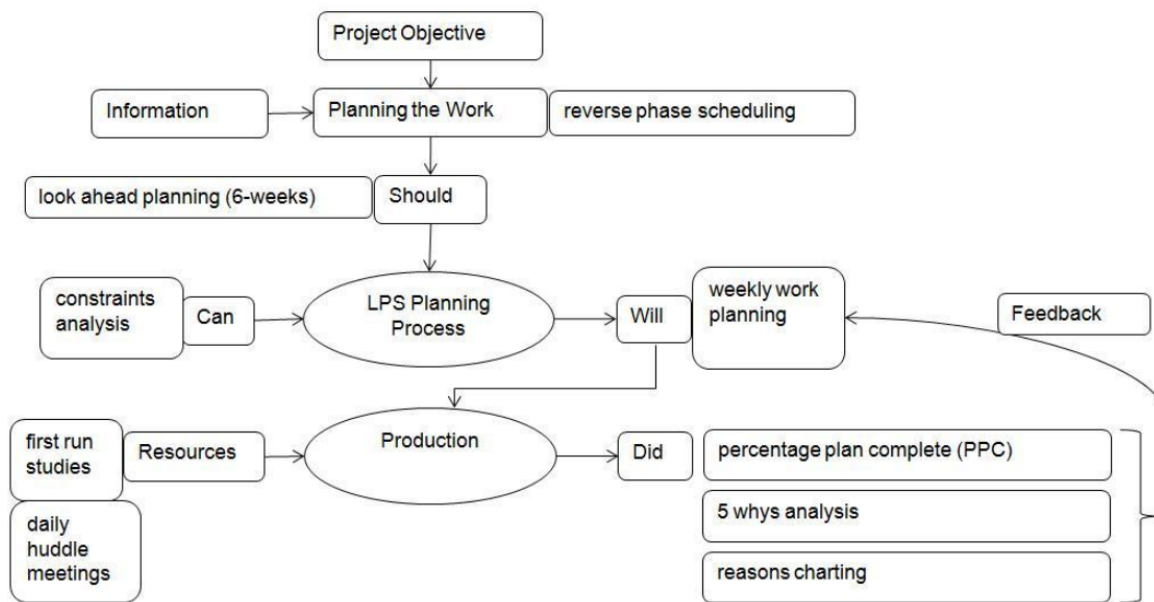


Figure 1.2. Last Planner System® Structure (Porwal et al., 2010)

- Master planning or milestone planning: which defines the overall road and the main milestones of the projects (identifying what should be done).

- Phase planning or pull planning: collaborative planning of phases to achieve the milestones (identifying what should be done).
- Lookahead planning: uses phase planning to make work ready. In this phase, the focus is on identifying constraints-free tasks (identifying what can be done).
- Weekly work plan (WWP): a detailed weekly plan that includes commitments and promises to deliver the tasks (identifying what will be done).
- Daily huddle meetings and learning: to identify what will be completed and what was completed, what needs to be re-planned, and how to prevent deviations from the plan (identifying what will be done and what was done).

Lean Construction principles

Several authors defined different principles for Lean Construction from operational or managerial views. For instance, Koskela (1992, 2000) identified 11 principles for Lean Construction. In turn, Diekmann (2004) presented five groups of principles (customer focus, culture/people, workplace organization/standardization, eliminating waste, and continuous improvement/ built-in quality). While Sacks et al (2010) presented 24 principles for Lean Construction based on four main groups: flow process, value generation process, problem-solving, and developing partners. **Table 1.3** summarizes the found principles in the three above-mentioned studies.

Over the years, there has been a lack of agreement on a specific definition for Lean Construction, but one of the definitions that were raised following studying a list of existing literature about Lean Construction was “a philosophy that aims to improve the collaboration between all project stakeholders to maximize value for all of them in general and the customer in particular, in addition to eliminating all kind of wastes, achieving continuous improvement, improving flow, reducing cost and enhancing safety and quality” (Albalkhy & Sweis, 2021).

Table 1.3. Lean Construction principles.

Koskela (1992, 2000)	Diekmann et al (2004)	Sacks et al (2010)
1. Reduce the share of nonvalue-adding activities	Customer focus Define value from the viewpoint of the customers	Flow <u>Reduce variability</u>
2. Increase output value through systematic consideration of customer requirements	Use flexible resources and adaptive planning	A. Get quality right the first time (reduce product variability)
3. Reduce variability	Optimize value	B. Focus on improving upstream flow variability (reduce production variability)
4. Reduce the cycle time	Culture/People	<u>Reduce cycle times</u>
5. Simplify by minimizing the number of steps, parts, and linkages	Training Employee empowerment Management Commitment	C. Reduce production cycle durations
6. Increase output flexibility	Workplace organization/standardization	D. Reduce inventory
7. Increase process transparency	standardization	E. <u>Reduce batch sizes</u>
8. Focus control on the complete process	Encourage workplace organization and use of 5S	<u>Increase flexibility</u>
9. Build continuous improvement into the process	Visual management Define work processes	F. Reduce changeover times G. Use multi-skilled teams
10. Balance flow improvement with conversion improvement	Eliminate waste Supply chain management Optimize production system Reduce process cycle time Optimize work content	<u>Select an appropriate production control approach</u>
11. Benchmark	Continuous improvement/ Built-in quality Use metrics and key performance indicators (KPIs) Response to defects Error-proofing Organizational learning	H. Use pull systems I. Level the production J. <u>Standardize</u> K. <u>Institute continuous improvement</u> <u>Use visual management</u>
		L. Visualize production methods M. Visualize the production process
		<u>Design the production system for flow and value</u>
		N. Simplify O. Use parallel processing P. Use only reliable technology Q. Ensure the capability of the production system
		Value generation process
		R. Ensure comprehensive requirements capture
		S. Focus on concept selection
		T. Ensure requirement flow down
		U. Verify and validate
		Problem-solving
		V. Go and see for yourself
		W. Decide by consensus, consider all options
		Developing partners
		X. Cultivate an extended network of partners

Lean Construction tools and practices

The construction industry has benefited from the implementation of several Lean tools and practices. LPS, Integrated Project Delivery (IPD), Target Project Delivery (TPD), Target Value Design (TVD), and Virtual Design and Construction (VDC) are examples of the tools and practices that were developed in the construction environment. However, most of the other tools were developed in other fields.

Several studies have reviewed Lean tools and practices. Nevertheless, there is no agreement on the exact number of Lean Construction tools. Salem et al. (2006) developed a Lean assessment tool to quantify the application of six tools of Lean Construction; LPS, increased visualization, huddle meetings, first-run studies, 5S, and fail-safe for quality. Sarhan et al. (Sarhan et al., 2017) used a list of 22 tools to assess Lean Construction implementation in Saudi Arabia. Hannis Ansah et al (2016) classified Lean Construction tools into three main categories, which are waste detection tools (e.g. VSM, construction process analysis, Muda walk, and spaghetti diagram), waste processing tools (e.g. 5 Why, Pareto analysis, and Fishbone diagram), and waste response tools (e.g. 5S, LPS, work standardization, check sheets, JIT, and A3 problem solving). In turn, in their review, Babalola (2019) identified four main areas for 32 Lean Construction practices applications; namely

1. Design and engineering (e.g. VDC, design structure matrix-DSM, prefabrication and modularization, IPD, TPD, and concurrent engineering).
2. Planning and control (e.g. LPS, location-based management system- LBMS, VSM, and error-proofing or Poka-Yoke).
3. Construction and site management (Gemba Walk, Total productive/preventive maintenance-TPM, Kanban, 5S, JIT, and Visual Management-VM).

4. Health and safety management (e.g. fail safe for quality and safety, plan of conditions and work environment, and health and safety improvement management).

Table 1.4 presents some definitions for some of the most known Lean tools and practices.

Table 1.4. Lean Construction tools and practices

Lean tool/practice	Definition	References
Value Stream Mapping (VSM)	“VSM establishes the current state of the construction process or supply chain to identify the wastes. The future state helps to develop improvement strategies”	(Sarhan et al., 2017)
Kaizen	“The Japanese word for continual improvement, Kaizen promotes the idea that every process can and should be continually evaluated and improved in terms of time required, resources used, resultant quality, and other aspects relevant to the process”	(Sarhan et al., 2017)
Target Value Design (TVD)	“This approach applies methods for the design to be developed in accordance with the constraints, especially cost (e. ‘deign-to-cost’ or ‘design-to-targets’. TVD considers the customers’/ clients’ and stakeholders’ vision to define such restrictions and deliver the required target values”	(Sarhan et al., 2017)
Visual Management (VM)	“In a Lean-based working environment, it should be easy and quick to understand what is the work situation in terms of status against the plan, whether there are any issues and, if so, who is dealing with them and the status of resolution. Good visual management enables this by communicating a message or an instruction in a quick, easy-to-understand way so that the right response or reaction is achieved”	(O’Connor & Swain, 2013)
Integrated Project Delivery (IPD)	“Project delivery approach that involves the signing of a contract between the client and key designers, contractors and other stakeholders involved in the project”	(Babalola et al., 2019)
5S	“5S provides a structured method for achieving, maintaining and improving the standard set-up, organization, and layout of a work area to ensure safe and efficient operations, with minimal waste” 5S: Sort, set in order, shine, standardize, and sustain	(O’Connor & Swain, 2013)
5 Why	“This is the Lean Construction iterative a question-asking technique that elucidates “cause-and-effect” mechanisms associated with a problem. It is a problem-solving tool that aims to find the root cause of a construction-related issue or problem. The questions are usually specific to the project and are not limited to five questions”	(Sarhan et al., 2017)
A3 Problem-Solving	“A sheet that provides a standard template that a team can use to ensure a structured approach is applied when resolving the root cause of a problem and proposing remedial or counter-measures”	(O’Connor & Swain, 2013)
Fishbone analysis or Ishikawa	“A visual or diagrammatic brainstorming process to identify factors most likely to contribute to the problem”	(O’Connor & Swain, 2013)
Plan-do-check-act (PDCA)	“Also known as the ‘improvement cycle’, is a structured four-step approach to process improvement. Typically drawn as a circle, PDCA has no end and should be repeated again and again. It supports small step continuous improvement and, when applied well, will help ensure sustainable improvement”	(O’Connor & Swain, 2013)
Design Structure Matrix (DSM)	“Used in the structuring of design and design process into sequential segments”	(Babalola et al., 2019)
Error-proofing or Poka-Yoke	“Poka-yoke is a Japanese word which can be defined as “error- proofing”. Shingo introduced Poka-yoke devices as new elements to avoid defective	(Sarhan et al., 2017)

Lean tool/practice	Definition	References
	parts from flowing through the process. It is a Lean tool that engages all forms of activities and devices that could help avoid an error from happening”	
Kanban	“This is an ancient Lean tool that involves the use of inventory control card or sign for stock taking on project site. This helps to promote effective inventory and recording keeping on construction project sites”	(Babalola et al., 2019)
Gemba Walk	“The Gemba walk is an opportunity for staff to take a step back from their daily tasks and walk the floor of their workplace to identify wasteful activities. A team walk the factory floor together to observe and record inefficiencies related to water use”	(Sodkomkham et al., 2021)
Location-Based Management System (LBMS)	“It models the construction process into locations of activities and each module is linked together based on their relationships”	(Babalola et al., 2019)
Takt-time Planning	“Takt-time is the unit of time within which a product must be produced (supply rate) in order to match the rate at which that product is needed (demand) rate”	(Frandsen et al., 2015)
Design BigRoom	“This is a room on site for meeting of project designers, where the entire design and its process are discussed and analyzed to remove difficulties and suggest creative ideas for the design solutions”	(Babalola et al., 2019)
First run study	“This is the modelling of important of construction site operations, especially when those involved have little or no idea about the operation. It requires investigation of errors and alternative approaches for preventing or mitigating them”	(Babalola et al., 2019)
Total Productive/ Preventive Management (TPM)	“This is a hands-on preventive approach for maintaining site operator's equipment. This ensures that operators take care of their equipment as they use it”	(Babalola et al., 2019)
Fail safe for quality or safety	“This is a Lean Construction tool that ensures no harm or minimum is sustained in the event of specific failures”	(Sarhan et al., 2017)

1.2 Construction 4.0

Construction 4.0 refers to the application of a broader concept (Industry 4.0 or the fourth industrial revolution) in the construction industry to enable the digital transformation and utilization of technology to respond to the challenges the industry faces.

1.2.1 Industry 4.0

In 2011, aiming to strengthen the competitive advantages of the German manufacturing sector, the German government revealed the first concepts for the fourth industrial revolution at the Hannover Fair as part of the “German High-Tech Strategy 2020 Action Plan” under the title “Industrie 4.0” (Kagermann et al., 2013). Since then, the concept of Industry 4.0 has attracted the attention of

researchers, managers, and policy-makers due to the potential contributions it may have while facing the modern challenges that face global manufacturing such as the increased global competition, decreased product life cycle, increased demand on customized products, and the need to improve productivity (Santos et al., 2021).

Historically, the world has witnessed four industrial revolutions as shown in **Figure 1.3**. The energy sources and disruption in production have been the main driver of these revolutions (Dakhli & Lafhaj, 2018; Valamede & Akkari, 2020), but the impact of the revolution was then affecting all life aspects. The four industrial revolutions are as follows (Bolpagni et al., 2022):

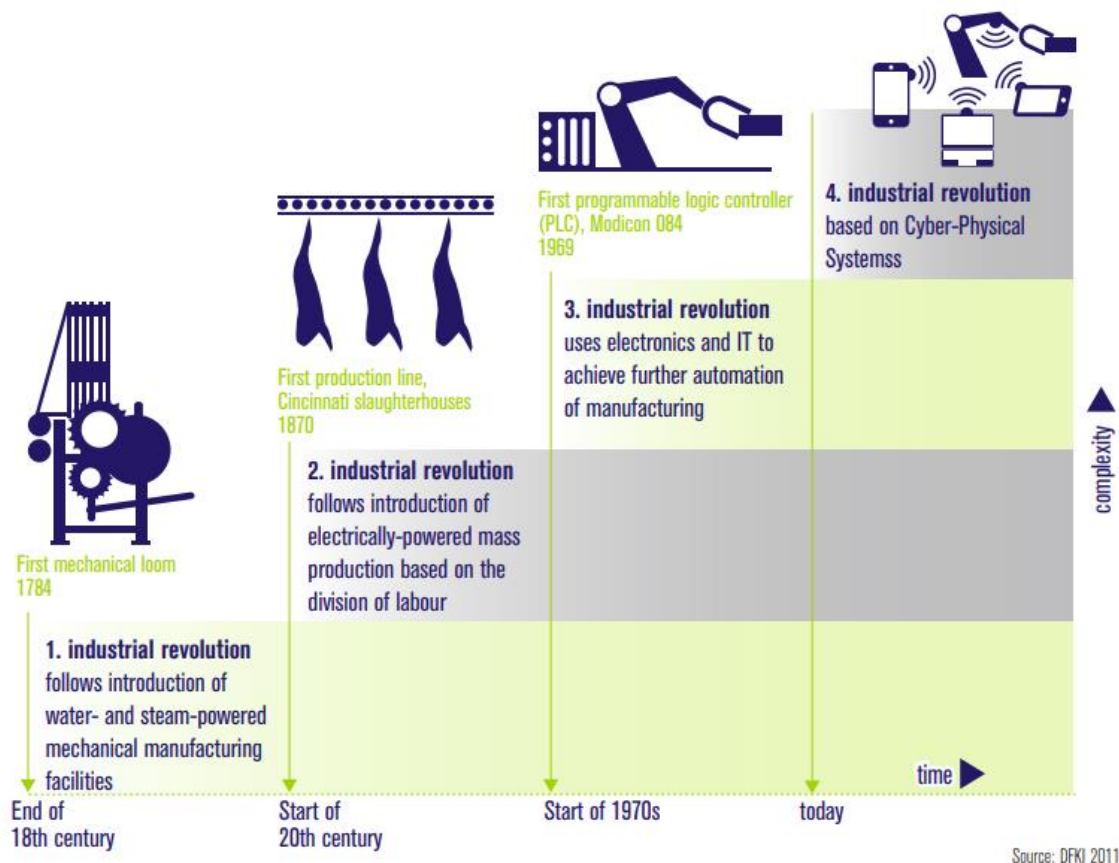


Figure 1.3. The four industrial revolutions (Kagermann et al., 2013)

- The first industrial revolution followed the invention of the steam engine. Nevertheless, despite the invention of the steam engine was in the seventeenth century, the transition to

factories and machine use started at the end of the eighteenth century. The transition from manufacturers to factories did not only affect the production systems but also society and urbanization.

- The second industrial revolution was in the late nineteenth century following the electrical energy inventions and the assembly line and mass production concepts. This era was characterized by massive changes in the ideas regarding improving the efficiency and organization of production systems. To cope with these changes, the world witnessed the introduction of new infrastructures based on new roads, railroads, telephone lines, sewage systems, and water supply systems. Nevertheless, until now, more than 15% of the world's population has not experienced the second industrial revolution as electricity has not made available to it yet.
- The third industrial revolution (the computer or digital revolution) followed the diffusion of electronic and information technology systems (e.g. semiconductors, personal computers, and the internet) and their application in the industrial sectors after the 1970s. The rise of these tools helped the presentation of new concepts such as digital manufacturing, total quality management (TQM), automation, renewable energy, and Lean production. Nevertheless, many areas around the globe have not yet benefited from the third industrial revolution due to the difficulty to get access to the internet. Additionally, not all sectors have experienced the full potential of the third industrial revolution; including construction.
- The fourth industrial revolution: unlike the previous industrial revolutions, the fourth revolution or Industry 4.0 was not observed but predicted. Industry 4.0 is still ongoing and its adoption is growing, thanks to increased technological innovation.

According to Lafhaj (2023) and as shown in **Figure 1.4**, Industry 4.0 refers to the industrial processes and technologies that are used to enable all actors in the production process to interact and communicate. In this system, organizations, devices, and processes are communicating and exchange information autonomously and continuously to enable simulation and information-based decision-making processes.

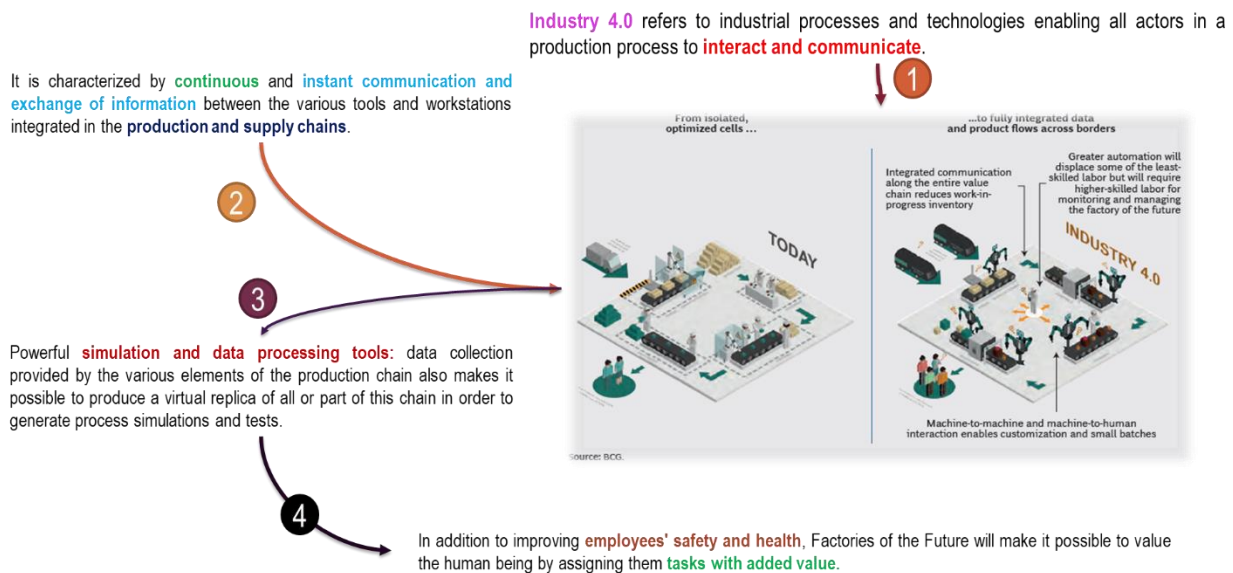


Figure 1.4. The concept of Industry 4.0 (Lafhaj, 2023)

In their review of the definitions in the literature, Nosalska et al (2020) proposed the framework shown in **Figure 1.5** and the following definition for the concept of Industry 4.0: “a concept of organizational and technological changes along with value chains integration and new business models development that are driven by customer needs and mass customization requirements and enabled by innovative technologies, connectivity, and IT integration”. Based on the proposed framework, Industry 4.0 has two-factor groups. The first one is the technological group that ensures the connection between the physical and the virtual world, makes autonomous decisions and connects with each other’s to meet the personalized expectations of the customer. The second group is the business factors that covered the changes in the value chain due to communication and data

exchange. The changes include three levels of integration (Ustundag & Cevikcan, 2018; Shiyong Wang et al., 2016):

- Horizontal integration: across the value chain between organizations to form an efficient ecosystem, in which, materials, finance, and information can flow. The integrated information system allows the optimization of the product life cycle due to shared functionalities between interconnected organizations (i.e. data sharing, information exchange, visualization, coordination, and decision-making).
- Vertical integration: between the different hierarchical subsystems in the organization (e.g. sensors, actuators, production management, and production planning). Through this integration, the production system can be more flexible and transparent.
- End-to-end engineering: across the entire value chain to optimize production customization.

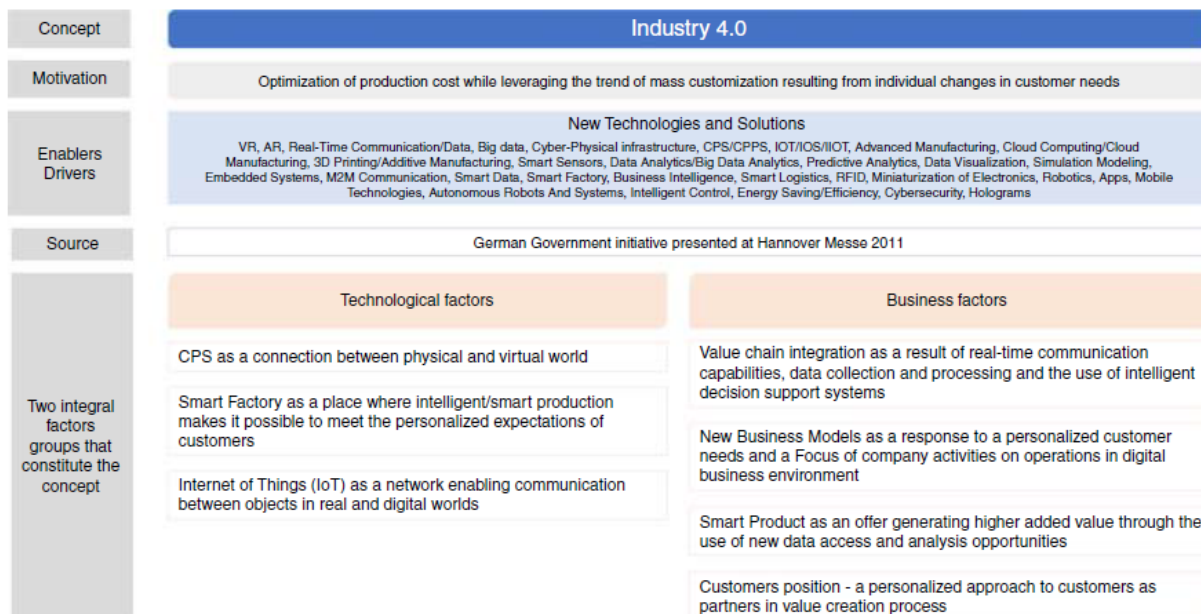


Figure 1.5. Industry 4.0 framework (Nosalska et al., 2020)

1.2.2 Industry 4.0 in France

Worldwide, there have been several initiatives and strategies to encourage the implementation of Industry 4.0 practices. As shown in **Figure 1.6**, these initiatives carried different titles based on the country they were developed in. For instance, the fourth industrial revolution strategy in Germany remained as was developed with the title “Industrie 4.0”. In turn, it was labeled in the European Union Projects “Horizon 2020” as “Factories of the future” and carried different names such as “New Industrial Revolution” by the Group of 20 (G20), “Advanced Manufacturing Partnership” in the US, “Manufacturing Catapult” in the UK, “Made in China 2025” and then “the Silk Road” in China, and others (Lafhaj, 2023).

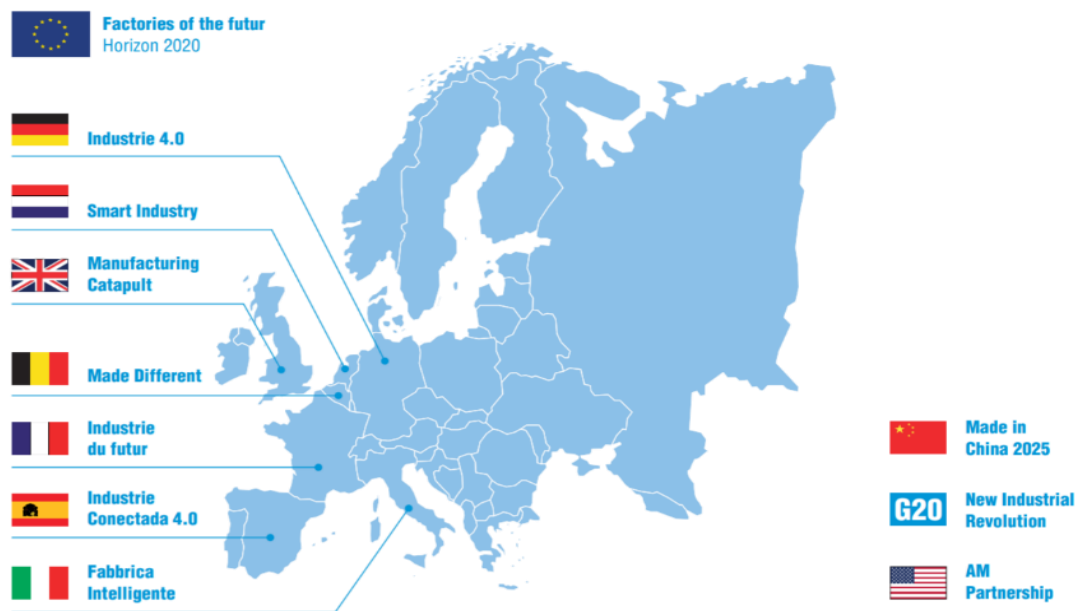


Figure 1.6. Global Initiatives for Industry 4.0 (Lafhaj, 2023)

In France, the work toward revolutionizing the French industry started when Mr. François Hollande, the former president of the republic, and the Minister of Economy jointly announced the 34 plans for the new industrial France “de la nouvelle France Industrielle” (Economie.gouv.fr,

2014). These plans gave strong signals regarding the need to make massive changes in the French industrial sector.

On 14th April 2015, the President of the Republic, Mr. Emmanuel Macron launched the program “Industrie du Futur” (IdF) (Lafhaj, 2023). IdF aimed at implementing the practices of Industry 4.0 in the French industrial sector by encouraging the deployment of digital technologies in the companies, transforming the companies and business models, and modernizing the production process (European Commission, 2017). Since then, there have been many plans and initiatives to support the reindustrialization activities and the implementation of IdF in France. Among them, the France 2030 call for expression of interest “Soutien à l’offre de solutions pour l’industrie du futur” that aims to support the dissemination of digital technologies and the adoption of new technologies in SMEs and Midcaps. The support covers financial aids to invest in robotics, 3D printing equipment, integrated machines for intensive computing, augmented and virtual reality equipment, software and applications development, and others (Economie.gouv.fr, 2021b, 2021a). Nevertheless, the low levels of awareness toward Industry 4.0, the gap between industry needs and available qualifications, the difficulty in bringing together all the actors under the IdF umbrella, the high initial investment costs, and the uneven deployment of technologies and smart solutions at the regional level are examples of challenges that face the transition toward IdF in France (Conseil National Industrie, 2021; European Commission, 2017).

1.2.3 Construction 4.0 applications

Innovation and technological development have been essential in the construction industry. However, they took different shapes over history. Bolpagni et al (2022) summarized these shapes as shown in **Figure 1.7**. More specifically, since the stone ages, humans were able to innovate to present improvements to the ways of building:

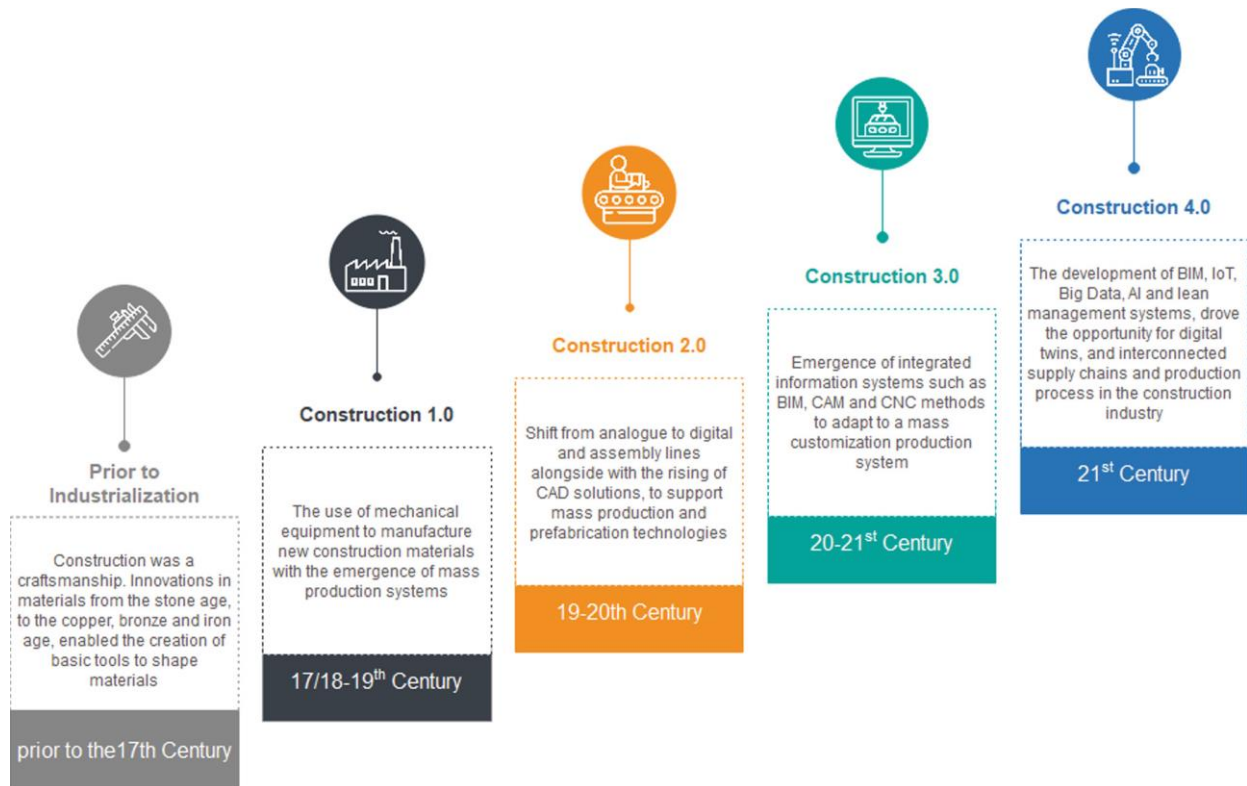


Figure 1.7. Timeline for innovation and technological development in the construction industry (Bolpagni et al., 2022).

The early examples of innovations can be seen when metal and other materials were used to enable shaping materials and building their shelters.

During the first industrial revolution, the use of mechanical equipment allowed the creation of new building materials. This featured the use of glass and cast iron in different forms and for different functionalities in a way that was not experienced or imagined before.

The second industrial revolution carried various opportunities to innovate in the field of construction. Affected by the need for new infrastructure to support the different industrialization activities, the construction industry witnessed new cost-effective and mass-production solutions to produce steel and masonry materials. This revolution led to the presentation of Computer-Aided

Design (CAD) as a way to transfer the design to the sites and the dissemination of more vertical and prefabricated construction.

Encouraged by the advancement in information technology (IT) and the availability of personal computers, the third revolution witnessed linking technology with architectural and engineering practices and shifting from analog to digital construction, and mass production to mass customization. As a result, work toward creating more complex structures in more economical and feasible ways became possible. This is due to the presentation of 3D CAD models, which were followed by BIM that enabled the creation of a more precise and efficient design. In addition to the use of Computer-Aided Manufacturing (CAM) in the prefabrication factories, which supported the mass customization activities.

Currently, the construction industry has the opportunity to benefit from the advancement in digital tools, big data, and online data, accessibility to digital and physical models, and automation technology to create the fourth industrial revolution in construction; Construction 4.0. Such a revolution will facilitate the transformation of the industry, the creation of smarter sites, supply chains, and facilities, and the transition from reactive practices to predictive and autonomous practices. To enable these objectives, several technologies can be used along the project life cycle.

Table 1.5 presented the expected impact of Construction 4.0 technologies in the life cycle of the construction project as discussed by Muñoz-La Rivera et al (2021).

Table 1.5. The expected impact of Construction 4.0 Technologies along the project Life cycle (Muñoz-La Rivera et al., 2021).

Technology	Technology	Conceptualisation	Criteria Design	Detailed design	Implementation Documents	Coordination	Construction	Operation and Maintenance	Demolition or Renovation		
		CON	CDE	DDE	IMP	DCO	CON	OPE	D/R		
Physical Domain / Automation	Additive Manufacturing	AM	1	1	1	1	1	3	1	3	
	Cyber-Physical systems	CPS	1	2	3	3	3	3	3	2	
	Digital Signage	DSi	1	1	1	1	1	3	3	2	
	Embedded system	ES	1	1	1	1	1	3	2	2	
	Human-Computer Interaction	HCI	1	3	2	2	2	3	2	2	
	Internet of Things	IoT	1	1	1	1	1	3	3	2	
	Mass Customization	MCu	3	3	3	2	1	1	2	2	
	Modularity	M	1	1	1	2	2	3	2	2	
	3D scanner	3DS	1	1	1	1	2	3	2	2	
	Off-site Construction	OSC	1	2	1	1	2	3	1	2	
	Product-Lifecycle-Management	PLM	3	3	3	3	3	3	3	3	
	Radio Frequency Identification	RFI	1	1	1	1	1	3	2	2	
	Simulation and Modelling	Robotics	R	1	1	1	1	2	3	2	2
Self-sustainability and Self-sufficiency		SS	1	1	2	1	1	1	3	1	
Sensors		S	1	1	1	1	1	2	3	2	
Supply Chain Management		SCM	1	1	1	1	1	3	3	2	
Unmanned Aerial Vehicle		UAV	1	1	1	1	1	3	2	2	
Wearable Technology		WT	1	1	1	1	1	3	3	2	
Simulations models and tools		SMT	1	2	3	2	3	3	3	2	
Artificial Intelligence		AI	1	3	3	2	3	3	3	2	
Machine Learning		ML	2	3	3	2	3	3	3	2	
Data mining		DM	2	3	3	2	3	3	3	2	
Neural Networks	NNs	1	3	3	2	3	3	3	1		
Digitalisation and Virtualisation	Predictive maintenance	PM	2	3	1	1	2	1	3	3	
	Improve Asset Utilization	IAU	1	2	1	1	1	1	3	2	
	Big Data analytics	DBA	2	3	3	1	2	3	3	1	
	Augmented Reality	AR	1	2	3	1	3	3	2	2	
	Virtual Reality	VR	1	3	3	1	3	3	2	2	
	Mixed Reality	MR	1	2	3	1	3	3	2	2	
	Building Information Modelling	BIM	3	3	3	3	3	3	3	3	
	Photogrammetry	Ph	1	2	3	1	2	3	2	1	
	Geographic Information System	GIS	2	3	3	2	2	2	2	1	
	Digitalisation and Virtualisation	5G	5G	1	1	1	2	1	3	3	1
		Mobile Applications	APPs	1	2	1	3	2	3	3	2
		Mobile Computing	MCo	1	1	1	1	2	3	3	2
		Industrial Internet	II	1	1	3	2	1	3	3	1
Social Media		SM	2	2	2	2	3	3	2	2	
Automated regulation checking and Audits		ARCA	1	2	3	3	3	2	2	1	
Big Data		BD	2	3	2	2	2	2	3	2	
Blockchain		B	1	2	3	3	3	2	3	1	
Cloud Computing		CC	1	2	1	3	2	2	3	1	
Common Data Environment		CDE	2	2	2	3	3	2	3	2	
Cybersecurity		C	1	2	2	3	3	3	3	2	
Data Sharing		DSh	2	3	3	1	1	1	3	2	
Deep Learning		DL	1	2	3	2	3	2	2	1	
Digital twin		DT	1	2	3	3	3	3	3	2	
Edge computing		EC	1	1	1	1	2	3	3	2	

3 High potential effect
 2 medium potential effect
 1 Low potential effect

CHAPTER 2. LEAN CONSTRUCTION AND IOT

Chapter 2. Lean Construction and IoT

This chapter aims to present the integration between Lean Construction and IoT in the built environment. The chapter is built over three works; a review of Lean Construction and IoT, an application of Lean and IoT to improve flow in brick manufacturing, and an application of Lean and IoT to improve flow in construction prefabrication.

2.1 Review of Lean Construction and IoT

IoT was first introduced in 1999 by Kevin Ashton when he presented the use of Radio Frequency Identification (RFID) in monitoring the supply chain of Procter & Gamble and defined it as a communication system of devices with sensors using a computer network (Ashton, 2009). According to the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC) (ISO/IEC, 2014), IoT is “an infrastructure of interconnected entities, people, systems and information resources together with services which process and react to information from the physical world and the virtual world”. This infrastructure allows the connection of things with everyone continuously and everywhere (Gamil et al., 2020) and helps to collect and analyze data to provide real-time information to human-friendly interfaces (Rafsanjani & Ghahramani, 2020). As a result, it helps to understand the system’s complexity, make context-aware and dynamic decisions, and achieve autonomy (Casini, 2021).

The use of IoT is remarkably increasing to support a myriad of applications in different fields such as manufacturing (Andrade et al., 2021; Centea et al., 2020; Drave, 2018; Rong et al., 2016; Ullah & Sarkar, 2020; Urso et al., 2020; Vlachos et al., 2021), agriculture (Anak Rechie et al., 2020; Azmi et al., 2021; Chien & Chen, 2018; Dewangga A & Suhono H, 2020; Martínez-Sala et al., 2009; Rayhana et al., 2021), transportations (Ahmed & Kumar, 2019; Akter et al., 2020; Y. W.

Chung, 2012; Floyd, 2015; Yuan Liu et al., 2015; Sharma et al., 2020), hospitality (Elkhwesky & Elkhwesky, 2023; Mercan et al., 2021; Nadkarni et al., 2020), healthcare (Kang et al., 2019; Rodrigues et al., 2022; J. Wu et al., 2019), and others.

With the challenges facing the construction industry, IoT adoption in construction projects have the potential to improve performance, productivity, cost-saving, efficiency, safety, and supply chain management (Gamil et al., 2020; Giovanardi et al., 2021; Khurshid et al., 2023). According to Teizer et al (2017), IoT will allow machines to talk to each other on-site so risks can be predicted and prevented using smart systems. Therefore, IoT was considered a “must-have” technology that will change the way we look at and manage construction projects (Khurshid et al., 2023; Lafhaj & Dakhli, 2021).

IoT has also been considered a key enabler for the fourth industrial revolution in the construction industry (Construction 4.0). For instance, with its ability to offer connectivity of various objects and devices to the internet and support that data collection and transmission to improve control, monitoring, visualization, and data analytics processes, It contributes to the diffusion of AI as it helps to feed the machine learning algorithms with the necessary data (Casini, 2021). It also allows the integration of customers, monitoring and control activities, reduction of wastes, and process efficiency during the 3D printing processes (Ashima et al., 2021; Butt, 2020). In addition, it is considered a main component in smart systems such as the digital twin (Hou, Wu, et al., 2020; Shahzad et al., 2022). Nevertheless, the adoption of IoT in construction is still among the lowest when it is compared with other industries (Barbosa et al., 2017; Khurshid et al., 2023).

With the increasing popularity of Lean Construction due to its potential to achieve improvements on different levels in construction projects, Lean adoption is still faced with a critical barrier, which is the inadequate information administration that hinders the opportunities to achieve

improvements and generate learning cycles (Albalkhy & Sweis, 2021; Fernandez-Solis et al., 2012). Even in some cases, where Lean is implemented, poor information management due to the use of no-software-based systems affects the flow of work and the identification and removal of constraints (Dave et al., 2016). To solve this problem, IoT can be an efficient and effective information system that can provide the project team with real-time information about materials locations and quantities, workers, workspaces, machines and equipment, and supply chain to improve flow, collaboration, problem-solving, error-proofing, and achieving continuous improvement all over the construction project life cycle (Dardouri et al., 2022; Dave et al., 2016; Tezel et al., 2022a; Tezel & Aziz, 2017). Therefore, there have been, recently, various efforts to support Lean-IoT integration. These efforts have resulted in some Lean-IoT applications and software such as VisiLean®, KanBIM™, and others (Dave et al., 2016; Kanai et al., 2021; Sacks et al., 2011). Nevertheless, the efforts to integrate Lean and IoT are still insufficient and the relationship between the two concepts is still not provided systematically. This review aims to study the links between Lean Construction principles and tools and IoT as an enabler technology for Lean.

2.1.1 Research methodology

The review aims to investigate the links between IoT and Lean principles and tools. The review was based on two rounds (as shown in **Figure 2.1**):

The first round

The first round aimed to cover publications about IoT in the construction sector to identify IoT applications and functionalities in the construction sector. In this round, the systematic literature review approach (SLR) was used. For this purpose, the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses” (PRISMA) guidelines to conduct the review were used (Moher et

al., 2009). Based on the PRISMA guidelines, SLR has mainly three main phases, which are the identification, screening, and eligibility to decide what should be included in the review process.

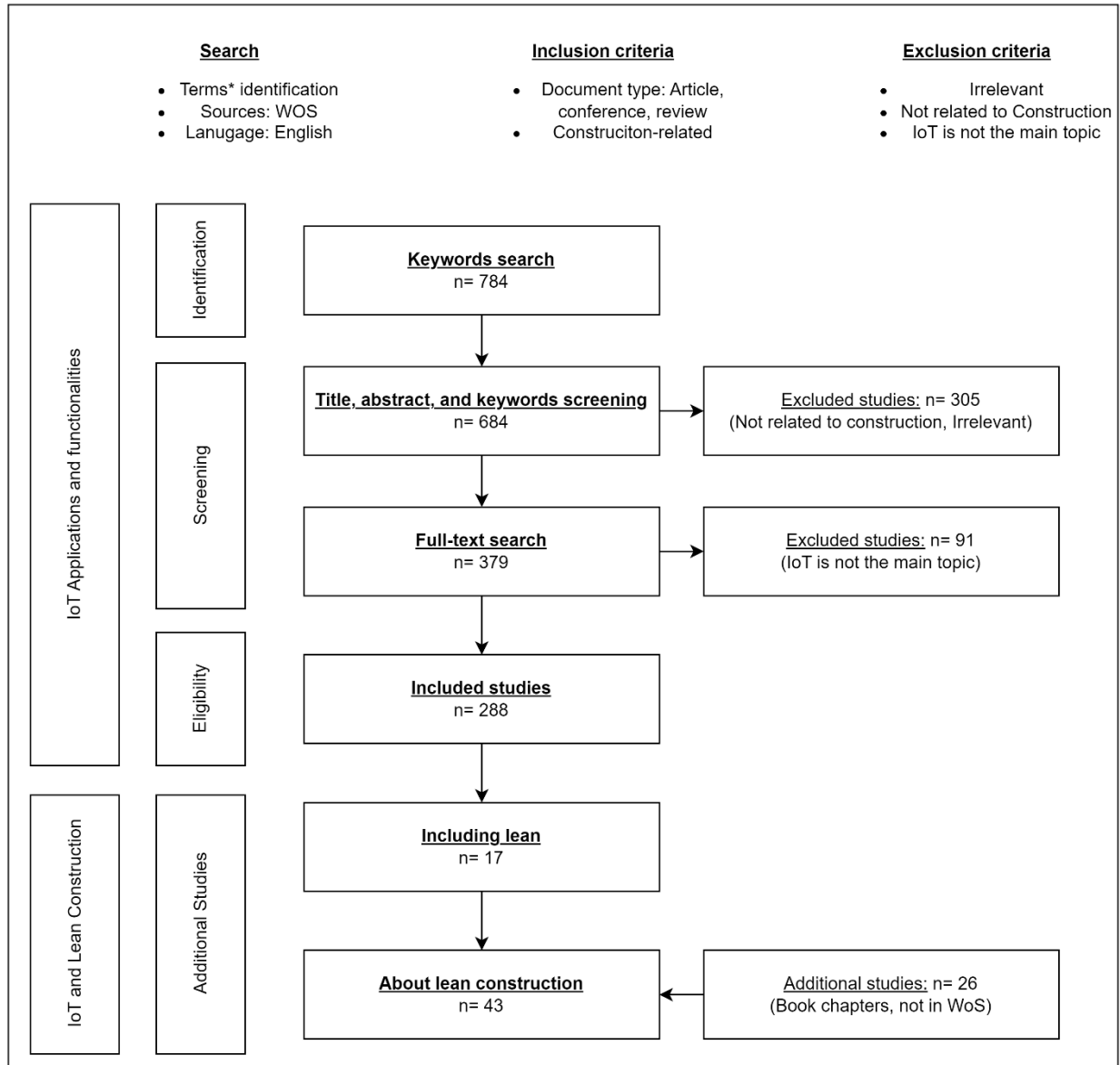


Figure 2.1. The used methodology to conduct a review about IoT and Lean Construction

The identification phase was conducted using the search on “Web of Science” using the different terminologies that refer to the IoT as defined by Čolaković & Hadžialić (2018) as follows:

(IoT OR “Internet of Things” OR “Internet of thing” OR IoE OR “Internet of Everything” OR M2M “Machine to Machine” OR CoT OR “Cloud of Things” OR WoT OR “Web of Things”) AND (“construction projects” OR “construction sites” OR “construction processes” OR “construction operations” OR building OR “built environment” OR “construction management” OR “construction industry” OR “AEC industry”).

The search included articles, conference papers, and reviews that were written in English. During this phase, irrelevant articles that appeared by mistake were removed (e.g. when using the word “building” to explain the process of building an IoT system in other fields). The total number of studies found in the identification phase was 784.

The screening phase aimed to identify the resources that are related to the topic of IoT applications in the construction industry. This phase was based on two-part; the first was searching the title, abstract, and keywords to identify the sources that are relevant to the topic. While the second was based on a full-text search to identify the eligible sources that can be included in the first round of the review. Accordingly, 288 studies were found eligible to study the functionalities and applications of IoT in the construction industry.

The second round

The second round of the review aimed to use the identified IoT functionalities from the first round and study their links with Lean principles, practices, and tools based on the studies found about the two topics. Out of 288 found studied in the first round, only 17 were about the integration of Lean Construction and IoT. Therefore, another search was done using Google Scholar to identify additional sources about this integration. The search resulted in additional 26 studies (in total, 42 studies were used in the second round).

This review uses Lean principles that were identified by Sacks et al (2010) to identify the interaction matrix between Lean Construction and IoT functionalities. In addition, it uses the TFFV theory pillars (Transformation- Flow- and Value) (Koskela, 2000) and a group of Lean Construction tools as defined in the literature (Bolpagni et al., 2017; Hannis Ansah et al., 2016; S. Singh & Kumar, 2020; Valamede & Akkari, 2020) to explain the integration between Lean and IoT.

2.1.2 Review results

Keyword cooccurrence analysis

To identify the patterns of publications about IoT in construction and enable the review of a large set of sources about the topic (Ellegaard & Wallin, 2015), the keyword co-occurrence analysis was conducted using VOSviewer. The latter allows the creation of a keyword network in which natural language algorithms and text mining methods are used to investigate the relationships between the most repeated keywords about the studied topic, and then cluster them accordingly (Ech & Waltman, 2014).

Instead of focusing only on the keywords that were defined by authors, the analysis covered the “index keywords” found in the full record of the source exported by Web of Science. This was to avoid the neglect of any overlooked keyword by authors (Ozturk, 2021). Accordingly, every time two keywords were found in the title, abstract, or keywords were considered as cooccurrence. Additionally, before conducting the cooccurrence analysis on VOSviewer, the keywords with similar meanings were merged (e.g. Building information modeling, building information modelling, and BIM).

In the end, the total number of found keywords in 288 sources was 1146 keywords. Out of them, 49 keywords met the set minimum number of keywords co-occurrence (5 cooccurrences). The most

occurred keywords were: IoT (163 occurrences), BIM (65 occurrences), safety (47 occurrences), management (38 occurrences), and construction (30 occurrences).

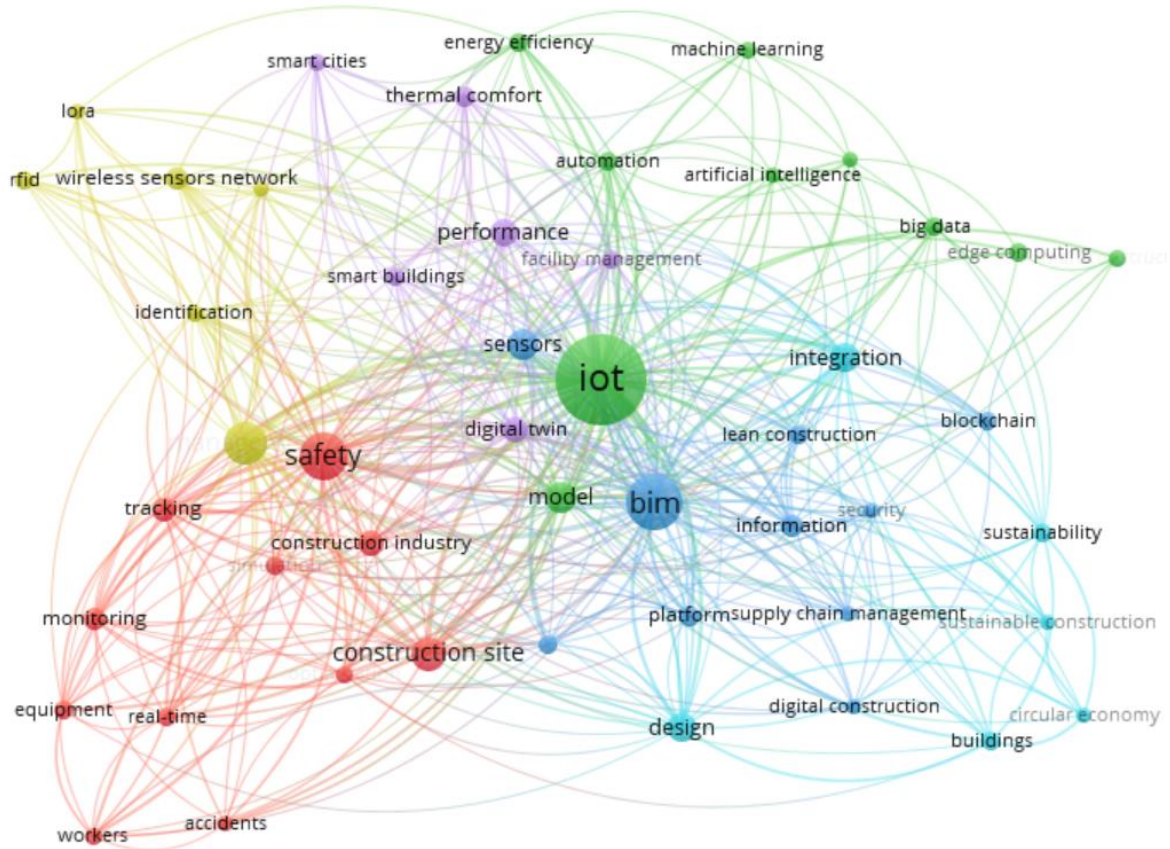


Figure 2.2. Keyword cooccurrence

The network of the keywords is shown in **Figure 2.2**. The analysis of the keyword revealed six clusters with 1114 links. The first cluster (in red) had keywords about the applications of IoT on the construction sites (“safety”, “tracking”, “construction site”, “monitoring”, “real-time”, “accidents”, “equipment”, “workers”, “optimization” and “identification”). The second cluster (in green) was more related to data management and decision-making support (“big data”, “artificial intelligence”, “machine learning”, “model”, “edge computing”, and “automation”). The third cluster (in blue) included other new technological and managerial integrated concepts with IoT

(“BIM”, “supply chain management”, “Lean Construction”, “blockchain”, and “digital construction”). The fourth cluster (in yellow) was more related to the enabling technologies of IoT (“RFID”, “wireless sensor network-WSN”, “LongRang- LoRa”, and “identification”). The fifth cluster (in purple) was more about the smart structure and post-construction phases (“facility management”, “smart buildings”, “smart cities”, “digital twin”, “performance”, and “thermal comfort”). The last cluster (in cyan) was more about sustainable applications of IoT (“circular economy”, “sustainability”, “sustainable construction”, “design”, and “integration”).

IoT Architecture and enabling technologies

The literature has several definitions for the different layers that constitute the IoT structure. In some studies, IoT structure was explained based on having seven layers (things, data acquisition, fog networking, data aggregation, data centralization, data analytics, storage, and applications) (Minoli et al., 2017). Nevertheless, it can be said that the typical IoT system has at least three main layers; each of these three layers includes different enabling technologies as follows (Giovanardi et al., 2021) (as shown in **Figure 2.3**):

- Perception layer or the physical layer: this layer has hardware platforms, embedded devices, or mechanical and electrical parts that are responsible for sensing, actuating, and gathering data about the environment (Čolaković & Hadžialić, 2018; Sethi & Sarangi, 2017). The most known enabling devices in this layer are the sensors, which are normally low-cost and low-power consumption devices that are responsible for sensing and monitoring different environmental parameters (Lawal & Rafsanjani, 2022). Examples of the possible used sensors in the construction environment are energy sensors, motion sensors, health-tracking sensors, chemical and environmental sensors, and cameras (Giovanardi et al., 2021). The second type of device is the actuators, which can control changes in the environment such

as adjusting temperature levels and switching on or off the alarming or electrical systems (Lawal & Rafsanjani, 2022). In addition to RFID tags, which are the most IoT technology in the construction industry; especially for logistics management (Dardouri et al., 2022; Giovanardi et al., 2021).

IoT Structure and Enabling Technologies

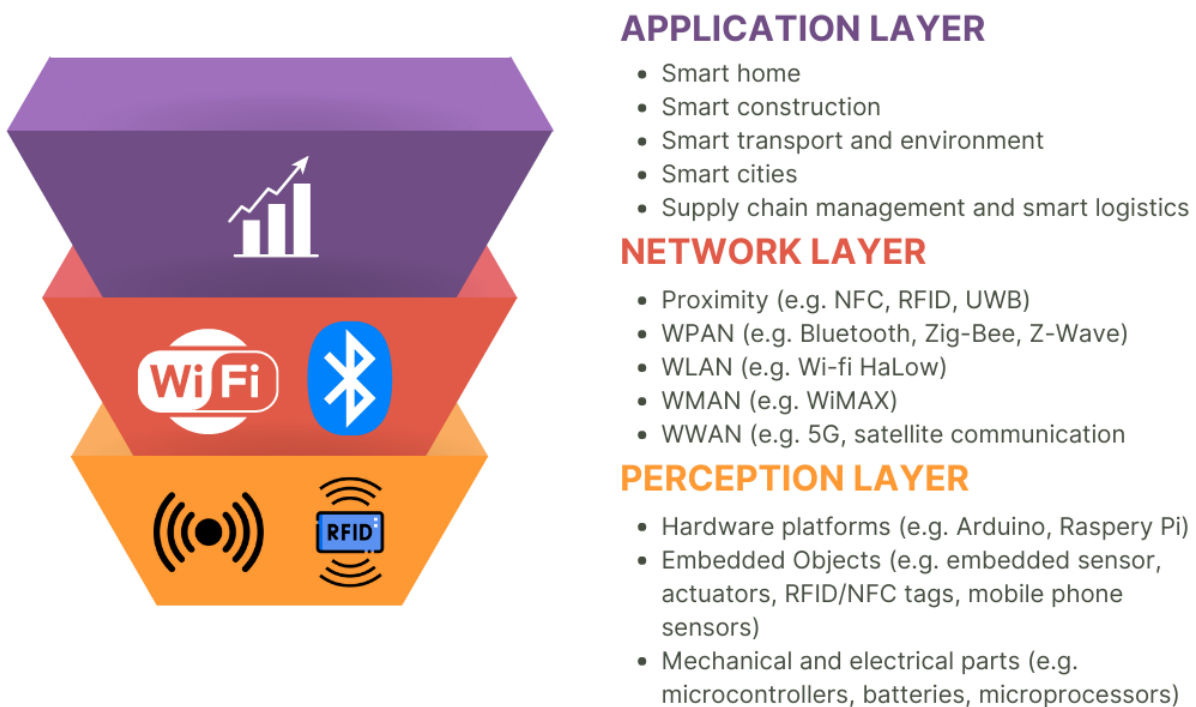


Figure 2.3. IoT structure and enabling technologies

- Network layer or the communication layer: this layer is responsible for the connectivity between objects and with the IoT system via network technologies (Lawal & Rafsanjani, 2022). This layer is based on different hardware, software, technologies, and protocol that should enable different types of communication such as device-to-device, device-to-cloud, device-to-gateway, and back-end data-sharing connection models (Čolaković & Hadžialić,

2018). To ensure the effectiveness of the IoT system, the network layer should meet several requirements among them the security of data, privacy, quality, location-based capabilities, coverage, interoperability, scalability, energy efficiency, and autonomic networking and service provisioning (Čolaković & Hadžialić, 2018; Giovanardi et al., 2021; Lawal & Rafsanjani, 2022). Examples of the used communication technologies that are used in the built environment include ethernet, Wi-Fi, WiMAX, ZigBee, Long Range Wide Area Networks (LoRa WAN), Bluetooth Low Energy (BLE), RFID, and Near Field Communication (NFC) (Giovanardi et al., 2021; Lawal & Rafsanjani, 2022).

- Application layer: the main aim of this layer is to link the IoT system with its users via various tools and user interfaces and manage the applications of the system such as smart homes, smart cities, smart logistics, and smart construction (Giovanardi et al., 2021). BIM and Geographic Information System (GIS) serve as examples of these interfaces that help link the IoT system with the users to manage smart applications in the built environment (Giovanardi et al., 2021). It is worth mentioning here that many tools that can be used in the application layer have various embedded systems that allow different features such as data aggregation, filtering, processing, analytics, and storage. That is why, it is popular to see different classifications for the IoT structure in the literature. For instance, Lawal and Rafsanjani (2022) differentiate between two layers that can be considered in the current presentation of the application layer, which is the service layer and the cloud layer. Similarly, Minoli et al (2017) presented the application layer based on “data aggregation”, “data centralization”, “data analytics and storage function”, and “application” layers.

IoT applications and functionalities in the construction sector

In the construction sector, IoT has potential to be used for a large set of purposes including real-time monitoring and control (Bucchiarone et al., 2020), site management (Bucchiarone et al., 2020; L. Wu et al., 2022), security and safety (William Wong Shiu Chung et al., 2020; Jin et al., 2020; Kanan et al., 2018; M. Khan et al., 2022; Zhong et al., 2014; C. Zhou & Ding, 2017), material and supply chain management (Dardouri et al., 2022; Teizer, Neve, et al., 2020; L. Y. Wang, 2012; J. X. Zhou et al., 2021), disaster management (L. Y. Ding et al., 2013), human resources management and monitoring (Ma & Cha, 2020), productivity improvement (Baskova et al., 2020; Bian & Ren, 2017; A. U. Khan et al., 2022), modular construction (H. Ding et al., 2023; X Li et al., 2022; Turner et al., 2021; L. Wu et al., 2022), in addition to its applications in smart homes and facility management, design, and end of life of the buildings (Jeoung et al., 2022; W. Li et al., 2021; Ruiz-Zafra et al., 2022).

Čolaković & Hadžialić (2018) asserted that IoT systems have four main functionalities, which are monitoring, control, optimization, and autonomy. In turn, Khanam et al (Khanam et al., 2020) listed data formation, presentation, monitoring, alerts, management of data, and autonomous operations as examples of the functionalities of the IoT system. This review used keyword analysis and the different applications and benefits that IoT systems can offer to their users in the construction sector to identify the functionalities as follows:

- 1- Monitoring and visualization: with its ability to connect to anything, everywhere, and at any time, IoT system helps users in the construction sector to identify, track, visualize, and localize workers, materials, machines, tools, and equipment on the site and along the supply chain. Additionally, it helps visualize the process and the system components and conditions (Abbasianjahromi & Ghazvini, 2022; Besklubova et al., 2021; Cho et al., 2018;

W W S Chung et al., 2023; Gaba et al., 2018; Han et al., 2022; M. Khan et al., 2022; D. Miller et al., 2023; Yuan et al., 2021).

- 2- Control and management: while monitoring refers to the process of identifying deviations from the planned or normal situation, control refers to the actions that are taken to correct or minimize the deviations and improve performance (Isaac & Navon, 2014). With its ability to support automation and deliver real-time alerts and notifications, IoT helps to control machines and equipment, conditions on-site, and production processes (C.-C. Chen et al., 2019; S.-K. Kim et al., 2021; Y. Liang & Liu, 2022; Rashid et al., 2019; L. Wang & Jiang, 2021; Wen et al., 2021; Y. Zhao et al., 2021).
- 3- Autonomy (autonomous operations): the autonomy of a system can be understood as an extension of its ability to make automated operations but without outside interventions and based on the changes in the dynamic environments (H. Chen et al., 2021). IoT autonomy in construction can be seen based on different levels such as the automation of a specific machine to the autonomous generation of actions (e.g. for safety purposes) (Kanan et al., 2018; J. H. Kim et al., 2021; Nechifor et al., 2015; W. Wu et al., 2010).
- 4- Data management: this includes three main functionalities; a) data transfer and real-time information sharing, b) data storage, and c) data analytics and decision-making support.
- 5- Integration: this refers to the ability of IoT systems to achieve seamless real-time information integration for different stakeholders in the construction environment (Dave et al., 2016).

Lean Construction-IoT matrix

As mentioned in **Table 1.3**, Sacks et al (2010) identified 24 principles for Lean Construction that can be gathered into four groups; flow, value generation, problem-solving, and developing partners.

The relationship between these principles and IoT functionalities is explained based on the developed Lean Construction-IoT matrix. The matrix is shown in **Figure 2.4** and **Table 2.1**. The used statements to develop the matrix are presented in **Annex 1**. The analysis of the matrix shows that interaction levels were found between most of Lean principles and IoT functionalities. The highest interaction level can be found between IoT functionalities and “flow”. In turn, “data transfer and real-time information sharing” and integration of different systems as IoT functionalities seem to have the highest interaction levels with Lean principles.

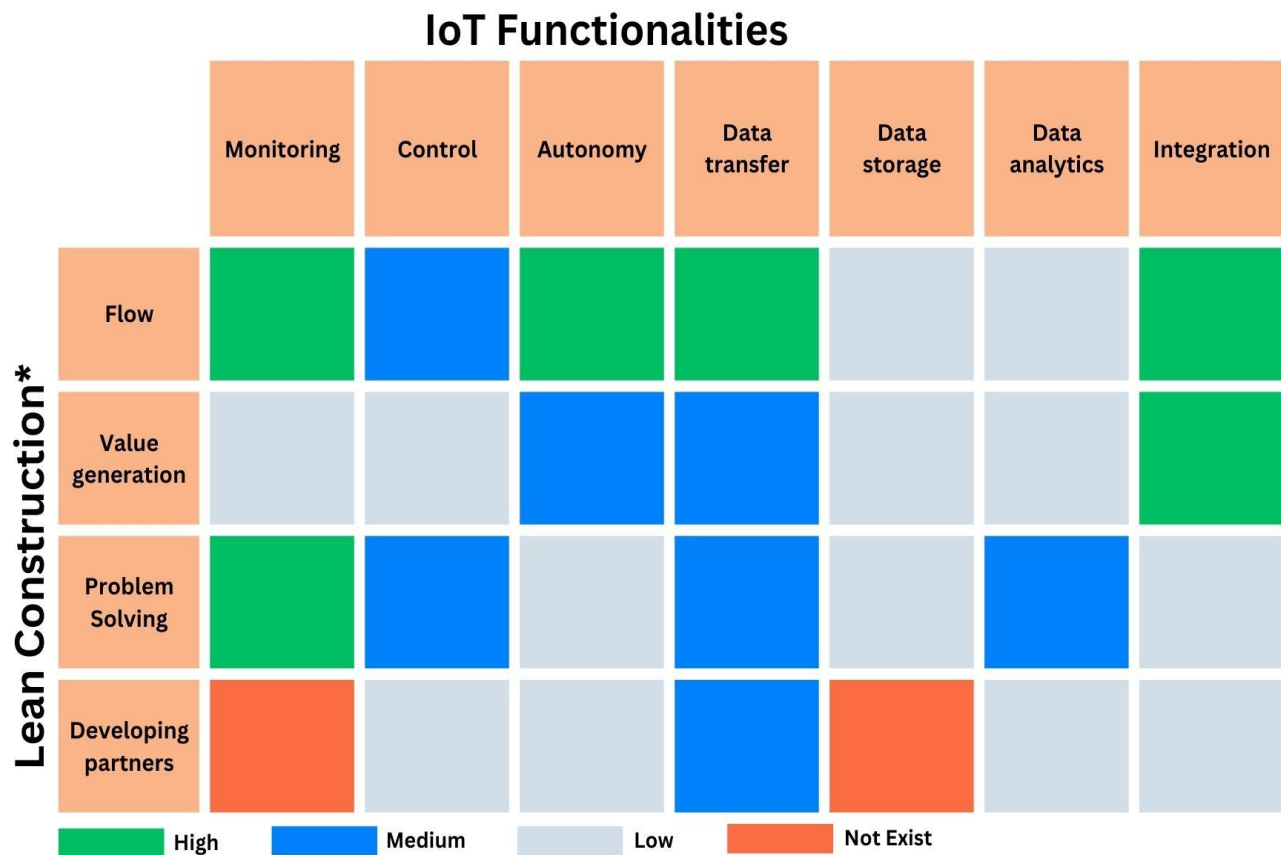


Figure 2.4. Lean Construction-IoT Matrix

Table 2.1. Lean Construction-IoT Matrix

IoT Functionalities			Monitoring	Control	Autonomy	Data Transfer	Data Storage	Data Analytics	Integration
			1	2	3	4	5	6	7
Flow	Reduce variability	A	52, 33, 54	52, 49	4, 27	27, 43, 54		16	45, 54
		B	7, 24	5, 49		41, 42		16	41, 42
	Reduce cycle times	C	31, 44			1, 35	37	1, 6	45
		D	13, 28, 44, 45			29, 35, 41, 42			41, 42
	Reduce batch sizes	E			27		37		
	Increase flexibility	F	44			1, 48		1, 6, 48	
		G		2		2, 45		2, 14	2
	Select an appropriate production control approach	H	9		22, 23, 26, 27	27			
		I	20	20		20		20	20
	Standardize	J				25			
	Institute continuous improvement	K	20, 18, 19, 25, 36			19, 25, 43		19, 48	25, 43
	Use visual management	L	9, 24, 47	3	21	21, 47, 48		3, 48	
		M	9, 12, 18, 24, 25, 30, 32, 33	3	27	25, 27, 48		3, 48	25
	Design the production system for flow and value	N	44		4, 34, 53, 46	38, 39	53		38, 39, 46
		O	20, 28, 29, 30, 31, 32, 33, 34	20	26, 27, 28, 29, 30, 31, 32, 33, 34	20, 25, 27, 28, 29, 30, 31, 32, 33, 34		20	20
P									
Q		11	10		15			15, 45	
Value generation	Ensure comprehensive requirements capture	R				40, 43	5		40, 43, 45, 51
	Focus on concept selection	S			21	21	50	50	45, 51
	Ensure requirement flow down	T	12	49	23, 27	27, 42	8		8, 12, 42, 45
	Verify and validate	U	18, 25, 26					18, 25	
Go and see for yourself	V	11, 52, 32	3, 10, 52	52	48		3, 48		

Problem-solving	Decide by consensus, consider all options	W	12, 52, 32	3, 52	52		50	3, 50	12
Developing partners	Cultivate an extended network of partners	X		2	4	2, 17, 35, 54	50	2, 14	2, 17, 54

Flow and waste elimination can be significantly improved using IoT. In contrast to traditional ways of communication and reporting, IoT offers possibilities to reduce time between data capture or information generation and decision-making. As a result, more flexible systems are possible to create and more agility is resulted to reduce to variability and ensure work continuity (Ben-Daya et al., 2019). It can also reduce variability by supporting quality and safety control and ensuring traceability of clients' needs and early warning to avoid stoppages of work (A. Kumar & Shoghli, 2018; Tang et al., 2019). IoT can also help virtualizing the supply chain and track and monitor logistics and inventory levels. This will help accurate and timely delivery of materials, maintaining inventory levels, minimizing losses of material, reducing time spent on searching for material, automating pull signals, ensuring using and delivering only what is needed, and minimizing work-in-progress (Teizer et al., 2017; Tezel & Aziz, 2017; G. Xu et al., 2018). In addition, thanks to the use of sensors, different environmental conditions for materials storage areas can be tracked, which allows minimizing defective materials on-site and in warehouses (A. Kumar & Shoghli, 2018; Tezel & Aziz, 2017). In turn, tracking capabilities for workers support tracking work progress, minimizing motion waste, optimizing productivity, and improving safety conditions (Tang et al., 2019; Tezel & Aziz, 2017). For machinery, IoT can even support remote control of equipment and tools, which helps improving flexibility and decrease cycle time (A. Kumar & Shoghli, 2018). The use of IoT support monitoring structural and environmental conditions on-site (Tezel & Aziz, 2017). Due to monitoring strains, temperature, weather, gas leaks, site lightening, and other conditions flow of work can be ensured due to minimizing accidents and reworks.

IoT also enhance value creation by integrating internal and external information, facilitating communication, and ensuring meeting clients' needs and requirement (L. Y. Wang, 2016). The integration of bid data collected from IoT systems can also help predicting clients' needs (Ben-

Daya et al., 2019; L. Y. Wang, 2016, 2012). Moreover, monitoring functionalities including tracking, localization, and traceability supports supply chain transparency and lifecycle management (Tezel & Aziz, 2017; G. Xu et al., 2018).

Concerning problem-solving, through its visibility uses, IoT support “go and see yourself” principle and real-time detection of issues and even early warnings before the problem happens. Issues facing the work can be also shared with work supervisors, suppliers, managers, and all stakeholders when integrating IoT with BIM models or when using integrated mobile applications (Dave et al., 2016; McHugh, Dave, & Koskela, 2022b; McHugh, Dave, Tezel, et al., 2022; Tezel & Aziz, 2017). In addition to solving the above-mentioned problems related to site conditions, material storage, accidents, and other, with its ability to control machinery, IoT can support error-proofing activities through the identification of possible hazardous areas that machines should not reach (A. Kumar & Shoghli, 2018).

IoT can support developing partners and collaboration between all stakeholders in construction projects. When sharing information with them, IoT allows different stakeholders to be acknowledged and participated in decisions about what is happening and how work can be improved. Using BIM to integrate real-world data with the IoT addresses the issues of outdated information and information silos in construction projects. This integration enables seamless communication between systems, humans, and the overall construction ecosystem. Which ensures capturing and delivering accurate information at the right time to the right stakeholder (Reinbold et al., 2019). Moreover, by integrating IoT technology into supplier management, it becomes possible to monitor and classify suppliers based on their performance within the supply chain. This facilitates the selection of strategic partners and supports the establishment of long-term relationships with best performing supplier (Dave et al., 2016).

Moreover, IoT can support Lean tools implementation in numerous ways. Examples include supporting JIT application through the ability to track inventory levels and identification of material location and conditions onsite. Which allows ordering only what is needed to be placed on the right location and at the right time (Dardouri et al., 2022). Another example is supporting 5S by providing supervisors with real-time information over a large construction site for 5S audits (Tezel & Aziz, 2017). Additionally, sharing locations and updates about flow of logistics and people can significantly support the implementation of TAKT and Location-Based Management (LBM) (McHugh, Dave, Tezel, et al., 2022). Using wearable sensors and IoT-based smart devices, workers and managers can receive early warning to ensure successful application of error-proofing tool (Poka-Yoke) (Tezel & Aziz, 2017). Visual performance data needed to implement visual management can be also automated using data shared by IoT devices (Tezel & Aziz, 2017). Similarly, updates regarding performance, plans, constraints, indicators, and PPC measures can significantly improve the implementation of LPS. Additionally, continuous flow of data coming from distributed IoT devices on site are helpful to monitor the progress of PDCA and VSM tools. Attaching sensors to equipment to monitor their conditions and support predictive maintenance are also very helpful to optimize equipment performance and workflow and ensure successful Total Productive Maintenance (TPM) (McHugh, Dave, Tezel, et al., 2022).

2.1.3 Discussion

IoT is one of the most important technologies that drive the implementation of Industry 4.0. This is due to its connection with many other technologies such as DT, AI, ML, and others. It serves as a supporter and enabler for many of these technologies. In this section, results from a two-round review showed that IoT can be also a significant enabler for different Lean tools and principles. More specifically, with its different functionalities (i.e. monitoring, control, autonomy, data

sharing, data transfer and information sharing, data storage, data analytics, and integration), IoT can help successful implementation of Lean principles; improving flow, value creation, problem-solving, and developing partners. Its use is helpful to achieve continuous improvement, waste elimination, and implementation of Lean tools. In the following sections, two cases about Lean-IoT integration are presented.

2.2 Lean and IoT in Brick Manufacturing

With roots going back thousands of years ago, brick manufacturing is one of the oldest industries in the world whose products (i.e. bricks) are among the oldest materials used in buildings and remain a basic ingredient in modern construction (Brick Development Association, 2017). Bricks nowadays are used in more than 25% of houses and construction projects (H. Singh et al., 2021). Therefore, brick manufacturing is considered among the most important industries to respond to the increased global housing problems resulting from different factors such as exponential population growth (Karmaoui et al., 2022).

Despite its significant role, brick manufacturing is facing numerous challenges. One clear challenge that has received a lot of interest in the last few years is the negative environmental performance of the brick manufacturing process and brick factories. This includes energy consumption, pollutants, and large amounts of physical waste. In 2018 CO₂ emissions reached 37.9 billion tons, 12% of which results from industrial processes such as brick manufacturing (Baude et al., 2021). Another important challenge that received less attention is related to the operational performance and the efficiency of the manufacturing processes while maintaining a high-quality final product. This includes efficiency, lack of adequate funding, lack of skills, poor operational performance, and low productivity and effectiveness (Arevalo-Barrera et al., 2019; Chavez et al., 2019; Utami Handayani et al., 2020).

Similar to any industry, and within the era of digitalization, brick manufacturing has the opportunity to benefit from the applications of Lean and Industry 4.0 to find solutions for the problems it encounters (Aka et al., 2019, 2020).

2.2.1 Lean and Industry 4.0 in brick manufacturing

Brick manufacturing is characterized as small-medium enterprises (SMEs)-based industry (S. Kumar & Sharma, 2021). This type of enterprise has many opportunities to benefit from the adoption of Lean Industry 4.0 such as cost reduction, faster growth, and flexibility increase (Elhusseiny & Crispim, 2022). Nevertheless, many barriers hinder this adoption in SMEs. Among them, the lack of financial capabilities, lack of information communication technology (ICT) infrastructure, lack of managerial flexibility and support, fear of change, lack of knowledge, and lack of skilled employees (Agostini & Nosella, 2020; Elhusseiny & Crispim, 2022; Kolla et al., 2019). In addition, according to Kolla et al (2019), most of the Lean Industry 4.0 frameworks and models are too complex and do not fit the nature of SMEs.

All these barriers might explain the lack of sufficient studies about Lean Industry 4.0 adoption in brick manufacturing. Only a limited number of studies were found about both topics. The aims of these studies were the identification and removal of Lean wastes in brick manufacturing processes (Aka et al., 2019, 2020; Arevalo-Barrera et al., 2019), identification of possible actions for quality improvement (Cabrera & Oliveros, 2017; Carrero et al., 2021), and design of status analysis system for brick machines using IoT (Z. Xu et al., 2020). In this thesis, the integration of Lean and Industry 4.0 is covered in the **current chapter** and **Chapter 4 (Section 4.2)** when studying the cases about the integration of Lean and IoT and digital twin, respectively. In this chapter, an example of the applicability of IoT to improve flow in a brick factory is presented.

2.2.2 Case description

The case was conducted in a brick manufactory company based in the north of France. The company has mainly four types of activities, which are brickworks, inert materials fill, a recycling center, and a materials trading site. Brickworks in the company started more than 100 years ago

and include producing clay bricks (solid bricks, perforated bricks, and clay brick plates). The company is a brick provider for many construction sites and projects in France, England, Ireland, and many other locations. Nevertheless, the company has faced several challenges in the last few years; for instance, high levels of wastes (waiting times due to high preparation and adjustment times, high breakdown times, low machinery performance, and repetition of activities due to equipment failure), high competition, and shortages in the skills that affect the ability to respond to the demand by customers. Additionally, due to the recent pandemic of COVID-19 and the impact of Brexit, the pressure became higher as the company has to respond to the rising need for local innovativeness and higher productivity due to the challenges facing the local and global supply chain and the increasing prices in the materials. Consequently, the company started a series of automation and quality improvement actions to respond to these challenges and eliminate the wastes in the production processes and improve the value provided to the customers. The current case reports one of these actions, which was mainly developed to prevent stoppages in the workflow of the activities and reduce the waiting time in the chain.

Process Description and encountered problems

The process of brick manufacturing in the studied case can be divided into different phases as shown in **Figure 2.5**, including the extraction of raw materials (clay), preparation of the clay to be used in the production (grinding and mixing, and dosage mixing), shaping of the bricks, drying, firing and cooling, and packaging the final products before shipping them to the customer.

Based on local observations made in the company, many stoppages were noticed between the cooling and packaging stages. Between these two phases, bricks that are cooled after they were taken from the kiln move on a conveyor, where a quality control stage is done by two workers who work to ensure that the final product meets the quality standards and does not have any stain, crack,

or damage. The bricks that fail to meet the quality standards are put in a dumpster to be recycled. Two robots are also found in this area; the first one is responsible for grouping the bricks in uniform rows after the quality control and before being sent to the other robot that is responsible for putting the bricks on pallets before packaging them to be sent to the customer or the storage areas.

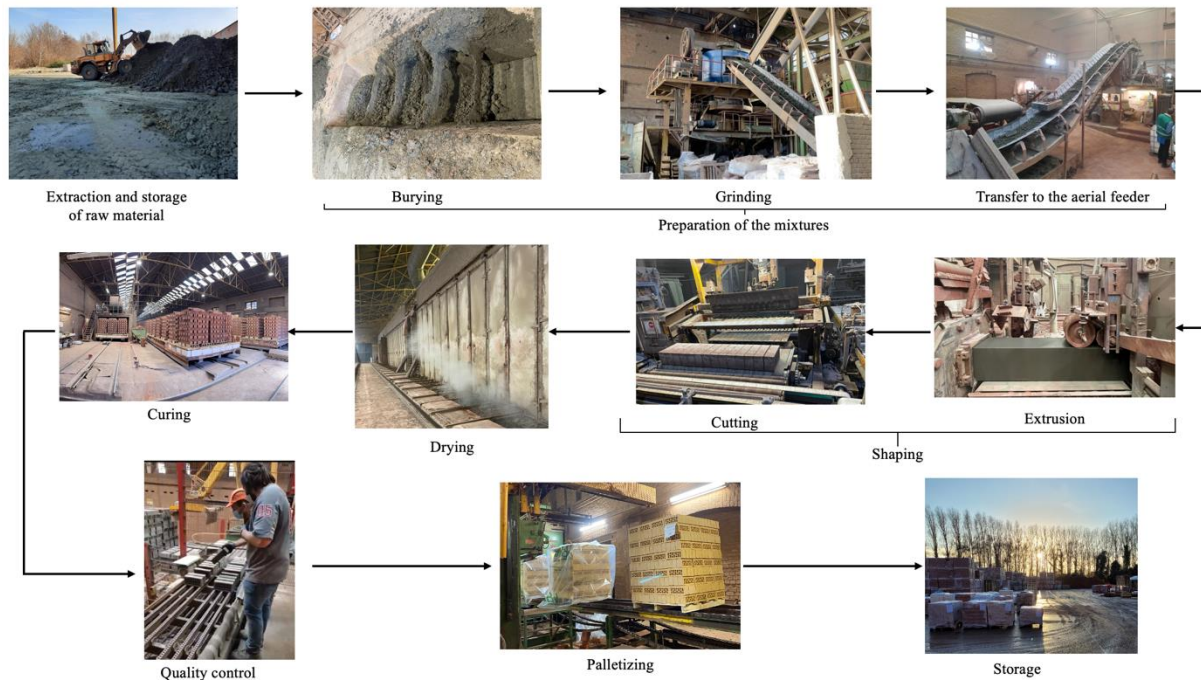


Figure 2.5. Brick manufacturing process

Development of the IoT system

Due to these stoppages in this area, the whole production line was affected and the production time was increasing very frequently. Accordingly, there was a need to identify the amount of wastes in the production line that affect the flow of the activities in the production process (i.e. stoppages in production), and the root causes for these wastes. To do so, an IoT system was used. As discussed above, every IoT system has three main layers; the perception, network, and application layer. Accordingly, the used system was as follows:

- **The Perception layer:** sensors that capture the movement of the bricks were attached to the first robot to calculate the needed time to close the two sides of the grouping robot (every grouping activity is an event). Based on data collected earlier about the normal time for the events, it was decided that the shortest cycle time is (15 seconds) and that is when having no defects in the production; and the maximum normal time for the cycle when having defects is (180 seconds). Accordingly, it was decided to consider any event that takes more than 180 seconds as a stoppage or slowdown in the process. The location of the sensors is shown in **Figure 2.6**.



Figure 2.6. The location of the installed sensors

- **The Network layer:** the collected data from the sensors about the running time of the grouping machine is sent via Bluetooth Low Energy to a tablet that is fixed close to the conveyor to make it reachable by the operators in the same area. The tablet is accessed via users' accounts and passwords to ensure the security of the data. The interface in the tablet shows the time and duration of events and an option to allow the operator to add the reason for any slowdown or stoppage in the production. In turn, the table is connected to an online server via Wi-Fi in the secure protocol (SSL). The tablet and its interface are shown in **Figure 2.7**.

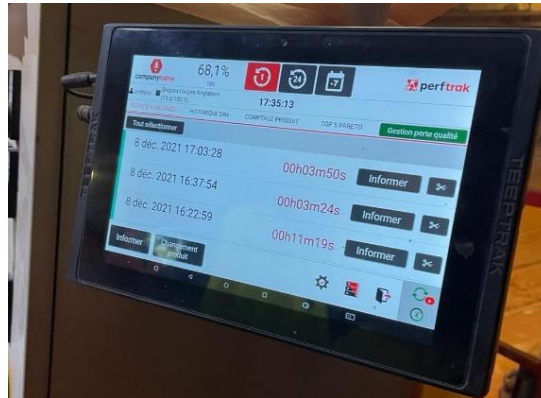


Figure 2.7. The installed tablet and its interface

- **The Application layer:** The online server that is connected to the tablet is responsible for saving, analyzing, and visualizing the data. The application layer also includes a mobile application that is connected to the online server. The system is connected also to the mobile phone of the manager and allows him to be alerted by a notification every time the chain is stopped. The results of the data analysis include information about product counting, performance assessment, and reasons for having unreliable workflow. Particularly, product counting was based on calculating the number of grouped products that are sent for packaging after the end of the quality control phase. The interface provides the total number of products per hour, day, or week based on multiplying the number of bricks in each group by the number of grouping events (every closer of the two sides of the grouping machine).

The system was able to identify the percentage of defects, which is the total number of produced bricks minus the number of grouped bricks that are prepared for packaging. In turn, the performance assessment was based on the ratio of the real number of the produced bricks per a specific duration on the expected number of bricks in the same duration using the normal cycle time (180s).

Finally, to detect the most affecting factors on the flow of the produced bricks in the studied area, a list of expected reasons was developed and the operators in the area were asked to select the factor for every stoppage or slowdown in the process using the tablet. The list includes several factors including factors related to the operability of the machines (robots, or conveyors), or other factors related to the nature of the workplace or phase of the process (e.g. cleaning time of the workplace, the need for maintenance work, delays in the previous phases, preparation of the work area...etc.).

Figure 2.8 shows the results that appear on the interface after analyzing the data that are related to the counting and performance assessment. In turn, **Figure 2.9** shows an example of the most affecting factors on the workflow in December 2021. The interface allows the users to export these results and to link them with email.



Figure 2.8. IoT Platform interface- Performance assessment and product counting



Figure 2.9. IoT Platform interface- Factors affecting workflow

2.2.3 Implementation and results

The system was implemented in February 2021. Since then, the system was helpful to identify the counting of final products and the performance of the production line. Accordingly, the data gathered from the system is helpful to identify the levels of defects in the production line. Nevertheless, since starting the implementation of the system, the identification of the reasons for stoppages or slowdown has witnessed some changes that have been made in order to improve the implementation of the system. In the beginning, the allocated time for each cycle was 15 seconds, following that the system was supposed to send alerts of stoppages or slowdowns in the flow of the activities. Nevertheless, at that time, it was noticed that the system was issuing alerts without having a real problem. It turned out that a change should be made in the cycle time to be more realistic (180 seconds). Additionally, the list of reasons behind the stoppages and slowdowns was also modified, re-categorized, and simplified. This is because workers mentioned that the list was too long to be followed and that the reporting of the stoppage reasons during the work is difficult and time-consuming, so they requested to modify it to be easier to follow on time.

The implementation of the system showed that some of the reasons behind the stoppages in the production line are recurring very frequently. One of the most repeated problems is that during the quality control and when the defective bricks are thrown into the dumpster, some bricks may fall into the chain, which blocks the wagons from moving forward. Additionally, it was noticed that bricks sometimes fall from the kiln and pile up on top of each other's, which requires at least 2 hours to put them back in place. In addition to problems that happen in the palletization area and grouping robot, and those related to wagon preparation and blocking and packaging roll. Accordingly, recommendations to make improvements in these areas were delivered. Examples of the recommendations include for instance providing continuous maintenance for the machines, continuous monitoring to prevent fallen bricks in the chain that affect the movement of the wagon, and providing a transition system between the kiln and chain to prevent the piling of the bricks.

The implementation of the system was faced with some difficulties that are mainly related to the human and technical aspects. For instance, the use of the tablet remains, until now, a little difficult for some workers who find it difficult to deal with the problem in progress and to inform it on the tablet, which prevents the management from being in touch with the instant reporting of the problems. Additionally, the reporting of the reasons was affected by the feeling of accountability by the workers. Also, once there is a problem with the internet network the data and alerts cannot be retrieved instantly.

2.3 Lean and IoT in Construction Prefabrication

Construction prefabrication is the term that describes the practice of producing a certain quantity of building components partially or fully in a factory to further assembly on the construction site (B. Qi et al., 2021). As one of the most important examples of industrialization of construction (Cheng et al., 2023), construction prefabrication has attracted attention and is considered an effective way to improve performance in the Architecture, Engineering, and Construction (AEC) industry. This is due to the various improvements it could present when it is compared with conventional on-site construction practices (Cheng et al., 2023; G. Xu et al., 2018). Examples of possible improvements include time and cost savings, reduction in greenhouse gas emissions (GHGs), safety improvement, reduction in materials consumption, and productivity gain (Arashpour et al., 2015; Mossman & Sarhan, 2021; B. Qi et al., 2021; G. Xu et al., 2018). Prefabrication also effectively reduces more than half of the physical waste (Jaillon et al., 2009). While comparing fully on-site construction with prefabrication, Horman et al (2006) presented a list of prefabrication's economic, social, and environmental benefits. Some of these benefits were the establishment of long-term supply chain planning, less maintenance work and reworks due to the improved quality, fewer defects, variety in materials choices, improved de-constructability, and improved working conditions.

Nevertheless, prefabrication in projects faces various challenges that may hinder the smooth flow of processes. According to Mossman and Sarhan (2021), synchronizing flow between offsite prefabrication and onsite construction is essential to ensure success when depending on prefabricated components. This synchronization has to cover all flow phases starting from the arrival of the raw materials at the factory and ending with the onsite assembly. Failure to achieve such synchronization can prohibit the delivery of materials or components and cause an increase

in time and cost of the project (Kanai et al., 2021). The heavy dependence on the critical path method (CPM), delivery of materials based on pushing strategies, and lack of focus on optimizing the overall production system in the factory and site are among the most affecting factors that limit the flow synchronization (Mossman & Sarhan, 2021). The use of Lean principles and tools such as LPS, JIT, and Kanban or pull signals can help mitigate the impact of these problems by focusing on the end-to-end process flow, collaboratively working and planning based on what can be done rather than what should be done, and produce and deliver only what is needed and when it is needed (Kanai et al., 2021; Mossman & Sarhan, 2021). Additionally, as mentioned above, the use of IoT when implementing Lean principles can improve the visualization of processes and share it with different stakeholders to improve flow, collaboration, problem-solving, error-proofing, and achieving continuous improvement (Dave et al., 2016; Tezel et al., 2022b). While the use of IoT in prefabrication and modular construction has been discussed in various studies (H. Ding et al., 2023; X Li et al., 2022; Turner et al., 2021; L. Wu et al., 2022), the problem of unsynchronized flow between the site and the factory is still overlooked.

2.3.1 Construction prefabrication and modularity definitions

Offsite construction (OSC) is the main umbrella of modular and prefabrication practices. However, the three words have been used interchangeably in the literature to refer to the process of “planning, design, fabrication, and assembly of building elements at a location other than their final installed location to support the rapid and efficient construction of a permanent structure” (National Institute of Building Sciences, 2022).

Modularity is “the quality of consisting of separate parts that, when combined, form a complete whole” (*Cambridge English Dictionary*, 2021). It is also “breaking up a system into discrete chunks, which communicate with each other through standardized interfaces, rules, and

specifications” (Baldwin et al., 2000). The aims of modularity include building a structure of the system of modules and achieving functionality and customization within this system (T. D. Miller & Elgård, 1998).

Modularity responsibilities and applications include three main areas; product modularity, process modularity, and supply chain modularity (as shown in **Figure 2.10**) (Fine, 2009). Product modularity includes the identification of performance specifications of the product/building, process modularity includes the work done to modularize the use of technology and process planning, and supply chain modularity includes improving all practices and relations along the supply chain (Voordijk et al., 2006).

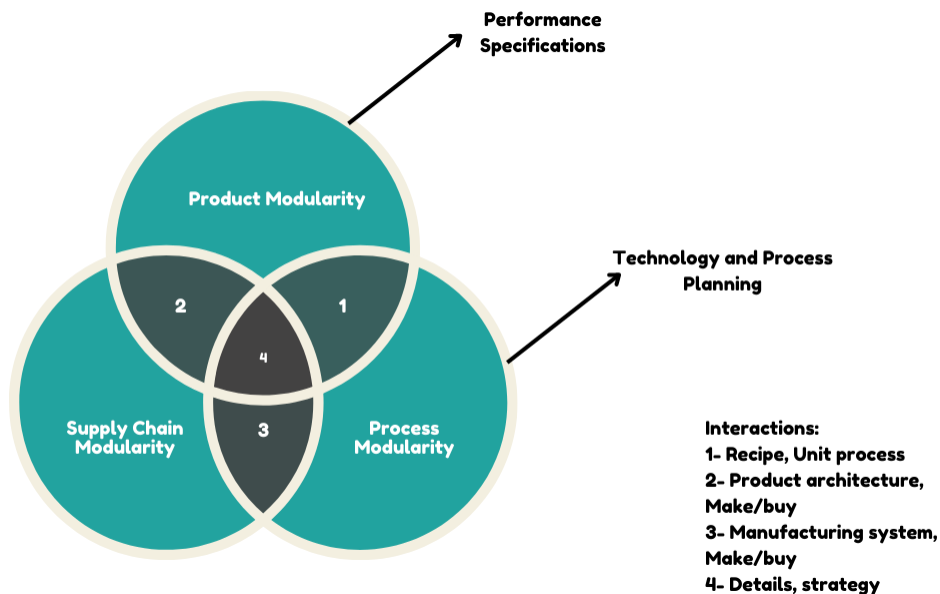


Figure 2.10. Modularity application area (Lennartsson & Björnfot, 2010; Mossman et al., 2022)

Modularity has gained popularity in manufacturing for several decades (Gravina da Rocha et al., 2020), but its use in construction is still underdeveloped (Bridi et al., 2019; Rocha & Koskela, 2020). Nevertheless, the positive impact of modular housing and buildings in construction was

seen in several experiences. For instance, the use of modularity in the Japanese construction industry helped many companies to offer preassembled and customized building units with lower costs and shorter delivery times (Barlow et al., 2003). The benefits of modularity in housing also go beyond improvements in cost, time, and quality of the projects as it can be helpful to innovative and customized facilities that meet the requirements of different categories and groups, achieve sustainability and better environmental performance of buildings, avoid maintenance cost and reduce lifecycle cost, achieve higher value and better-customized quality for the residents, improve practices, process and supply chain management during construction phases, and achieving better contractual relationships between different construction stakeholders (Bridi et al., 2019).

The literature has several definitions for the prefabrication process. For instance, Cheng et al (2023) considered that the process can be depicted in three main stages such as design, manufacturing, and onsite assembly. According to Liu et al (2020), the process comprises ordering, manufacturing, transportation, and assembly. In turn, Qi et al (2021) stated that the prefabrication process includes design and planning, production and manufacturing, delivery and store, and the assembly stages. In their study, Qi et al (2021) affirmed that challenges along all these phases can appear. The traditional approaches, which consider mainly architectural and performance requirements in the design stage can lead to a decrease the efficiency; therefore, manufacturing, delivery, and assembly aspects have to be considered. In the production stage, the lack of real-time information to monitor quality, location, and performance aspects can hinder optimal productivity. In the delivery process, errors in logistic management can affect the performance of the whole project.

2.3.2 Technology use in prefabricated construction

Cheng et al (2023) classified technologies in offsite construction (OSC) based on data perspective technologies into data acquisition, data integration, data analysis, and decision-making

technologies. For the acquisition, their study listed paper-based monitor and sensor techniques. They highlighted the use of long-range radio communication techniques (LoRA), RFID, GPS, laser scanning, and photogrammetry techniques. The integration technologies connect data with web platforms. In the making decision field, most of the decisions are taken by human actors and some are taken by smart systems. Liu et al (2020) found in their review, advances in the management and implementation levels for OSC. In the management process, strategic research, overall design, and supply chain integration and management are key. At the technological level, supply chain process design and optimization and application of advanced technology.

2.3.3 Technological gaps and challenges in prefabricated construction

According to Xu et al (2018), despite the numerous expected benefits when presenting technological solutions to construction prefabrication companies, these companies face various challenges. Among these challenges, is the reliance on traditional methods and the resistance to adopting new technologies, which results in inaccurate and inefficient practices. The second problem is the low level of coordination and collaboration, which prohibits the dissemination and sharing of information with the prefabricated companies; as a result, causes late and misplaced delivery. The third problem is related to the nature of the prefabricated companies as most of these companies are SMEs. Similar to the case of brick manufacturing companies, this type of company faces several challenges when trying to adopt technology such as the lack of financial capabilities, lack of managerial flexibility, resistance to change, lack of skilled employees, and lack of knowledge (Agostini & Nosella, 2020; Elhusseiny & Crispim, 2022; Kolla et al., 2019). The fourth problem is that most of the provided technology-based practices do not fully address the nature of the prefabricated construction and the link between the onsite and offsite production in construction. As a result, these solutions cannot be directly applied in prefabricated companies (G.

Xu et al., 2018). Additionally, in their review, Qi et al (2021) classified the technologies that are currently applied in prefabricated construction into business digitalization, computer-integrated design, data acquisition, optimization, predictive analytics, and robotics and automation. According to their analysis, most technological applications to improve prefabrication processes have been done in a research context.

Based on the above-mentioned challenges, more practical and scalable technologically supported solutions should be proposed and put into use. However, these technologies should fit with the nature of work in the prefabricated construction sector. They also should ensure high levels of collaboration between different stakeholders in the project and synchronization of practices and flow on the site and at the factory. This means that the proposed frameworks should be based on linking the three pillars of production systems, which are technology, process, and people. Linking these pillars is essential in Lean thinking (Sacks et al., 2010).

2.3.4 The proposed framework

The proposed framework is based on linking planning and control deliverables of the construction processes with the manufacturing processes in the prefabricated companies to ensure the synchronization of flow processes between the two production systems. To do so, the proposed framework tries to cover deliverables from the planning and control tool (LPS), application of JIT and pull signals, and development of IoT architecture to continuously track, monitor, and localize prefabricated components. The proposed framework was based on studying different cases in offsite and onsite construction (Q. Chen et al., 2020; Dave et al., 2016; Kanai et al., 2021; Xiao Li et al., 2018; Von Heyl & Teizer, 2017; G. Xu et al., 2018) and based on studying a process map in a prefabrication company in Canada.

According to Mossman and Sarhan (2021), the short-term collaborative planning approach in LPS facilitates the synchronization of flow between onsite and offsite fabrication and creates the conditions for JIT delivery, which aims to reduce the volume in inventory and ensure the delivery of materials to the right place at the right time. With a technological application such as BIM and IoT, LPS planning can integrate real-time information that can create reliable flow, improve visibility, and reduce variability (Dave et al., 2016; Mossman & Sarhan, 2021; Sacks et al., 2010).

Figure 2.11 shows the various layers of the IoT architecture in the proposed framework. The developed architecture is based on using barcode tags, RFID antennas, and readers for collecting data. The data transmission is done by Wi-Fi to databases that are accessible to the plant operators and project managers to conduct analysis and make decisions. As shown, the proposed architecture consists of three main layers: perception, network, and application layers.

The perception layer represents platforms for planning the tasks, using the application, and monitoring and controlling systems. It also represents units that are responsible for coding, information extracting, data processing, controlling, and monitoring. In the coding phase, an ID number is assigned to each prefabricated component. The component can be recognized in the whole cycle of the IoT. Then, the obtained information will be transmitted from the collection phase in the perception layer to the Lean analyzing phase in the network layer. The network layer is a network platform based on IPV6. It consists of an intelligent network, which connects all the resources in the network. In this layer, data is collected and objects are identified via RFID tags. Then the information is integrated into the cloud, to manage and control the collected data in real-time. In this layer, the data is reorganized, filtered, shared, and transformed into the content service in the Service-oriented architecture (SOA).

Finally, the application layer integrates the service capabilities and provides the application service to the clients. Users can use different applications to access their required information, such as smart transportation, smart material tracking, and logistics optimization. For instance, barcodes are installed on prefabricated components. The users can use a smart material tracking application to scan these barcodes with their smartphones, which directs them to any used storage (e.g. company's database or website). This application can be equipped with mobile tag reader technologies, which are used by the clients to make sure they have collected all received steel bars in returning racks. In addition, clients can use this application to send automated alerts to project managers to inform them that prefabricated components or pallets are ready for pick-up.

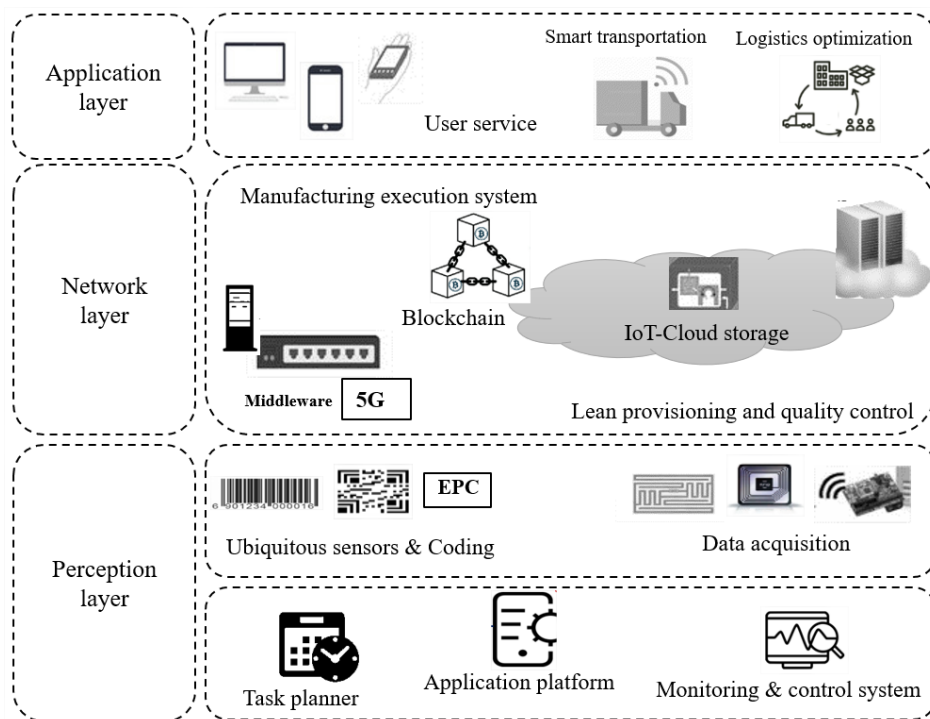


Figure 2.11. IoT-based architecture for the proposed framework

Process Description

Figure 2.12 shows the process in the proposed framework. The proposed framework covers the different phases of the prefabrication process and the onsite and offsite fabrication. It also integrates

different LPS levels with the IoT tracking system for the delivery and installation of prefabricated components. The framework is integrating the pull concept, buffering, and JIT during the production and manufacturing and delivery, and storage phases. It is also linked with nD BIM models to improve the tracking of the process flow.

More specifically, the process starts with the development of master planning, which is the first level of LPS planning. At this level, the main milestones of the project are identified and the development of the BIM models starts. The next phase is the phase or pull planning, in which the supplier of the prefabricated elements should participate and define the estimated lead times to deliver the orders. Using the results from the pull planning, the requirements and orders can be estimated and the look-ahead plans can be developed.

Estimates of the orders and requirements are useful to identify the production schedule and initiate the production process of the elements to be stored in warehouses. Simultaneously, the work on site focuses on the identification and removal of all possible constraints that may hinder the installation of the prefabricated elements onsite using logs from the look-ahead plans. Following the identification and removal of constraints, onsite demands and transportation plans are created to deliver the elements on time to the site. Based on the transportation plan, elements can be pulled from warehouses to be tagged and identified in the IoT system. The trucks can be tagged and linked to the IoT system as well.

The IoT system is responsible for delivering real-time updates about the delivery process including tracking, localizing, and counting the delivered elements and reporting any problem that may happen. Once the elements arrive at the site, they can be directly integrated with the weekly work plans, then installed, and then integrated into the daily huddle meetings and learning sessions.

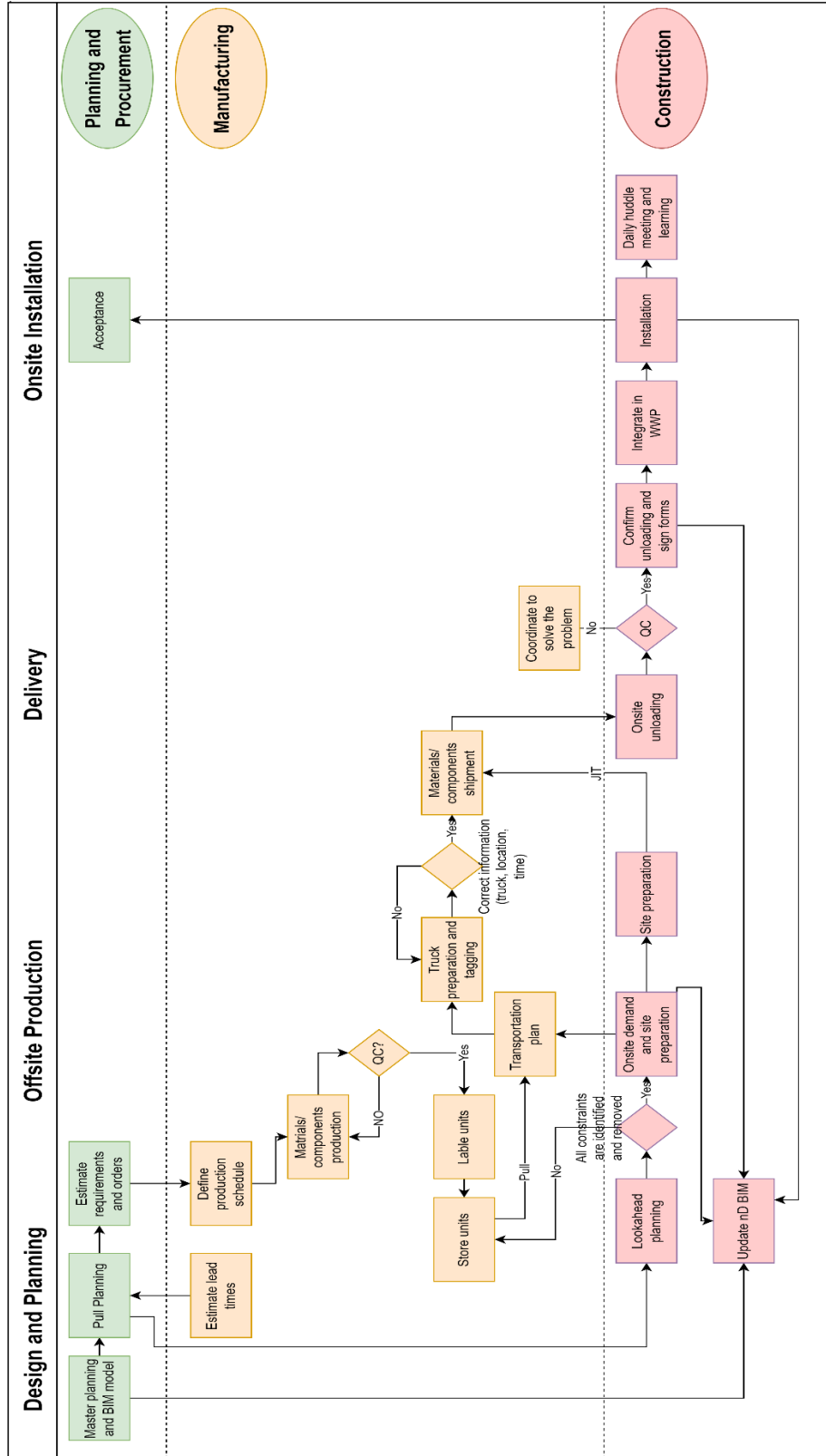


Figure 2.12. Process description in the proposed framework

Implementation and possible improvements

The proposed framework can be effective in linking the supplier schedule and the production plan of the project, which is very helpful to achieve improvement along the whole process rather than achieving fragmented changes that might not result in time reduction, cost saving, or quality improvement. Moreover, the proposed framework aims to reduce flow variability, cope with complexity, increase flexibility, and improve the decision-making process in prefabricated construction.

The proposed framework is to be tested to deliver construction prefabricated steel components in a Canadian company. The preliminary experiments utilizing the proposed IoT-based platform show initial promising results concerning the ability to track the delivery and installation of steel components. Nevertheless, despite starting the implementation of the framework, its results are not yet evaluated and validated. Therefore, further extensive experimental studies on-site and in manufacturing plant environments are required to validate the proposed framework. In addition to conducting more cases, future work can be conducted to identify possibilities of framework improvement using, for instance, digital twin technology to improve on-time tracking and monitoring and artificial intelligence (AI) to predict delivery dates. Further research can also focus on studying different performance indicators for the proposed framework or different barriers to adopting it.

2.4 Chapter Conclusions

The objective of this chapter was to study the relationship between Lean Construction and IoT in the built environment. The used methodology in this chapter was based on conducting a systematic literature review (SLR) about the integration of Lean and IoT in the construction industry, studying

a framework to integrate Lean and IoT in the material production phase (brick factory), and proposing a framework to integrate Lean and IoT in prefabrication.

The results of the chapter can be summarized as follows:

- 1- While reviewing 288 sources about the use of IoT in the construction industry, the most found applications were related to safety improvement and performance optimization by tracking, monitoring, identification, and sharing real-time information about workers and equipment on the construction site.
- 2- The review defined seven main functionalities for IoT in construction, which are 1) monitoring and visualization, 2) control and management, 3) autonomy, 4) data transfer and real-time information sharing, 5) data storage, 6) data analytics and decision-making support, 7) Integration of different stakeholders.
- 3- The second round of the review which was based on reviewing 43 studies about Lean and IoT summarized the relationship between the seven functionalities of IoT and Lean Construction principles. Based on this review, it was found that IoT can be an essential enabler for all Lean principles including flow, value generation, problem-solving, and developing partners and collaboration. The review also summarized the opportunities for the use of IoT as an enabler for different Lean tools such as visual management, error-proofing, JIT, and LPS.
- 4- The first case study showed that Lean-IoT integration was helpful to improve the flow of the brick production process. It was also helpful to identify different measures of production, detect stoppages in production, and notify managers of these stoppages and the reasons behind them.

- 5- The second case study showed the possibility of integrating Lean and IoT to improve the flow of prefabricated components and avoid the problems of lack of synchronization between the onsite and offsite fabrication. Integrating the plans from LPS and IoT in the proposed framework can help to improve the efficiency of prefabricated delivery. This is due to improving the traceability, localization, and identification of these components, enhancing the communication between the plant and the site, and avoiding errors resulting from the low levels of coordination.

**Chapter 3. LEAN CONSTRUCTION AND INTEGRATION
AND COLLABORATION TOOLS FOR DESIGN
MANAGEMENT**

Chapter 3. Lean Construction and Integration and Collaboration

Tools for Design Management

This chapter aims to present the integration between Lean Construction and digital tools for collaboration and integration in the design phase. This chapter is built over two cases; the first one is about the use of digital tools to improve planning for design activities during the pandemic of COVID-19, while the second is based on the integration of Lean and BIM and its impact on the performance in the design phase. The two works were conducted in France.

3.1 Lean Design Management

It is widely believed that decisions in the design phase of construction projects result in changes that cannot be adjusted without affecting the time, cost, and/or quality of the project (Haponava & Al-Jibouri, 2009; Sweis, Sweis, AbuHammad, et al., 2008). For instance, **Figure 3.1** shows that any taken decision in the preliminary stages of the construction project has a significant impact on the construction cost. As a result, design management is believed to be a critical factor that affects the success of construction projects (Chaize et al., 2022; Hattab & Hamzeh, 2013).

Design management refers to the planning, organization, and management of processes, people, knowledge, and information flow during the design phase to meet the client's needs and requirements (Herrera et al., 2020, 2021). During this phase, specialists from different disciplines work to translate the value proposition by the clients, meet their expectations, comply with the standards, and avoid making errors in the design (Hattab & Hamzeh, 2013; Tauriainen et al., 2016). Nevertheless, achieving all these objectives is still questionable in the presence of weak and traditional design practices (Tauriainen et al., 2016).

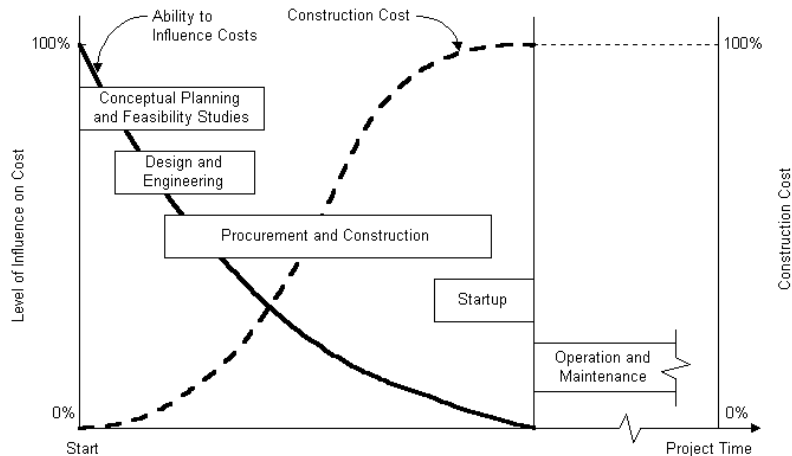


Figure 3.1. Ability to influence construction along the project life cycle (Hendrickson & Au, 1989)

Traditional design management can be understood as a linear process that includes a set of tasks done by designers who work fragmentedly to deliver the design based on a predetermined schedule and due dates (S. Khan & Tzortzopoulos, 2015). In this understanding, collaboration and interrelations between design teams are unappreciated (Tauriainen et al., 2016). It also indicates that design continuous improvement is not the focus. This is due to the understanding that the linear design process helps to achieve higher productivity in design and the iterative approach, which normally contributes to improving value and innovation, is wasteful (Abou-Ibrahim & Hamzeh, 2016; S. Khan & Tzortzopoulos, 2015). Another consequence of this understanding is the neglect of the flow of information between the right people at the right time, which may result in design errors (Hattab & Hamzeh, 2013).

The presentation of digital technologies is useful to improve construction design. Nevertheless, technology is not sufficient to ensure successful design management. Design management requires skills to manage design iterations and conversations in a way that differentiates between value generation and negative iterations (Ballard et al., 2007). The presentation of Lean philosophy to the design management has helped to maximize these skills and create systematic approaches to

increase the involvement of the client and different other stakeholders in these iterations, maximize the value generation, identify the needs of stakeholders, and reduce rework in design (Herrera et al., 2021). According to Ballard et al (2007), Lean design is based on cross-functional teams, set-based strategy, structured design to reach Lean concept, implementation of LPS, minimization of negative iterations, and use of technology (as shown in **Figure 3.2**). In turn, Herrera et al (2020) defined 19 items for lead design management based on three main groups, which are stakeholder management, planning and control, and decision-making.

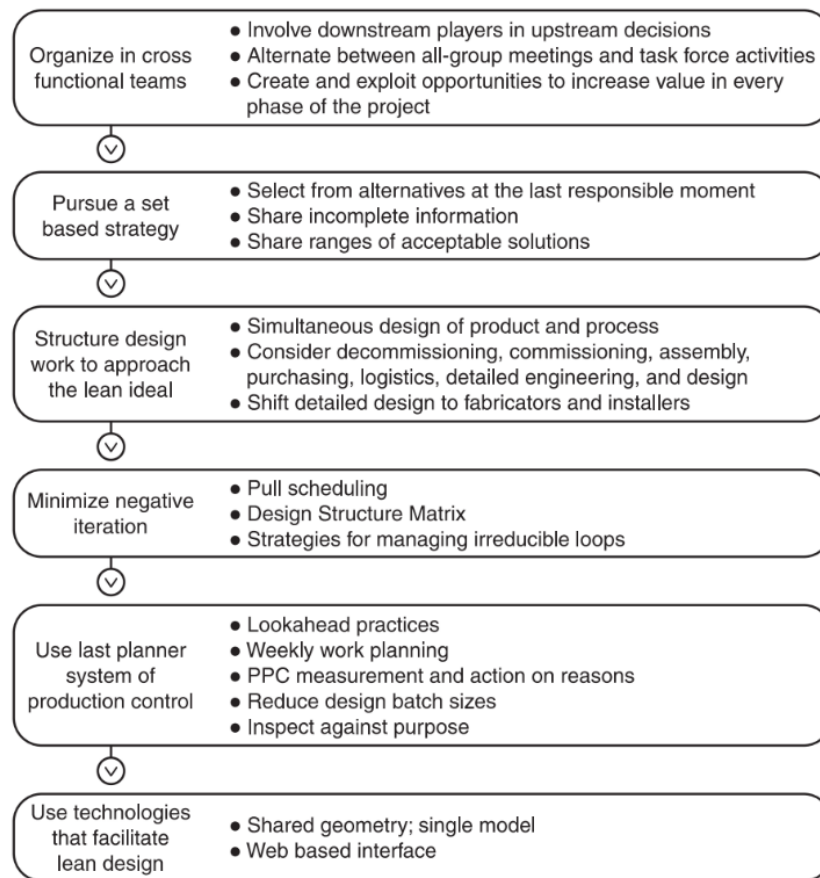


Figure 3.2. Lean design approach (Ballard & Zabelle, 2000).

3.2 Impact of Lean Practices in the Planning of Design Tasks

One of the essential keys to achieving success in construction projects is having reliable planning (Rizk et al., 2017). Reliable planning is the planning that allocates the resources properly, defines the criteria and needs to achieve the objectives of the project, and helps to anticipate the risks early enough to be properly managed and mitigated (Aziz & Hafez, 2013). Accordingly, it is not surprising that some construction managers invest more than one-third of their time in planning activities (Daniel et al., 2020; Mustapha & Langford, 1990).

Despite its importance, design in construction still includes high levels of variability in workflow due to poor planning of design activities (Bolviken et al., 2010; Hamzeh et al., 2009; S. Khan & Tzortzopoulos, 2015). The traditional planning for design in construction is usually based between the upper management and the client who regularly meet to define the needed objectives and deliverables without matching between what should be done and what can be done and without considering if the designers can achieve these deliverables. Additionally, the planning is usually done based on the master schedule and due dates, and meeting these dates through the definition of timing for the activities is left to each design department to decide, which confirms the levels of fragmentation and the lack of collaboration in design. Moreover, performance measurement, in most cases, is neglected (S. Khan & Tzortzopoulos, 2015; Koskela et al., 1997).

The above-mentioned problems that face traditional planning for design are similar to those cited by Ballard (2000) when he introduced LPS to improve planning and control of construction processes (i.e. Planning is understood based on the skills and talents of planners rather than being understood as a system, neglection of crew level planning and focusing only on a schedule, lack of constraints removal and matching between “should” and “can”, and lack of performance indicators and learning process). Therefore, following the success of LPS and due to having similar problems

in planning for construction and planning for the design, it is worthy to shed light on the possible ways to integrate Lean tools and LPS to improve the planning for design.

Hamzeh et al (2009) investigated the applicability of LPS in the design phase and presented the adjustments that can be presented to LPS to better suit the design activities. Kerosuo et al (2012) presented a case study about the use of LPS in the design of renovation in a school. The study showed that the design was completed on time and the communications were improved between the team due to the implementation of LPS. Rosas (2013) investigated the impact of the integration between the design structure matrix (DSM) and LPS in design management. The study showed that this integration can improve the reliability of the planning and the identification of corrective actions by the team. Fundli and Dervland (2014) introduced an LPS-based method that is usable during the planning for design activities and is called Collaborative Design Management (CDM). The presented method was helpful to improve communication, collaboration, understanding, and commitment in the design phase. Khan and Tzortzopoulos (2015) showed how weekly work planning was effective to improve workflow, reliability of planning, and collaboration during the design of two building projects. Fosse and Ballard (2016) stated that LPS can help to improve quality, reduce time, and save the cost of the design.

Nevertheless, despite all these studies, efforts to integrate Lean practices in general and LPS in particular in the planning for design are incomparable to those made in the construction phase. Additionally, the last pandemic of COVID-19 affected the implementation of Lean practices in general and planning activities and the last planner systems in particular. This is due to the measures that were taken to limit the spread of the virus, including social distancing, traveling reduction, and reducing the opportunities to organize meetings between the different projects' stakeholders. As a result, digital tools are more commonly needed to connect different parties and stakeholders to

achieve more proper planning. The use of these tools while implementing Lean Construction has the potential to mitigate the impact of fragmentation, disseminate the Lean culture, integrate different partners in the project, and decrease workload related to sticky notes management during the implementation of LPS (Hua & Schwartz, 2021; McHugh et al., 2021; Pedó et al., 2020; Salhab et al., 2021). Nevertheless, digitizing Lean Construction is still in its infancy and its acceptance of it still needs further investigation.

This section, and through a presentation of two case studies that were conducted in France where Lean Construction is still not routinely practiced; especially in the design phase (Dakhli et al., 2017), aims to: Investigate the impact of Lean tools adoption by support of digital tools to improve the planning for design activities.

3.2.1 Research methodology

The used methodology in this section was based on three main phases: the first phase was conducting a preliminary survey that aimed to evaluate the current challenges and difficulties faced in the French construction sector based on the perspectives of different stakeholders in the sector. The second phase followed the analysis of the results of the preliminary survey and aimed to implement Lean tools and practices in two projects in France, while the third phase aimed to investigate the perspectives of the participants in the two cases about the implemented tools and practices through a second survey.

Preliminary survey

The first phase consists of the realization of a preliminary survey that was conducted as market research and developed to make a general understanding of the difficulties that face the different actors in the French construction industry. The development of the survey was using Google Forms and the survey was distributed by email to a list of 1,750 practitioners in the French construction

industry representing different types of companies (contractors, owners, design and engineering offices, suppliers...etc.). The survey was developed to include six main parts with 23 questions. The questions covered the demographic profile of the participants, client's requirements and involvement, cost-related issues, time-related issues, methods of working, and current managerial practices.

The total number of participants in the survey was 260 participants; 29% of them were from general contracting companies, 25% were from project management offices, 13% were owner representatives, and 10% were from engineering studies offices. The participants were working on different types of projects including real estate, residential, hotels, industrial, and commercial projects.

The analysis of the results of the preliminary survey revealed the following key findings:

- More than half of the participants believe that the client's requirements and inputs are incomplete and that these requirements and inputs are not stable and keep changing.
- 35% of the participants believe that the client is not sufficiently involved in the development of the project.
- 88% of the participants believe that sharing knowledge between project partners would contribute to problem-solving and 39% believe that it would increase profitability.
- Around two-thirds of the participants believe that sharing success and financial gains between the partners of the project is difficult.
- To face the different challenges facing the management of construction projects starting from the design phase, participants believe that the most effective measures are the use of a shared software or a platform between the partners (reported by 82% of the participants)

and establishing a collaborative and integrated unit between different companies (reported by 77% of the participants).

The results of the preliminary survey confirmed that although collaboration between project stakeholders and client involvement is considered very important, especially in the design phase, participants considered this collaboration not easy to do. Accordingly, Lean tools and LPS were adopted as it is evident that these tools are very useful to focus on client's needs and satisfaction and improve collaboration in projects (Fundli & Drevland, 2014; Hamzeh et al., 2009). Additionally, as the majority of the participants believe that a shared platform in the way of software is a possible solution to improve collaboration, the decision to use digital tools to improve Lean adoption was taken.

Case studies

Following the analysis of the results from the preliminary survey, the work focused on presenting Lean practices in two case studies. The two cases were selected based on having similarities in the design duration and teams. In both cases, the client, main contractor, specific sub-contractors, architect, and engineering consultants were involved during the design phase. Therefore, it was possible to implement the same tools in both cases.

Case study 1-

The first case was an aquatic complex project built as part of the Paris 2024 Olympic games. This aquatic center offers a total surface area of 1588m², including a sports pool 21m wide and 33m long, an activity pool of 150m² free forms, a 70 m² free-form awareness pool, and a wellness area. The project met solid environmental requirements to reduce water and electricity consumption and reduce the carbon footprint in the construction and maintenance phases. The construction contract was a Build-operate-transfer (BOT) contract. BOT is a contractual relationship between a public

owner and a contracting company that is responsible for providing the design, constructing the facility, and then operating it for some time before transferring the operations to the owner. The intervention to introduce Lean practices in the project was between February 2021 and October 2021. Lean practices were implemented to improve the design management starting from the beginning of the conceptual design phase, then the preliminary design phase, until the detailed design phase.

Case study 2-

The second case study was a 40 000m² office and business campus on 11 levels. The project is schematically constituted by three parallel buildings in the direction of the slope, drawing sloping valleys, like "scarifications" on the hillside. The project includes the following activities: Labor code building for the office areas, business center, common areas, parking, technical premises, one arena located on the ground floor, four shops located on the ground floor, one fitness area, one wellness area, and one crèche. The project had to meet ambitions in terms of sustainable development facing future users and local partners. The project would also respond to local efforts led by the public authorities, particularly the Greater Paris Climate Plan. The contract was a private contract of the Guaranteed Maximum Price type (GMP). This type of contract includes a maximum price that can be paid by the owner to the contractor (unless having a formal agreement on scope change). If the project costs less than the GMP, the owner retains the savings or may have an agreement to share them with the contractor. The intervention on the project was from January 2019 to August 2021, from the preliminary design phase, until the detailed design phase.

Implemented practices and tools in the case studies

Following analyzing the results of the first survey, a team seminar was presented for the design and construction stakeholders. This seminar aimed to raise awareness about Lean management in

the construction industry and covered the following topics: sharing the vision of the project by all the participants (clients, architects, design, studies, contractor), reviewing the conditions of satisfaction of the project by the client, risks and opportunities for each stakeholder, and initiate the collaborative planning using LPS.

LPS was implemented in the design phase by planning the whole deliverables and levels starting from the master schedule to the daily meetings. To do so, a series of meetings had to be done to reach all partners in the design phase. The plan to do the meetings was based on:

General study steering meeting: this is a remote meeting. It enables the progress of the design to be monitored (indicators, tasks to be carried out, blocking points, decisions, and customer feedback).

Weekly organization meeting: 30-minute telephone meeting to confirm everyone's commitment to the tasks to be done, the agenda for the general meeting, and the topics to be covered during the week.

Owner's meeting: monthly meeting allowing to fix the reviews of the decisions to be taken by the owner, the thoughts on the evolutions and modifications of the project, and the reviews of the specific expectations of the owner.

The internal meeting between the project manager and the company: this meeting is used to deal with specific technical issues that do not require the presence of the whole team.

Measuring performance and progress between the planned and the actual work and identifying the root causes for the variance in the performance are among the essential differences between LPS and other traditional planning and control practices. Therefore, to support the implementation of LPS, Key Performance Indicators (KPIs), which are quantifiable measures that are used to assess

the actual performance, were developed and used in the two cases. The list of KPIs included the following (as shown in **Figure 3.3**):

KPI 1: is a general key performance indicator for the whole project management in the design phase that shows the percent plan complete (PPC) for the project and was depicted as two curves; one is for the planned work and the other is for the actual finished work. **KPI 2:** was used to assess the involvement of partners in the meetings by presenting the present rates in each meeting. **KPI 3:** was to monitor the needed inputs from the client. This KPI was digitally controlled by a vertical histogram bar showing the weekly number of client input data, and their status (to be received, late, received). **KPI 4:** was to track the completion of weekly tasks per stakeholders. It shows the status of the different number of tasks assigned for each stakeholder involved in this phase of the project (Architect, Company, Steering, Owner), the other status of each task shown in the bar of the histogram are: To do, in progress, late and done. **KPI 5:** was to show the overall number of tasks to be processed in the project design. **KPI 6:** This was used to show the consolidation number of changes and the sources of the changes. In addition, two other KPIs were used to show the progress in documentation production; one KPI was used to show PPC for the planned delivered documents by each employee involved in the studying phase in both projects. While the other shows the needed number of days required by each employee to deliver the remaining deliverables.

In addition to LPS, Visual Management (VM) and the KANBAN board were used in the two cases to manage and track the design of the two projects, visually present the progress of the work, and support the involvement of all employees in the work. **Figure 3.4** shows the used digital KANBAN boards in the two cases. The Figure shows the classification of different tasks in the design phase to improve the monitoring of these tasks and the identification of actions to be taken.

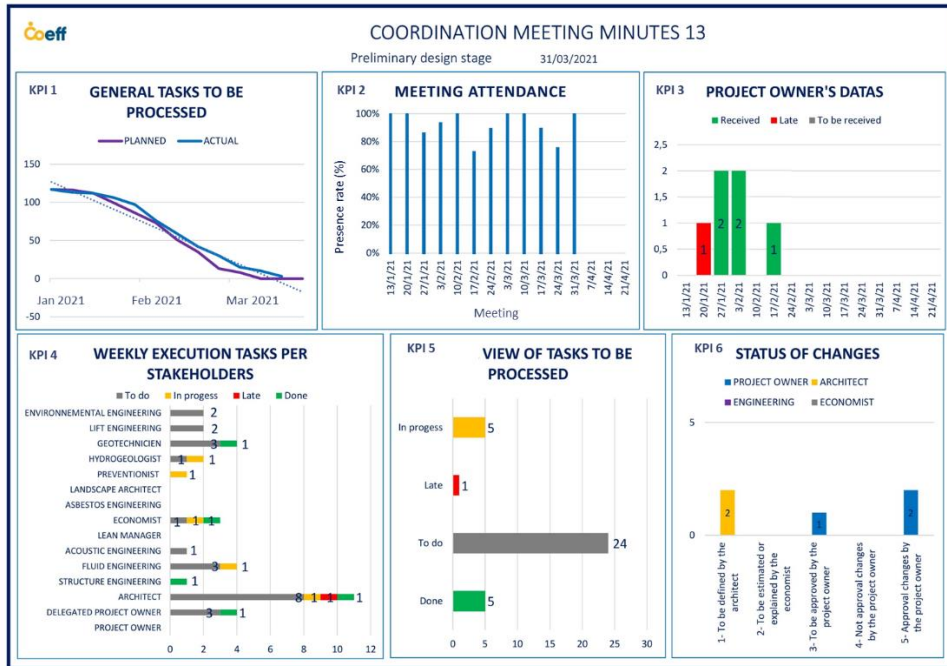


Figure 3.3. Key Performance Indicators (KPIs)

ALL REQUESTS FOR ACTION OR INFORMATION ARE RECORDED ON THIS DAILY MONITORING TABLE OF SHARED TASKS

6° GENTILLY - WEEKLY MONITORING OF TASKS TO BE DONE BY THE TEAM

AREA	BACKLOG	TO DO	IN PROGRESS	LATE	DONE
All area	[Task cards]	[Task cards]	[Task cards]		[Task cards]
Z1 – Building A		[Task cards]	[Task cards]		[Task cards]
Z2 – Building B	[Task cards]	[Task cards]	[Task cards]		[Task cards]
Z3 – Building C	[Task cards]	[Task cards]	[Task cards]		[Task cards]
Z4- Exterior Works	[Task cards]	[Task cards]	[Task cards]		

Figure 3.4. KANBAN Boards

The integration of Lean and digital tools was done throughout the whole design phase. In addition to the use of building information modeling (BIM) and digital meeting platforms to conduct online

meetings between different partners, a digital space for sharing project information was established. This space served as a room for all managers, leaders, and employees to share their ideas, collaborate, and ask questions. This space was based on two main tools:

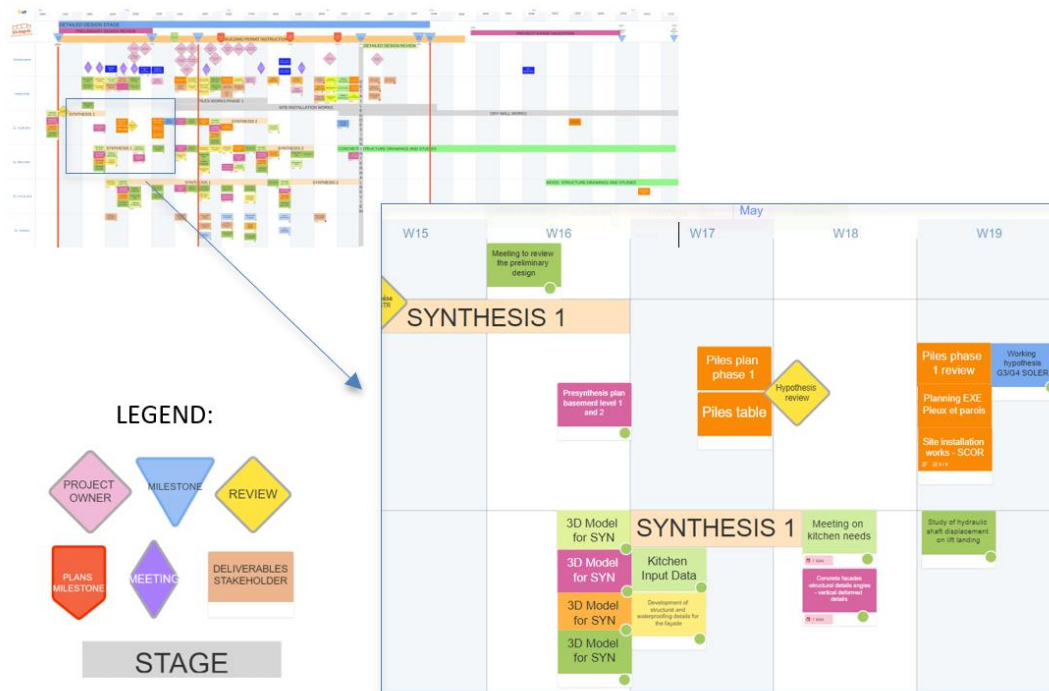


Figure 3.5. Use of digital tool “iObeya” to deliver the planning for design tasks

1. “iObeya”: a virtual collaboration platform that is based on the Obeya method, which is based on establishing a room for project partners designed to improve communication, collaboration, and decision-making. The use of the Obeya method is helpful to track progress, discuss the design, and engage different stakeholders in the discussions. For the two studied cases, “iObeya” included panels for LPS and KANBAN. **Figure 3.5** shows an example of the use of “iObeya” in the planning for the design tasks. The figure depicts how partners were able to use notes and stickers during the implementation of LPS.

2. “SharePoint”, which is a collaborative document-sharing platform. In this platform, partners were able to access all project information including project information and organization, details about meetings, weekly tasks, progress toward KPIs and milestones, requests for order and information, and reports and drawings, in addition to links to emails, shared calendar, and “iObeya” room.

The second survey

To assess the impact of Lean implementation and the effectiveness of the used tools in the two cases, a second survey was developed. The survey was developed using Microsoft Forms and distributed to the emails of 37 stakeholders who participated in the design phase of the projects.

The survey included five main sections, which are:

1. The role of participants
2. The created impact in the two projects due to the implementation of Lean practices in planning for the design tasks (four point-Likert scale: 1) strongly disagree, 2) disagree, 3) agree, 4) strongly agree)
3. The contribution of the tools used to improve the planning for design activities (yes/no questions)
4. The benefits of Lean implementation in the design phase (yes/no questions)
5. Readiness to implement Lean management again (yes/no question)

3.2.2 Results and analysis

The second survey was filled by 25 participants, representing a response rate of 68%. The participants were from the engineering studies and design office (9 participants), architectural office (5 participants), owner representatives (5 participants), and general contractor (3

participants), in addition to three participants who were working as a BIM manager, landscape manager, an employee in the control office.

The analysis of the results revealed that participants that the use of Lean tools in the planning for design tasks helped to present different outcomes (as shown in **Table 3.1**). The highest impact was found on compliance with the study deadline (mean= 3.48 out of 4.00), which was the second most challenge found in the first survey. While the lowest impact was on compliance with cost, which was the most difficult challenge found in the first survey. Nevertheless, the rate is still acceptable as the mean equals 2.64 out of 4.00 (66%). Participants also give high and approximately similar rankings to improved design brief quality and consistency improved working and collaboration conditions (mean= 3.36), Improved design brief quality and consistency (mean= 3.33), better consideration of customer expectations (mean=3.30), and better responsiveness to integrate project changes (mean= 3.25). In comparison between the perspectives of the participants from the two projects regarding the impact of Lean implementation, the analysis showed similar rankings for most statements with slightly higher ratings in the second case for the responsiveness to integrate project changes, compliance with the deadline, and improved working and collaboration conditions.

Table 3.1. Created Impact in the two projects due to Lean implementation

Lean Implementation Impact	Overall	Case 1	Case 2
Better consideration of customer expectations	3,30	3,28	3,31
Better responsiveness to integrate project changes	3,25	3,00	3,37
Compliance with work costs	2,64	2,67	2,64
Compliance with study deadlines	3,48	3,22	3,64
Improved working and collaboration conditions	3,36	3,00	3,47
Improved design brief quality and consistency	3,36	3,37	3,36
Better preparation for the works phase	2,89	2,80	2,91

Regarding the benefits of Lean implementation in the planning for the design phase. **Figure 3.6** shows that most participants agreed that Lean can help to organize the study/design smoothly,

improve the efficiency of the planning, understand and share the objectives and expectations of the client, improve the collaborative environment between all stakeholders, and improve the decision-making process and validate the study effectively.

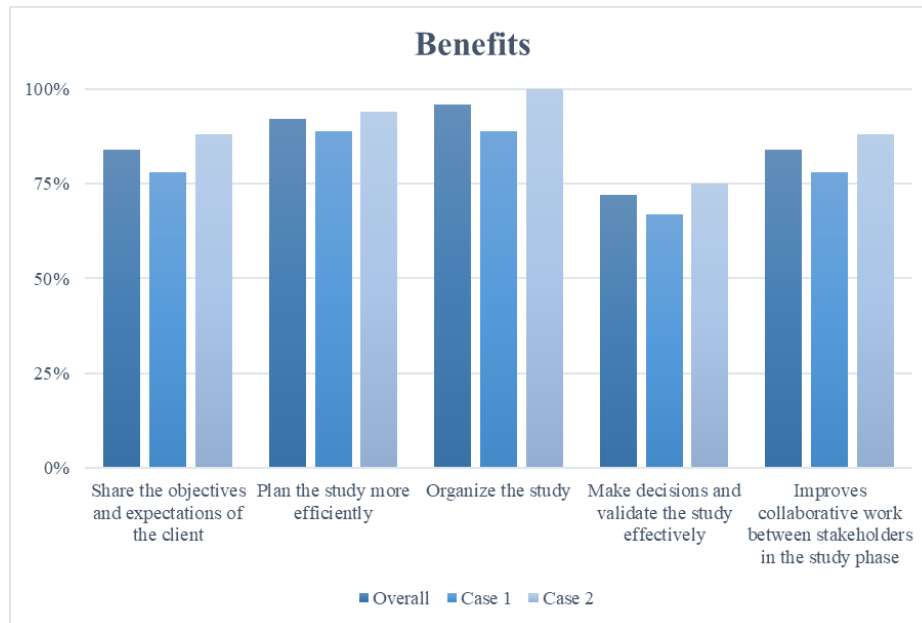


Figure 3.6. Perspectives of participants about the benefits of Lean implementation in the design phase

Regarding the contribution of the tools used to improve the efficiency of the planning for the design, the highest ranking was for the meetings organized to conduct the planning; all the participants in the survey stated that these meetings were effective to improve the planning for the design. The meetings with the owner and phase planning that was done during the seminar received the second-highest rating (88% and 86% respectively). The implementation of digital tools (Sharepoint – iObeya) was considered effective to improve planning efficiency by 16 participants (64%). While the lowest ranking was for scheduling delivery of BIM models based on studies (48%) and establishment of production indicators (52%).

3.2.3 Discussion

The results showed that most participants believed that the adoption of Lean tools (LPS, KANBAN boards, and visual management) is helpful to deliver the design on time, meet customers' expectations, improve the quality of the design, and achieve better collaboration between the team members. These results are consistent with the studies about the applicability of Lean tools in design management (Fosse & Ballard, 2016; Fundli & Drevland, 2014; Hamzeh et al., 2009; Kerosuo et al., 2012; S. Khan & Tzortzopoulos, 2015; Rosas, 2013). Additionally, it was noticed that the use of KANBAN boards improved knowledge sharing, transparency, and decision-making during the design phase as it helps to improve information flow, focus on the priorities and pull the design to be consistent with the needs instead of pushing the design to finish based on predetermined deadlines. This result supports the finding of Modrich and Cousins (2017) who stated the combination of LPS and KANBAN is necessary to improve design management. This combination was supported in the two cases by visual management, which helped to ensure better workflow and knowledge sharing among the partners.

Moreover, the results showed that digitizing the used Lean tools was effective in the design phase. The used digital tools helped to keep the partners connected with each other's and improved the collaboration environment, communication, and transparency between the partner. Additionally, these tools served as an easily-accessible reference that included information about the plans and progress of the projects. This was very helpful especially during the times of the lockdown due to the COVID-19 pandemic. The ranking for these tools was even higher than that given to BIM. This might be because the partners had already some knowledge about BIM, while Lean and digital tools were newly presented to them.

Finally, during the analysis of the results, a slightly higher ranking for the impact and benefits of Lean was given in the second case study. While this difference was not investigated during the conduction of the study, the duration of the intervention might be the reason for this difference. This might be due to two reasons; the first is the needed time to build a culture of Lean and see the impact of Lean adoption while the second is the impact of COVID-19 as in this project, participants were able to be exposed to the use of Lean before and after the pandemic and noticed how Lean can be a key for managing the design during the times of uncertainty.

3.3 Impact of Lean and BIM Integration on Design Performance

The use of BIM offers opportunities to collaboratively work on a “live” version of the design between stakeholders and helps to increase transparency and information flow between all the stakeholders (Hattab & Hamzeh, 2013). The features of BIM allow for achieving numerous improvements in the design phase such as the decline in design errors and clashes, increased visualization, quicker and easier design alternatives, reduced design cycle time, improved coordination, and easier cost estimation (Besklubova et al., 2021; Herrera et al., 2021; Rojas et al., 2019; Tauriainen et al., 2016).

Nevertheless, BIM as a technology is not sufficient to ensure successful design management. Lean Construction, with its principles and tools, helps to facilitate the generation of the value of the client and improve the social system during the design process. For instance, the presentation of the LPS during the design process can contribute to improving transparency, communication, trust, efficiency, and quality of the design (Hamzeh et al., 2009; S. Khan & Tzortzopoulos, 2015). Big room/iroom/co-location is also effective to increase collaboration, decreasing design errors, and reduce latency in decision-making (Tauriainen et al., 2016) and Design structure matrix (DSM) is helpful to improve planning for the entire design phase (Rosas, 2013).

Therefore, the Lean-BIM integration has been topical in many research works and applications (Abou-Ibrahim & Hamzeh, 2016; Bolpagni et al., 2017; Dave et al., 2013; EL Mounla et al., 2023; Hattab & Hamzeh, 2013; Herrera et al., 2021; Mollasalehi et al., 2016; Rojas et al., 2019; Sacks et al., 2010; Sbiti et al., 2022, 2021; Tauriainen et al., 2016; Uusitalo et al., 2019). In France, a limited number of investigations have been carried out about this integration. Additionally, there is still some missing information about the adoption of both concepts in all phases of the construction despite different calls to adopt them (Joblot et al., 2017; PLANBIM, 2022; Tranchant et al., 2017).

Moreover, despite the global efforts to study Lean-BIM integration, there has still insufficient studies that link Lean-BIM integration and design performance. Aiming at increasing the understanding of Lean-BIM integration in France and its impact on design performance, this section reports the results from a survey that was conducted to achieve these purposes.

3.3.1 Research Methodology

This section aims to identify the levels of BIM and Lean adoption and their impact on design performance in a group of French companies. To achieve this aim, a survey was developed based on studies from the literature. The survey included four main sections as follows (Annex 1):

Section 1: general information about the company and respondents (three questions; participants' experience, company size, and role in the company).

Section 2: was about BIM purposes and uses. This section included 12 questions that were adopted from the studies of Bolpagni et al (2017) and Herrera et al (2021). The questions were about the experience of BIM adoption and training, purposes of BIM, and frequency of BIM uses on a five-point Likert scale from 1 (refers to never) to 5 (refers to always).

Section 3: was about Lean principles and tools and was based on Lean adoption and training and used tools. The section included three main questions that were adopted from the study of Bolpagni et al (2017).

Section 4: was about Lean-BIM integration in design and evaluation of design performance. The section was based on 20 questions adopted from the studies of Dave et al (2013) and Herrera et al (2021). For the Lean-BIM integration, the questions were based on a five-point Likert scale where 1 (refers to never) to 5 (refers to always), while for the performance, the scale was from 1 (refers to strongly disagree) to 5 (strongly agree).

The survey was translated into French and developed using Microsoft Forms. It was then distributed using emails and LinkedIn was filled by respondents from design and engineering studies firms in France. The analysis of the results was done using Microsoft Excel 2019.

3.3.2 Analysis of the results

Participants and company profile

49 participants answered the questions of the survey. The analysis of the results showed that the vast majority of the respondents had a long experience in construction design and studies as 40 participants had more than 10 years of experience in the field. The roles of the participants ranged between directors, project managers, BIM managers, heads of departments, architects, engineers, and one Lean manager.

Concerning the companies' profile, the participants represented the different sizes of companies as 21 participants were from companies with more than 100 employees, 7 were from companies with 50-100 employees, 13 were from companies with 10-50 employees, and 8 were from companies with less than 10 employees. The participants were also from companies with different areas of work including architecture, public and infrastructure projects, residential and real-estate projects, industrial buildings, commercial buildings, hotels, and renovation projects.

BIM adoption and uses

The responses regarding BIM adoption showed an acceptable range of BIM adoption as most of the participants stated that BIM had been applied in their companies for at least five years (38 respondents). Only one participant in the study stated that BIM was still not adopted in the company. Two other participants stated that BIM was new to their company and its adoption started less than one year ago. 38 respondents (78%) declared that their companies were offering training on BIM.

Regarding the purposes of BIM implementation, architectural purposes (n= 38 respondents), structural (n=25), mechanical (n=25), and plumbing (n=25) works were the most found motives for BIM adoption in the studied companies. BIM was also used to manage and develop electrical works, maintenance and alarm systems, facades, environmental studies, and others.

Concerning the BIM applications in the design phase, **Figure 3.7** shows that 3D coordination (mean=4.16), code validation (mean=3.76), and cost estimation (mean=3.02) are among the most frequent uses of BIM in the studied firms. While 4D planning (mean=1.96) is the least frequent use of BIM.

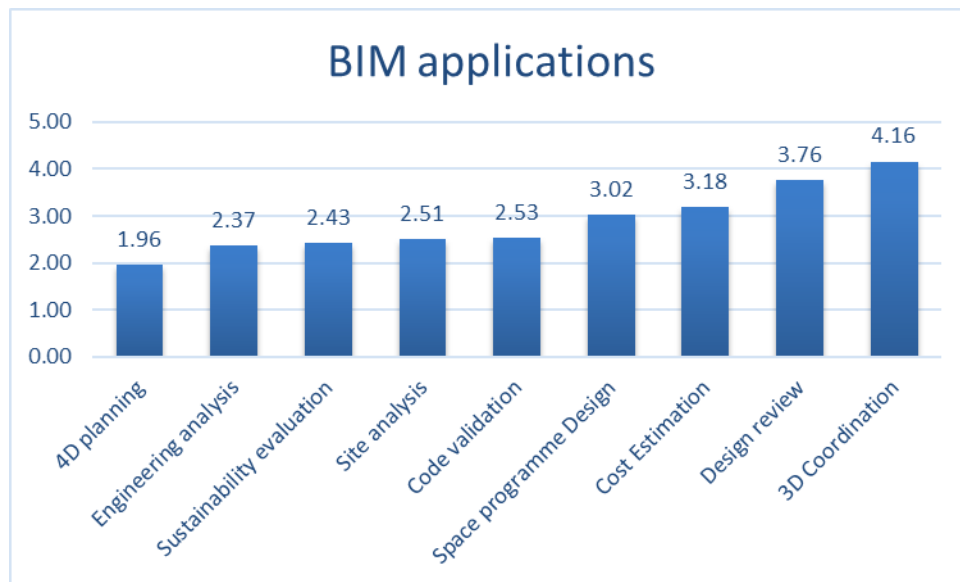


Figure 3.7. BIM uses in the design phase

Lean adoption and Lean tools

The adoption of Lean was significantly less in comparison to BIM. This is because only 11 participants (22.45%) stated that Lean was adopted in their firms. Among them, only one firm was adopting Lean for more than ten years and eight firms were adopting Lean for 1-5 years. Additionally, only two participants stated that their companies provide training on Lean.

Nevertheless, despite the lack of a declaration of Lean as a whole philosophy, some participants believed that their companies use some tools that might facilitate the future implementation of Lean. **Figure 3.8** shows that the most applied tool/practice is the A3 problem-solving reports (n=13), then Big room or co-location to improve collaborative planning and design (n=12), and then the last planner system (LPS) (n=10). Other tools such as design structure matrix (DSM), plan-do-check-act (PDCA), value stream mapping (VSM), and 5S were less implemented. The least implemented tools/practices were the target value design (TVD), which was implemented by two companies, and the integrated project delivery (IPD), which was implemented by only one company.

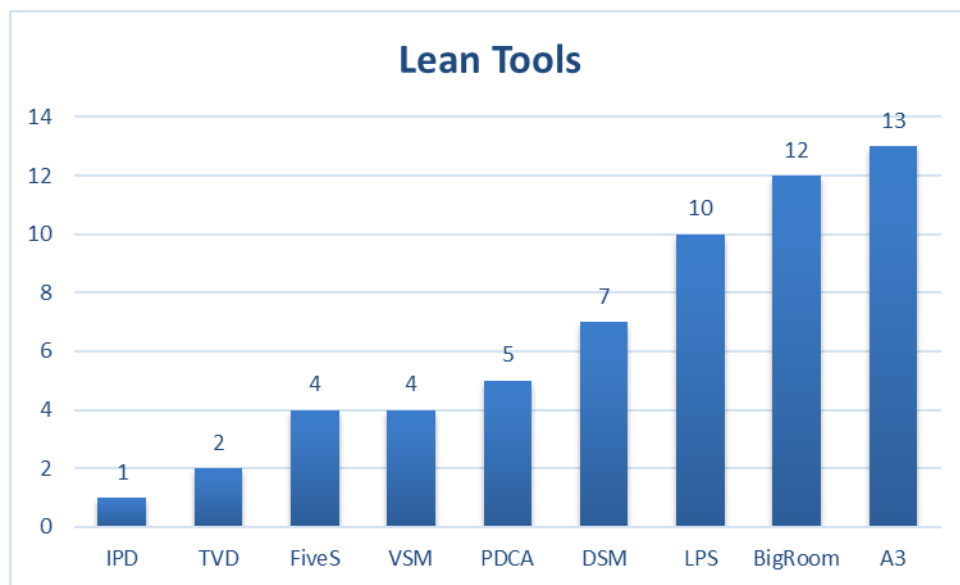


Figure 3.8. Applied Lean tools/practices

Lean-BIM design management

Lean-BIM design management in this study refers to the integration between Lean and BIM and the use of BIM models to support Lean principles. **Table 3.2** shows that the overall evaluation for Lean-BIM integration was neither very high nor low as the mean was 3.73 out of 5.00. The highest

evaluation was for the client value (mean= of 3.77), while the lowest was for the early involvement of construction stakeholders (mean= of 3.09). In this regard, it is apparent that other stakeholders (e.g. contractors and suppliers) are not involved early enough before the end of the design phase.

The results also show that design firms try to avoid the linear process of design and provide different iterations to improve the design aiming at satisfying the needs and requirements of the client. Nevertheless, the use of early BIM models for this purpose is still insufficient (mean=3.55). Concerning BIM as well, BIM models do not seem to be fully implemented to facilitate improving constructability in the later phases (mean=3.29). They are better used for visualization and assessment of design alternatives (mean=3.69) and for collaborative planning among the design teams (mean=3.8).

Table 3.2. Lean-BIM design management

Dimension	Item	Mean (std. dev)	Dimension means (std. dev)
Client value	Instead of one brief of requirements by the client, the early design is developed iteratively. In each iteration, the requirements of the client are evaluated and the design is refined	3.98 (1.051)	3.77 (1.010)
	BIM models are used to develop the early design to help evaluate the requirements of the client	3.55 (1.385)	
Set-based strategy	Designers consider sets of alternatives from the start of the design process rather than developing one alternative at the beginning	3.65 (1.200)	3.67 (0.927)
	BIM is used to enable rapid visual creation, communication, and assessment of project alternatives	3.69 (1.158)	
Early-involvement of stakeholders	Major project stakeholders (e.g. contractors, suppliers...) are involved early in the design process	2.90 (1.177)	3.09 (1.024)
	BIM models are used in the design phase to helping stakeholders plan and construct the building virtually	3.29 (1.275)	
Collaborative planning	BIM models for all design teams can be combined periodically for collaborative working and analysis	3.80 (1.190)	3.64 (0.930)
	The client regularly participates in meetings to support decision-making and problem-solving	3.49 (1.063)	
Overall Mean	Lean-BIM design	3.73 (0.890)	

Design performance

The analysis of the results showed that the overall performance of the design in the studied firms was neither high nor low as the mean was 3.66 out of 5.00. As shown in **Table 3.3**, the highest evaluation was for the indicators related to the client; specifically, for understanding the needs and requirements (mean=4.22) and then for achieving the client's satisfaction (mean=4.06). As the results showed, participants believed that they could also avoid future change orders (mean=4.04).

The table also shows that the lowest evaluation was for clash detection (mean=2.76), and then for engaging design teams (mean=3.00), the flexibility of decision-making (mean=3.02), and easiness of dealing with design changes (mean=3.04). The results also showed that delivering the design in compliance with the planned time and budget was not easy (means= 3.10 and 3.18 respectively).

Table 3.3. Design performance

Item	Mean (std. dev)
We are able to understand clients' needs and requirements	4.22 (0.678)
The definition of the scope of work is quick	3.18 (0.719)
Delivery of design is usually on-time	3.59 (0.855)
Design errors and reworks are minimal	3.37 (0.919)
Change orders are minimal	4.04 (0.807)
Dealing with change orders is easy	3.04 (0.807)
Clashes and are minimal	2.76 (0.980)
Disputes are minimal	3.39 (0.828)
Clients are generally satisfied	4.06 (0.652)
Decisions are taken flexibly	3.02 (0.915)
Stakeholders are engaged easily	3.00 (0.926)
Design process is delivered with the expected budget	3.10 (0.953)
Design Performance	3.41 (0.450)

To study the relationship between Lean-BIM integration and design performance, a simple linear regression analysis was conducted. The regression test (as shown in **Figure 3.9**) revealed that at a significance level of ($\alpha=0.050$), there is a positive and significant impact (P-value= 0.020) for Lean and BIM integration in the design phase on design performance. The coefficient of correlation for the relationship is ($r=0.44$) and the coefficient of determination is (R-square= 0.194). This means

that 19.4% of the change in the design performance can be explained by the change in the Lean-BIM integration.

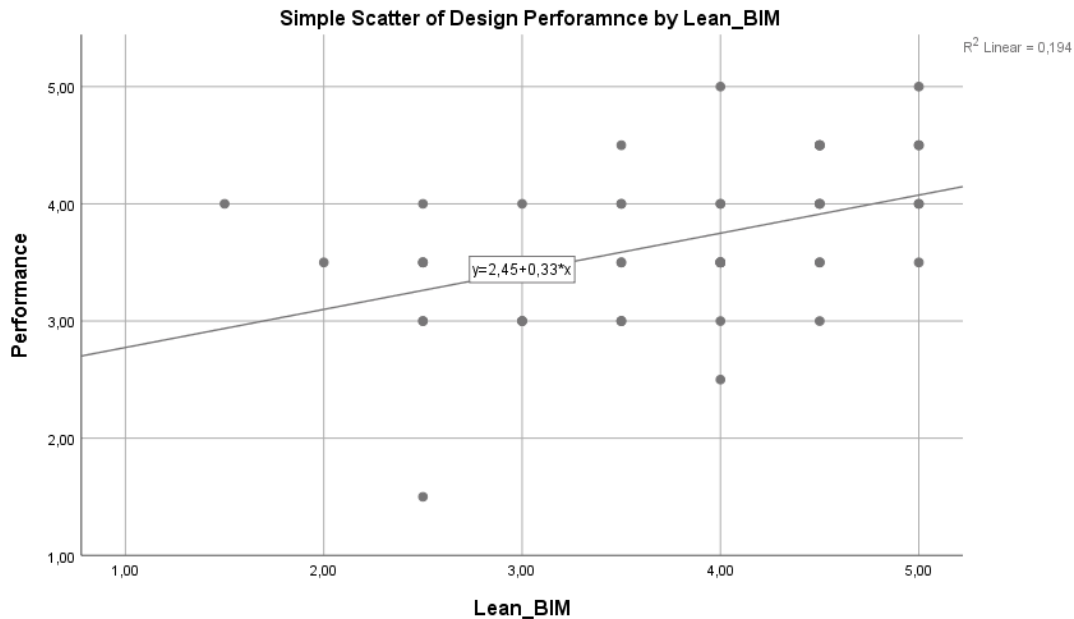


Figure 3.9. Relationship between Lean-BIM integration and design performance

3.3.3 Discussion

Despite the increasing interest in Lean and BIM in the Architecture, Engineering, and Construction (AEC) industry and the numerous efforts to study the synergies between them, the implementation of Lean principles jointly with BIM is still overlooked (Likita et al., 2022). Especially in design management (Herrera et al., 2021). In this section, the levels of Lean and BIM adoption in France and the impact of Lean-BIM integration on design performance were investigated. These objectives were achieved following the analysis of survey results filled by practitioners from different design firms in France.

The analysis of the results showed that BIM is more adopted in the studied firms in comparison to Lean. This is unsurprising, especially with the increased interest in BIM due to the recognition of

its different benefits and wide implementation around the globe to the limit that it was described as the “biggest change” that happened recently in the AEC industry (Tauriainen et al., 2016). The case for Lean is a little bit different. While Lean was labeled by some practitioners as the philosophy that can provide “revolutionary” improvements to the AEC sector, its adoption is still facing different barriers among them the lack of awareness and knowledge about it (Albalkhy et al., 2021; Albalkhy & Sweis, 2021). Additionally, for years, BIM has been a mandatory requirement in the construction sector in many countries (Bolpagni et al., 2017; Tranchant et al., 2017), which is not the case of Lean despite the different calls and initiatives to increase its adoption.

Despite the greater adoption of BIM, the results of the study showed that it has not delivered its full potential and is not regularly practiced for different purposes in French design firms. More specifically, the results showed that some companies still do not adopt BIM, and others started its adoption less than a year ago. These results are consistent with another study conducted in 2017 about BIM adoption in 206 Small and Medium-Sized companies (SMEs) from the French construction industry that showed BIM adoption was not very high despite increasing (Tranchant et al., 2017). The same study reported complicatedness in the transition toward BIM by the surveyed companies and felt that BIM would not present improvements in terms of cost and time savings for the companies. This might be an explanation for the absence of the full implementation of BIM in the studied firms in this study. Another explanation might be that BIM is not yet a mandatory practice in France.

Concerning Lean adoption, the results of the study are consistent with some claims in the literature that Lean is not fully or routinely adopted in France (Dakhli & Lafhaj, 2017). Nevertheless, due to the lack of studies about the challenges facing Lean adoption in France, it is difficult to define the

exact reasons behind this result. However, the lack of training on Lean in the vast majority of the studied firms might indicate the presence of two serious barriers to adopting Lean, which are the lack of support from top management and the lack of skills and knowledge (Albalkhy & Sweis, 2021).

Despite the lack of full implementation or adoption of Lean, the presence of some Lean tools was investigated as in some cases, these tools might be implemented without a full adoption of the philosophy of Lean. The results showed that co-location or big room and A3 problem-solving are the most adopted tools. This might show some orientation toward collaboration to find solutions for design problems and improve the design. However, the implementation of these tools is only found in around 25% of the companies and there is no evidence that these tools are implemented routinely or perfectly. The lack of Lean implementation in the design may cause losses of opportunities to improve trust, communication, collaboration, cost saving, and on-time delivery of the design (S. Khan & Tzortzopoulos, 2015).

Despite the absence of full BIM and Lean adoption, the results of the study showed some promising, but not full, results regarding the use of Lean-BIM integration in design management. This was due to the acceptable evaluation for the overall Lean-BIM integration (mean= 3.73 out of 5.00). This may show the opportunity to benefit from both concepts even if they are not fully adopted to improve the design. The results show that the client value is the most appreciated dimension while considering Lean-BIM integration. While studying the design performance, similar results were found as the highest evaluation was for client satisfaction, understanding of the client's needs and requirements, and ability to cope with the changes. This may show an achievement of one of the principles of Lean, which is the focus on the client. However, collaboration is still not enough; may be due to the used project delivery methods.

Studying the impact of Lean-BIM integration showed that the latter significantly affect design performance. This is consistent with many studies in the literature that showed that Lean and BIM together can work together to improve design deliverables, achieve higher client satisfaction, improve the quality of the design, and avoid delays (Bolpagni et al., 2017; Herrera et al., 2021; Tauriainen et al., 2016). Nevertheless, due to the small sample size in the study, this result needs to be validated in further investigations and with larger and different samples from different locations around the globe.

The small sample size is one of the limitations of this study, which hinders the full understanding of the overall evaluation of the studied variables. Future work with larger samples is recommended. Additionally, while this study uses the survey to achieve its objectives, further investigations can be conducted using other data collection methods such as interviews and case studies. Finally, while the survey included questions about the adoption of Lean tools, further investigations based on the assessment of maturity levels with these tools might be conducted.

3.4 Chapter Conclusions

The objective of this chapter was to investigate the relationship between Lean Construction and digital tools in design management. This chapter was based on two surveys in France. The used methodology in the two cases was collecting data using surveys. The first survey aimed to assess the impact of digital tools on planning for design activities, while the second aimed to study the Lean-BIM integration and its impact on design performance in a group of design offices/companies in France.

The results of the chapter can be summarized as follows:

- 1- Lean tools were found helpful to achieving timely design delivery, meeting customer expectations, enhancing design quality, and fostering improved collaboration among team members.
- 2- Digitizing Lean tools proved effective in the design phase, enhancing partner connectivity, collaboration, communication, and transparency among them.
- 3- The integration of Lean and digital tools was helpful to improve design management in uncertainty time (during the COVID-19 pandemic).
- 4- Despite implementing BIM for several purposes in design companies in France, BIM still had not delivered its full potentials. Additionally, some of the surveyed companies were still not implementing BIM or very new to it.
- 5- Only 22.54% of the surveyed companies in the second case were adopting Lean in the design phase.
- 6- Only two of the surveyed companies were providing training on Lean for their employees.
- 7- Lean-BIM integration was found to have a positive and significant impact on design performance in the design companies in France (P -value <0.050).

CHAPTER 4. LEAN CONSTRUCTION AND DIGITAL TWIN

Chapter 4. Lean Construction and Digital Twin

This chapter aims to present the integration between Lean Construction and Digital Twin in the built environment. In this chapter, the concept of digital twin and its uses in the built environment and a case about the use of digital twin and Lean integration are presented.

4.1 Review of the Concept of Digital Twin in the Built Environment

The Built environment (BE) industry is still slow to innovate and reluctant to adopt advanced technologies that may contribute to effectively reducing the long-standing risks it faces (J. Li et al., 2019). The emerging technology of digital twin (DT) has the potential to present many benefits to the BE industry by linking the virtual and the physical environment and managing the real-time data connection between them aiming at improving the data-centric decision-making processes along the whole assets life cycle (Delgado & Oyedele, 2021; Shahzad et al., 2022). As a result, the last few years have witnessed an increase in the studies about DT in BE industry (Delgado & Oyedele, 2021). Nevertheless, despite the increased interest in DT research in the BE industry, the concept itself is still ambiguous for many practitioners and researchers, and the DT research and application in this industry is still in its infancy in comparison to other industries such as automobiles, aerospace, logistics, and oil and gas where DT found its way to being effectively applied and recognized (Ammar et al., 2022; Bado et al., 2022). This is unsurprising due to the lack of knowledge and the previous experiences that happened in the BE industry with other technologies and concepts. A clear example of this can be seen when finding many pieces of evidence about the slow levels of adoption, confusion, and lack of knowledge and understanding of the Building Information Modeling (BIM) despite being developed in the BE many years ago

and being a mandatory requirement to be applied in BE projects in many countries (Gharaibeh et al., 2022; Hammoud, 2021; Olanrewaju et al., 2022).

When having increased levels of interest in an emerging concept or technology, a risk of increased confusion may appear due to the fragmentation of the presented knowledge about this concept and its application. As a result, the beneficial application of the concept is threatened due to the miss of key areas and improvement opportunities and the false understanding of its potential (Y. Xu et al., 2022). This is why there is always a need to conduct rigorous reviews to ensure the presentation of comprehensive and structured results about specific key questions about this concept.

One of the most known approaches to conducting reviews to provide knowledge about a specific topic or answer specific research questions is the systematic literature review (SLR). The use of this systematic approach ensures including only the related literature, avoiding bias in sources selection, achieving transparency that allows its repeatability by researchers, and identifying what is known and unknown about the studied topic (Albalkhy & Sweis, 2021; Moher et al., 2009; Schuldt et al., 2021a).

While the literature includes a few important studies about DT in the BE industry, most of these studies were built over other methodologies than the SLR such as general overviews or conceptual studies (Agrawal, Singh, et al., 2022; Balashova et al., 2020; Camposano et al., 2021; Correa, 2022), ordinary reviews (Akanmu et al., 2021; Bado et al., 2022; Guo & Lv, 2022; Sacks et al., 2020; Shahzad et al., 2022; Teizer et al., 2022), and other qualitative and quantitative data collection-based methods (Ammar et al., 2022; Shahzad et al., 2022; J. Zhang et al., 2022). Despite the importance of these studies and the use of different methods to get a comprehensive understanding of DT use in the BE industry, the lack of SLR studies about this topic increases the risks of having some biased results, focusing on specific applications, and missing the opportunity

to deliver all potential of DT, excluding important studies and views, and increasing ambiguity and confusions.

The current SLR studies about DT in the BE industry presented valuable information and insights about this new concept. Nevertheless, while conducting this study, it was noticed that some studies presented their results based on the review of other industries (Delgado & Oyedele, 2021), while other studies focused more on conducting bibliometric analysis for the existing literature, instead of providing clear information about the current applications, future directions, and applicability of DT in the different phases of the asset's life cycle (Almatared et al., 2022; Y. H. Liu et al., 2021; Ozturk, 2021). Additionally, some studies were specifically conducted to differentiate between BIM and DT and built over the discussion of understanding DT based on BIM applications rather than investigating the potential of DT itself (Alshammari et al., 2021; Boje et al., 2020; Deng et al., 2021; Feng et al., 2021). Moreover, the focus of other studies was on the relationship between DT and specific areas of application such as the integration between DT and modular and off-site construction (Xie & Pan, 2020), safety (Hou, Wu, et al., 2020), construction management practices (T. Salem & Dragomir, 2022), construction and maintenance of building geometry (Gan et al., 2023), and operation and maintenance (OM) operations (Delgado & Oyedele, 2021).

This section aims to provide a comprehensive literature review using the SLR approach about the applications of DT, the challenges facing DT adoption, and the future directions for DT in the different phases of the assets in the built environment. Accordingly, the current study tries to present a summary for researchers and practitioners about the current progress in the DT applications in the BE industry. To avoid confusion, it is worth mentioning that the digital twin in this study refers to the whole digital twinning system not only the digital components of the system.

4.1.1 Research methodology

This review adopts the SLR approach to answer its three main questions, which are:

1. How DT can be defined in the built environment?
2. What are the potential and current applications of DT in the BE industry?
3. How DT can facilitate decision-making in the BE industry?

The SLR value and ability to assess its quality significantly rely on reporting what has been done and the clarity of the reporting process. Accordingly, this study adopts the “Preferred Reporting Items for Systematic Reviews and Meta-Analyses” (PRISMA) guidelines to conduct the review (Moher et al., 2009). Based on the PRISMA guidelines, SLR has mainly three main phases, which are the identification, screening, and eligibility to decide what should be included in the review process. As shown in **Figure 6.2**, in the identification phase, the search was conducted on the two largest scientific research databases Web of Science (WoS) and Scopus using the following terms:

("digital twin" OR "digital twins" OR "virtual twin" OR "virtual twins" OR "digital twinning" OR "virtual twinning") AND ("construction" OR building OR "built environment" OR "construction management" OR "construction industry" OR architecture OR Engineering OR Operation OR "Operation and maintenance" OR "facility management" OR "asset management" OR "AEC industry" OR AECO OR AECOFM).

The search covered only scientific articles, conference papers, and reviews that were written in English. The search resulted in 1247 studies; among them, 63 were duplicated and removed. In the screening phase, the search was for the studies that included the defined search terms in the title, abstract, or study list of keywords. This is to ensure the use of studies that are directly related to the studied topic. In this phase, all studies that are irrelevant to the DT in the BE industry were

excluded. Examples of the excluded studies are the ones that include “construction”, “building”, or “architecture” to describe how to build DT for other fields rather than being related to the BE industry. Following that, a full-text search was conducted. In this step, the studies that are not directly related to DT were excluded (e.g. the studies that recommended building DT as a future recommendation in the abstract). Accordingly, 228 studies were selected to be included in this study.

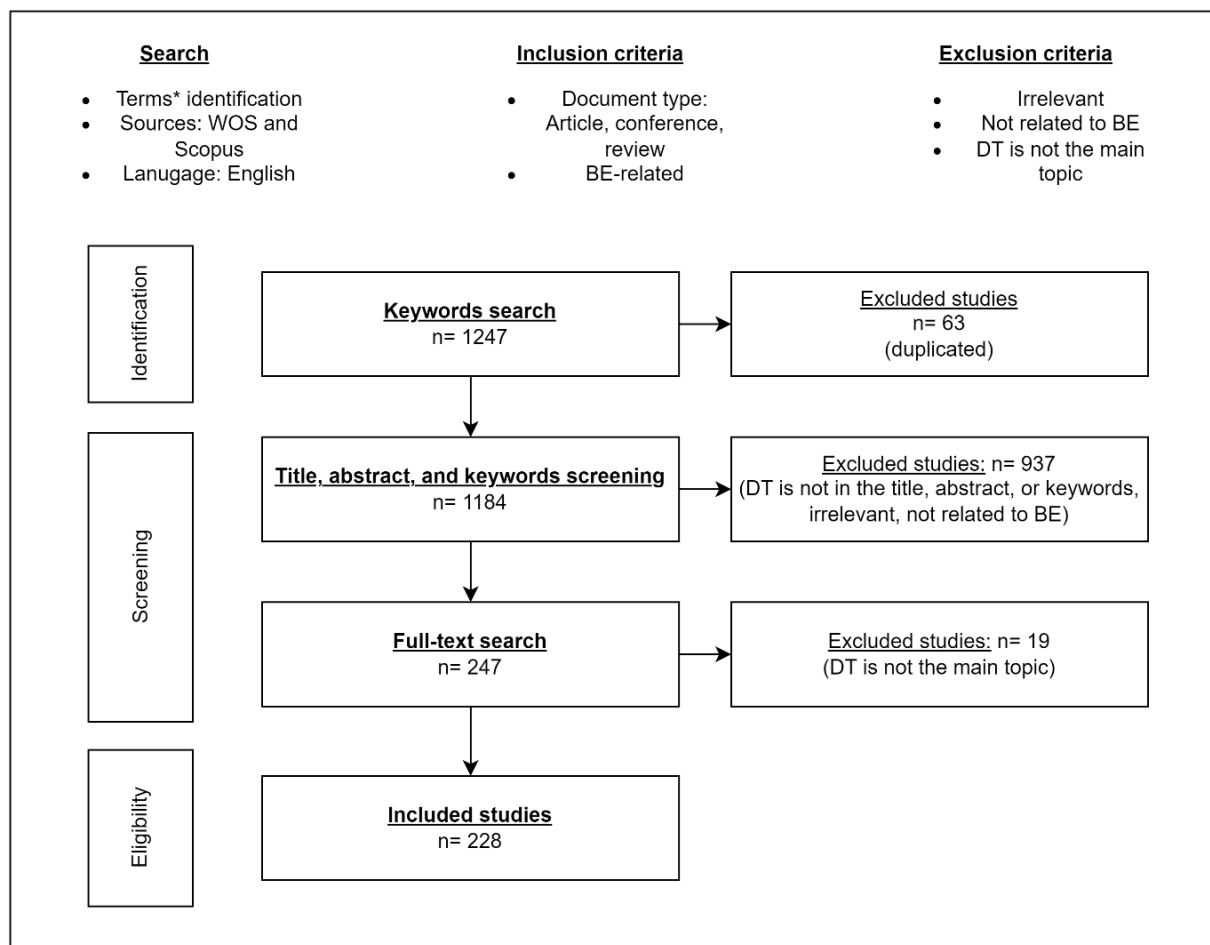


Figure 4.1. The adopted systematic review process about DT in the BE industry

4.1.2 Literature characterization and bibliometric analysis

In this review, 228 papers were studied. **Table 4.1** shows the characteristics of the found papers. As the table shows, the interest in DT in the BE industry is growing noticeably despite the late introduction in comparison to other industries (Ammar et al., 2022; Bado et al., 2022). Until the date of conducting this review (September 2023), the highest number of papers were published in 2023 (82 papers) and 2022 (78 papers). This very rapid increase in studies each year may show some signs of the awareness of DT potentials in the BE industry and confirms the need to clearly explain the meaning of DT and identify the possible challenges for its application. The increased interest in DT can also be seen in the number of papers that included case studies or examples about DT applications.

The analysis of the literature showed that Multidisciplinary Digital Publishing Institute (MDPI) (n=34 papers) and Elsevier (n=25 papers) were the most popular publishers of journal articles about the topic. “Automation in Construction”, “Buildings” and “Sustainability” were the top sources for journal articles about DT in the BE industry. For conferences, the proceedings of the “International Symposium on Automation and Robotics in Construction (ISARC)” (n= 20 papers), “IOP Conference Series: Earth and Environmental Science” (n= 4 papers), “Construction Research Congress 2022: Computer Applications, Automation, and Data Analytics” (n= 4 papers), and “Annual Conference of the International Group for Lean Construction (IGLC)” (n= 3 papers) included more than 75% of the conference papers that were reviewed in the study. The highest number of citations were for the articles: (Boje et al., 2020), (Khajavi et al., 2019), (Sacks et al., 2020), (Dembski et al., 2020), (Q. Lu et al., 2020), (Y. Pan & Zhang, 2021), (Q. C. Lu et al., 2020).

Table 4.1. The characteristics of the studies found in the literature about DT applications in the BE industry.

Characteristic	Categories	Frequency
Number of published studies per year	2018	1
	2019	6
	2020	15
	2021	46
	2022	78
	2023	82
Document Type	Journal article	172
	Conference paper	53
	Review	3
Distribution of studies based on the top sources	“ISARC”	27
	“Buildings”	17
	“Automation in Construction”	15
	“Sustainability”	13
	“Sensors”	9
	“Advances in Civil Engineering”	6
Most cited papers (source) (Google Scholar citations)	(Boje et al., 2020) (Automation in Construction)	554
	(Khajavi et al., 2019) (IEE Access)	336
	(Sacks et al., 2020) (Data-Centric Engineering)	240
	(Dembski et al., 2020) (Sustainability)	237
	(Q. Lu et al., 2020) (Journal of Management in Engineering)	235
	(Y. Pan & Zhang, 2021) (Automation in Construction)	218
	(Q. C. Lu et al., 2020) (Automation in Construction)	187

To identify patterns of publications about DT, keyword co-occurrence was conducted using VOSviewer. The latter allows the creation of a keyword network in which natural language algorithms and text mining methods are used to investigate the relationships between the most repeated keywords about the studied topic, and then cluster them accordingly (Ech & Waltman, 2014).

To do the keyword co-occurrence, four was identified as a minimum number of keyword occurrences. Then, every time two keywords were found in the title, abstract, or keywords were considered as a co-occurrence. Before conducting the co-occurrence analysis on VOSviewer, keywords with similar meanings were merged (e.g. Building information modeling, building information modelling, and BIM).

The results of the keywords co-occurrence analysis are shown in **Figure 4.2**. In detail, the analysis revealed that out of 963 keywords in the reviewed studies, 55 keywords met the threshold (i.e. 4 co-occurrences). It also showed that in addition to digital twin (179 occurrences), BIM (86 occurrences), IoT (26 occurrences), “design” (22 occurrences), “management” (21 occurrences), and “system”, “construction”, and “model” (20 occurrences) were the most repeated keywords in the literature.

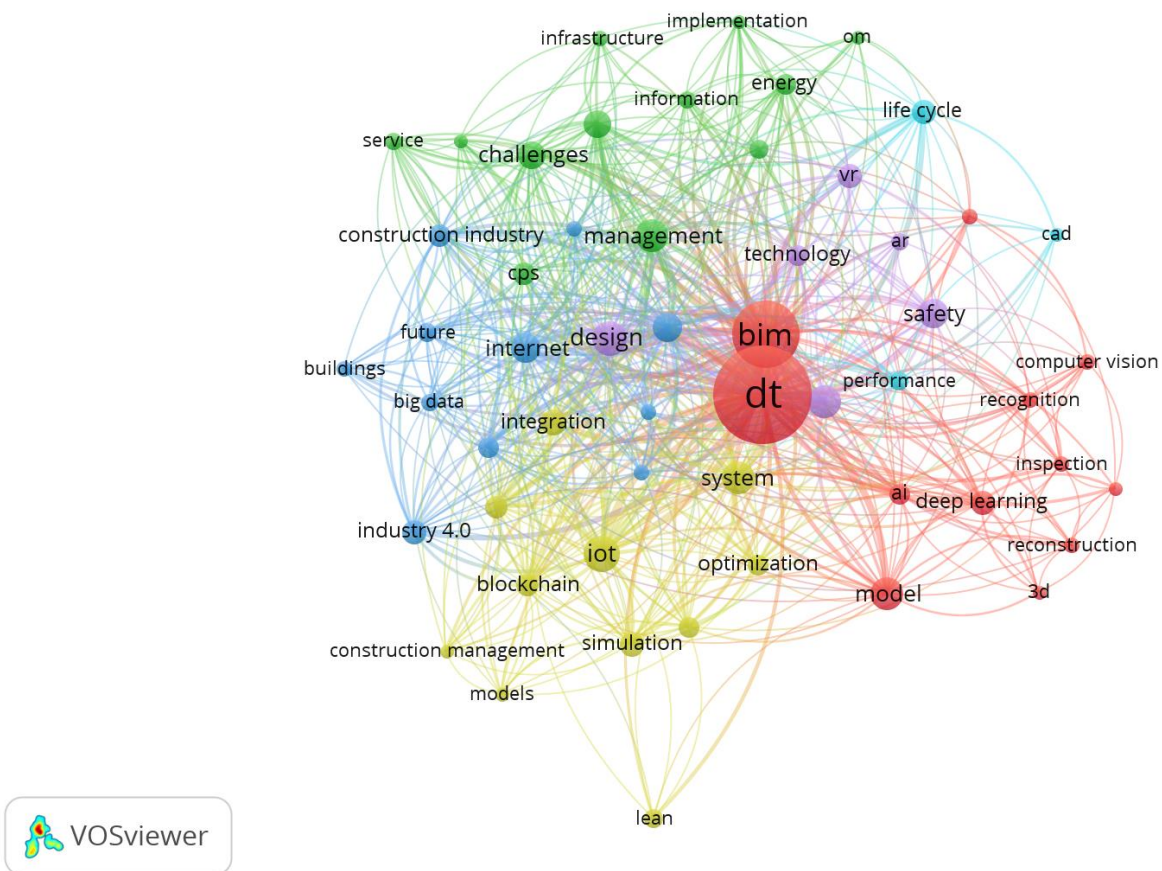


Figure 4.2. Keywords co-occurrence analysis

The analysis also showed that the 55 keywords can be gathered in six clusters with 1677 links. The first cluster (in red) is related to information modeling and data analysis as it has some keywords such as “DT”, “BIM”, “3D”, “Model”, “Computer vision”, “Artificial Intelligence (AI)”, and “deep learning”. The second cluster (in green) is related to the post-occupancy phase as it includes some

keywords such as “Facility Management (FM)”, “Operation and Maintenance (OM)”, “energy”, “services”, and “sustainability”. The third cluster (in blue) includes general areas of applications such as “buildings”, “built environment”, “smart buildings”, “construction industry”, “industry 4.0”, and “circular economy”. The fourth cluster (in yellow) includes data integration and construction management-related keywords such as “Lean”, “modular construction”, “blockchain”, “IoT”, and “simulation”. The fifth cluster (in purple) includes safety and reality capture technologies such as “Augmented Reality (AR)”, “Virtual Reality (VR)”, and “safety”. The sixth cluster (in light blue) includes three keywords “Computer-aided design (CAD)”, “lifecycle”, and “performance”.

4.1.3 Results

Digital Twin Definition

Several authors and researchers have presented definitions for the concept of DT in the built environment industry and other industries. However, there is no consensus on one definition. The list of DT definitions that were found in the literature and industry is presented in **Annex 3**.

The analysis of the definitions shows that DT systems were mostly understood based on the two main components of the system; the physical and digital twins and the bidirectional flow of data between them. However, this understanding seems to be insufficient to describe the DT systems as it ignores the potentials of these systems along the whole life cycle of the projects (Ammar et al., 2022).

In turn, considering the list of provided definitions, it can be concluded that the DT system can be understood based on its components, uses, ways of considering the data and data flow, and levels. More specifically, while looking at the table of definitions in **Annex 3**, it can be found that all proposed definitions agree that the DT is a virtual representation of the physical twin. The latter

can be a product, system, building, city, chain, process...etc. Additionally, most definitions agreed on the data exchange and synchronization to share information and feedback as a real need to build a DT system. This data flow and analytics system can be built using a set of possible tools including AI, IoT, machine learning, simulation models, sensors, building automation systems (BAS), and others. Another agreed point between these definitions is building an effective decision-making support system that is based on continuously updating and adapting the DT based on the changes in the physical twin. In terms of the uses of DT, the found definitions identified simulation, prediction, optimization, monitoring, control, and supporting autonomous activities as the main purposes of creating a DT system. Finally, DT can be built for different purposes, on different maturity levels, and along the different phases of the life cycle of the project or product. According to Madni et al (2019), DT maturity levels can range on five levels. The first level is building a conventional prototype to support early decision-making in the conception phase. The second level covers the incorporation of historical data, maintenance data, and operational performance coming from the physical counterpart. The third level introduces the concept of an adaptive DT with an adaptive user interface. This type of DT learns the priorities and preferences of the operator in different contexts and continuously updates itself in real time based on information received from the physical component. The fourth level encompasses all functionalities of the third level in addition to the self-learning possibility without supervision. The fifth level is when the DT becomes receptive to data from external sources is and able to analyze this data within a situational context. Similarly, Ammar et al (2022) and Sacks et al (2020) differentiate between the digital twins for different phases along the project (design, construction, and operation) and different types of projects (future, existing, and ongoing projects). In these two views, Ammar et al (2022) and Sacks et al (2020) affirmed that building a digital twin for future projects is based on a one-directional

flow of data using historical data that feed the digital models, while for existing projects, the flow of data (e.g. geometric, specifications, drawings, schedule, and financial reports) is bidirectional.

Based on the above discussion, this study proposed the following definition for DT in the BE industry:

“A digital twin is a living virtual replica of a physical twin such as a product, asset, component, process, or system. Supported by technologies such as AI, machine learning, sensors, and IoT, a flow of data between the digital and physical twins is made to ensure that digital twins are continuously updated and adapted to the changes in the physical twins. Which allows sharing insights, supporting decision-making, and enabling simulation, prediction, monitoring, control, and performance optimization of the physical twin throughout its lifecycle. Digital twins can range from simple prototypes to sophisticated models with self-learning and adapting capabilities, depending on their level of complexity”

Structure of the Digital Twin Systems

In many studies in the literature, the DT system structure was presented based on three main components (i.e. the digital twin, the physical twin, and the data between them) without providing details about these components. Other studies have different ways to address the components of the DT systems. For instance, Ogunseiju et al (2021) presented a digital twin-driven framework for improving the self-management of ergonomic risks based on six tiers, which are 1) sensing tier includes wearable sensors, vision-based sensors, and physiological sensors, 2) data tier coming from temperature records, construction workers, and construction work and resources, 3) communication tier, which includes internet, Wi-Fi, and Bluetooth, 4) storage tier, 5) computation tier, which includes AI and posture evaluation techniques, 6) and action tier which extends the applications of the system throughout the user interface, AR, and unity game engine. In turn, Boje

et al (2020) presented a structure of the DT system in construction based on four layers, which are 1) physical twin that includes the physical component (human resources, tools and vehicles, material resources, and site), 2) construction digital twin, which includes physical construction data (lifecycle, site monitoring, and site sensing data) and virtual construction data (optimization, prediction, simulation, and building model data), and 3) services, which includes real-time services and optimization services. Lu et al (2020) developed a DT model based on four main layers: 1) data acquisition layer, 2) data transmission layer, 3) data/model integration layer, and 4) application layer. Other ways to structure DT models were:

- Physical layer, virtual construction model, data processing, and functional application (Z. S. Liu et al., 2021; Z. S. Liu, Shi, et al., 2022)
- Physical layer, information layer, and system layer (Y. R. Wang et al., 2022)
- Perception layer, network layer, services layer, and application layer (Z. Liu et al., 2020)
- Sensors layer, database layer, application layer, and presentation layer (Lin & Cheung, 2020)
- Physical space, digital space, user interface and application, and users (Delgado & Oyedele, 2021; Hallaji et al., 2021)
- Physical layer, digital layer, services layer, and users layer (F. Jiang et al., 2022; Y. S. Jiang et al., 2021, 2022)

Based on that, this study proposes the structure that is shown in **Figure 4.3** to build a DT model in construction. The proposed structure is based on four main layers:

- 1- Physical layer: this layer includes the physical component or the physical twin and the data acquisition and communication tools. The physical component can be a building, city, system, process, resources (i.e. humans, materials, machines, and tools and equipment), or

a chain. These components are equipped with different tools to provide different types of data such as data coming from sensors and actuators, images, videos, and 3D scanners. In addition to data coming from historical records, social data (e.g. data coming from social media), public data, and data coming from management systems (reports, schedules, invoices...etc.). The gathered data can be transferred to the digital layer via different ways such as communication protocols, the internet, 4G, Bluetooth, or even entered manually.

- 2- Digital Layer: which includes data integration and modeling tools and data management and analytics approaches and system. In this layer, the virtual model can be built by integrating the gathered data from the physical layer and then processed and analyzed to support visualization, tracking, prediction, and control activities.

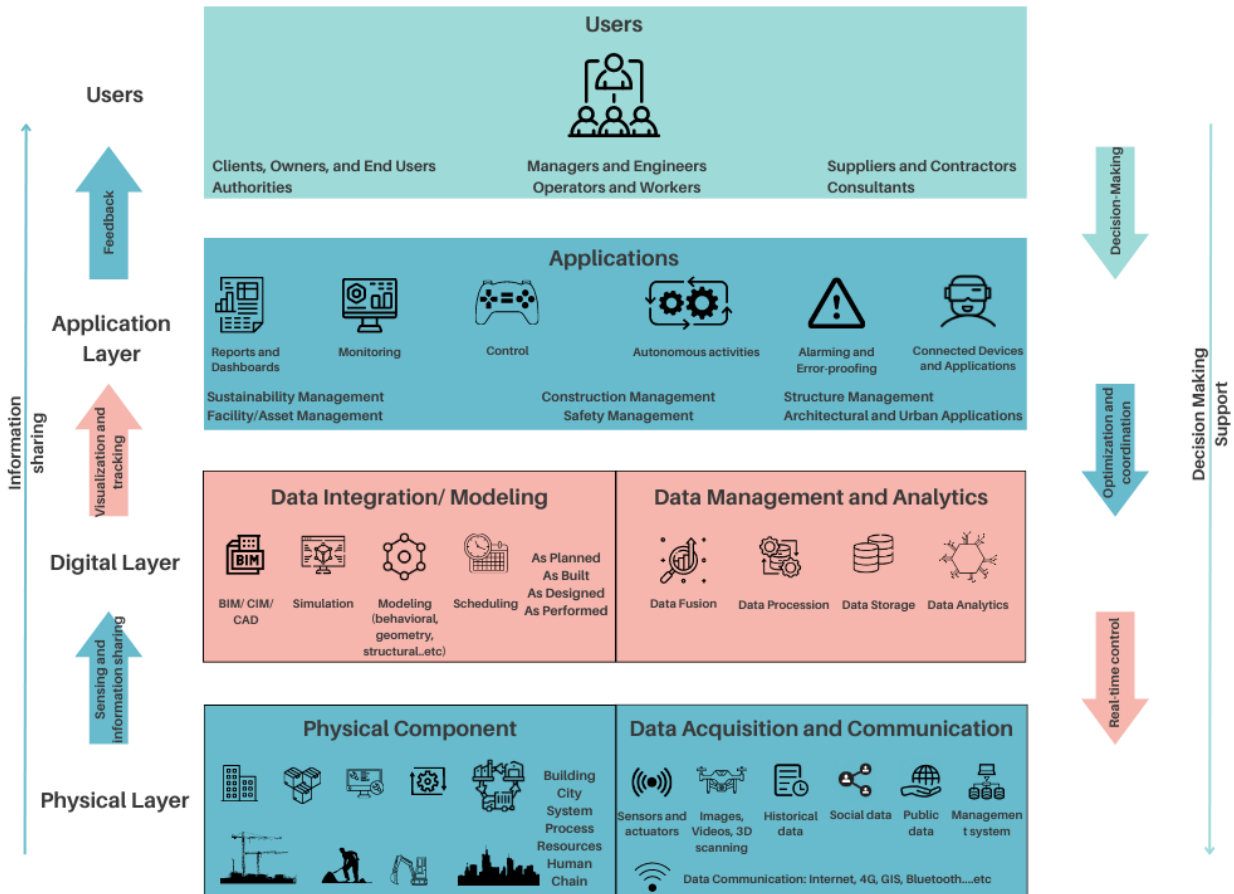


Figure 4.3. The structure of the DT system in the BE industry.

- 3- Application layer: in which users can benefit from the development of the two previous layers to achieve the objectives of the developed system for different purposes. As will explained in the next section, the analysis of the literature showed that DT has been used from DT models in different ways such as sustainability management, facility management, modular, Lean, and offsite practices, construction management, safety management, structural management, and architectural and urban applications. In this layer, user interfaces can help improve visualization of performance progress, monitoring, control, automation, and alarming. In addition, the application of DT can be extended to other devices such as VR and AR.

- 4- The final layer includes the users: who can be clients, owners, end-users, authorities, managers, engineers, operators, workers, suppliers, contractors and subcontractors, consultants, or any other type of users who can benefit from the DT system.

As shown in **Figure 4.3**, the relationships between the layers are based on information sharing (bottom-up) and decision-making support (top-down).

Digital Twin Applications in the Built Environment Industry

The analysis of the found studied showed that DT systems were used for several purposes in the literature. The applications of DT can be classified into six main categories, as shown below:

Sustainability and environmental performance-related applications

The use of DT systems to improve sustainable and environmental performance was found in different studies throughout the project lifecycle. For instance, Lydon et al (2019) a DT-based thermal design for lightweight roof structure whose structure was optimized to allow supplying the studied area with a renewable geothermal source. The study covered the whole building simulation in the design and operation phases using data about the structure and architectural design of the roof, energy sources, and online weather predictions. In turn, Liu et al (2021) proposed a DT system to improve eco design and decrease operational cost in green buildings. Zhao et al (L. Zhao et al., 2022) developed a DT system based on the integration of BIM, computational fluid dynamics models to simulate the diffusion of pollutants, and building energy consumption simulation to improve environmental and health performance in public toilets. The developed model showed ability to improve the design of the ventilation system of the toilets and decrease energy consumption and CO₂ emissions. In the construction phase, Meza et al (2021) developed a DT system based on the use of data coming from a network of sensors and BIM models to integrate

secondary raw materials in road construction. Chen and Huang (Chen & Huang, 2020) proposed an application to use DT to improve construction waste remanufacturing.

Most of the sustainable applications of DT were in the operational phase. Examples of these application included the use of DT to evaluate energy in zero-energy buildings using scan-to-BIM models (L. Zhao et al., 2021), implementation of WSN-BIM integration to improve safety and environmental monitoring and control management (gas leaks, humidity, and temperature) in underground garages (Lin & Cheung, 2020), and integration of user's behavior tracking and BIM models to assess indoor comfort, energy consumption, and air quality in educational buildings (Tagliabue et al., 2021). In addition to applying DT model to improve city environmental performance via some practices such as city energy mapping and modelling (HosseiniHaghighi et al., 2022; HosseiniHaghighi et al., 2022).

Facility and asset management-related applications

In addition to the environmental-related practices, the literature has various examples that cover the applicability of DT models for facility management purposes. The applications covered different types of buildings. For instance, Ni et al (2022, 2021) presented two studies about the use of DT to manage historical buildings in Sweden. The first study used sensors, historical data, and machine learning algorithms to improve energy efficiency, building conservation, and human comfort in three historical buildings in Sweden (Ni et al., 2021). The second study presented an IoT-based DT that was developed to improve preventive conservation of a theater in Norrköping in Sweden. Lu et al (2020) presented a developed DT to enable anomaly detection in a heating, ventilation, and air-cooling (HVAC) in an educational building in Cambridge. Wang et (2020) al proposed a DT system to improve green building maintenance and automatic management using

Bentley Systems software that was developed using 3D laser scanning and sensors attached to monitor equipment, energy consumption, temperature, security, humidity, air, and water.

DT systems were also used to manage infrastructures. Examples of the applications in this area covered geometry of bridges and railways (Ariyachandra & Brilakis, 2020; R. D. Lu & Brilakis, 2019), inspection of bridges using robots and AI (Yamasaki, 2020), and predictive maintenance of bridges (Agrawal, Fischer, et al., 2022; Shim et al., 2019), water treatment plants (Hallaji et al., 2021), and urban underground infrastructures (M. Wang & Yin, 2022).

Safety, health, and risk management-related applications

DT can play a significant role in improving safety conditions and preventing risks in buildings, cities and on construction sites. This is due to its ability to control actions and provide right-time information to all stakeholders and decision-makers (Teisserenc & Sepasgozar, 2021; Teizer et al., 2022). According to Teizer et al (2022), DT has the potential to enhance safety management in the construction industry through three primary methods: promoting safe design and planning to prevent hazards, proactively predicting and warning about risks through monitoring and control, and facilitating continuous performance improvement for personalized or project-focused learning. Similarly, in their SLR, Hou et al (2020) affirmed that due to the utilization of sensor technology and virtual simulation and visualization technology in DT allows identifying unsafe construction environment in a timely manner, positioning individuals on site, monitoring workers' behavior, improving planning for safety, visualize construction activities, and train workers for safety.

Accordingly, many DT systems were built to achieve safer construction environment. Among these system, Kamari and Ham (2022), proposed a vision-based DT system to improve hurricane preparedness on site. The system was based on collecting visual data and using deep learning and 3D models to twin the wind-borne debris, estimate their quantities, and assess potential hazards

from debris. Messi et al (2020) proposed a system that is using IoT and 3D serious game engine to detect hazards in accessible, unprotected, and risks workspaces at height on site. Ogunseiju et al proposed a DT model to allow workers understand and enhance the self-management the self-management of ergonomic exposures. The model was based on connecting data from wearable sensors to an AR replica. Shariatfar et al (2022) integrated 4D BIM models, data from sensors, AI models, and cloud computing database to visualize potential hazards, potential affected body parts, and nature of events during the different activities on site such as scaffolding, excavation, and welding. In addition to different other models to predict, analyze, and mitigate risks while using heavy machines such as cranes and drilling rigs (Agrawal, Fischer, et al., 2022; Lai et al., 2022; Z. S. Liu, Li, et al., 2022; Z. S. Liu, Meng, et al., 2022; Riquer et al., 2022).

In buildings and cities, researchers have shown many potentials for DT to improve resilience improvement of buildings (Alibrandi, 2022), social sensing during disasters using textual, visual, and geo data coming from social media platforms (Fan et al., 2020), and monitoring and control of indoor safety and health conditions (Lin & Cheung, 2020; Z. Liu et al., 2020; L. Zhao et al., 2022).

Structural performance-related applications

Researchers have built various DT systems to analyze and predict performance of assets and building components along the various phases of projects' lifecycle. Examples of the built DT systems is the one developed by Posada et al (2022) to monitor concrete maturity and evaluate its mechanical properties during the construction phase using temperature sensors, a mobile application connected to the sensor via Bluetooth, BIM geometry model, and a Finite Element Analysis (FEA). Another example in the operation phase was presented by Liu et al (2021) who system to integrated geometric data, data coming from sensing equipment about materials parameters, connection parameters, and behavioral models to detect and prepare unsafe structural

events in a prestressed steel structure. In turn, Kaewunruen et al (Kaewunruen et al., 2021) and Ramonell & Chacón (Ramonell & Chacón, 2022) proposed two DT-based approaches to test loads on bridges.

The work in this area has also covered developing DT systems to support renovation works of historical buildings by assessing their structural performance and detecting structural damages in this type of buildings (Angjeliu et al., 2020; Bruno et al., 2020; Funari et al., 2021; Moyano et al., 2022). In addition to evaluating building structure after earthquakes using Unmanned Automated Vehicles and BIM-based DT (Levine & Spencer, 2022) and understanding root causes for collapsing at the end of life of the building using BIM and FEA-based DT (Z. Zheng et al., 2022).

Construction management-related applications

The found studies about the use of DT in construction management practices ranged to include several practices such supply chain management-related practices, stakeholder's integration and resources allocation, site preparation, monitoring. Using results from interviews with industrial practitioners, Ammar et al (2022) classified 40 DT capabilities in construction into seven themes; 1) increased transparency of information, 2) real-time monitoring, analysis, and feedback, 3) better stakeholder collaboration, 4) advanced preventive measures, 5) advanced what-if scenario analysis and simulations, 6) real-time tracking, 7) high accuracy.

One of the applications in the early phases of construction was proposed by Shi and Wang (2022) in their study about building DT system for subsurface geological models. In their study, limited site-specific boreholes and images were integrated in a 3D geological model that was built using deep learning method to get prior geological knowledge about the construction site.

With regards to supply chain management. Greif et al (2020) developed a DT supply chain model that integrates data from silos, trucks, and materials orders to visualize and predict logistics routes. In turn, Sun and Liu (2022) used an AI-based visualization for BIM model to manage logistics on construction site. The proposed model was able to identify of shortages in materials, analyze requirements, and support dispatching and decision-making processes. Liu et al (2022) summarized the use of the Dijkstra algorithm, RFID, and other IoT technologies in a DT model for planning material-allocation path in a project in Beijing Winter Olympics 2022.

Deria et al (2022) proposed an audio-based DT model that integrates data from sensors into a deep learning model to autonomously optimize work cycle and manage resources allocation in road construction projects. Kim et al (2021) integrated a queuing model as a decision-making model in BIM to develop a 4D digital twin system for subcontractors allocation in apartment buildings. Saini et al (2022) built a multi-DT system to support decision-making during well construction processes. Their study was based on building DTs for borehole cleaning operations to prevent pipe's stuck, and then creating DTs to support operational planning and logistics management.

Other studies in the field of construction management included building DT systems to monitor and control machinery onsite using 4D BIM and AR (Hasan et al., 2022), improve human-robot interaction and communication (Kaiser et al., 2021; Kramberger et al., 2022; D. Lee et al., 2021; C J Liang et al., 2020; Ravi et al., 2021; X. Wang et al., 2021), detect small objects (Y. D. Pan et al., 2022), track and monitor work and worker (Huang et al., 2021; Y. Pan & Zhang, 2021), and support modular and offsite construction processes (Barkokebas et al., 2022; Chatzimichailidou & Ma, 2022; Dong et al., 2021; Y. S. Jiang et al., 2021, 2022; Tran et al., 2021; Wei et al., 2022; Xie & Pan, 2020; Y. H. Zhao et al., 2022; Y. Zhou et al., 2021).

Concerning the integration with Lean, Abou-Ibrahim et al (2022) proposed a process to capture BIM model dynamics and identifying how design BIM models change based on three KPIs; average movement of elements, number of elements clashing, and average movement due to clashes. Nevertheless, despite the different calls to integrate Lean and DT, not enough cases were found about the integration of Lean and DT (Alsakka et al., 2022; Gan et al., 2023; Sacks et al., 2020).

Architectural and urban applications

Various applications can be found when investigating the applicability of DT in architectural and urban practices. For instance, at the level of buildings and in the design phase, Kalantari et al (2022) presented a toolset to mirror adjustment by users on a physical prototype to be mirrored and analyzed on a DT. While for a city, various systems were used to map energy (Hosseinihaghighi et al., 2022; HosseiniHaghighi et al., 2022), design for future planning (Dembski et al., 2020; F. Jiang et al., 2022; Kikuchi et al., 2022), select sites for facilities (K. Zhang et al., 2022), manage traffic and inspection activities (Songchun Wang et al., 2021; Z. H. Wu et al., 2022), or model a city (Q. Lu et al., 2020; Schrotter & Hurzeler, 2020; Visconti et al., 2021).

Decision-Making in the Found Studies in the DT Studies

According to Agrawal et al (2022), the taxonomy of Gartner (2013) to analyze analytical capabilities for digitalization frameworks can be considered one of the most effective ways to analyze how DT can support decision-making in the BE industry. Their developed model to understand decision-making capabilities of DT systems is shown in **Figure 4.4**. Based on this model, it can be understood that DT systems can support decision-making in four ways, which are 1) description: when DT helps to describe what is happening in the physical environment and humans can use this information to make the suitable decision. 2) Diagnostic: when DT helps to

provide information about the root causes of what is happening. 3) Predictive: when DT has predictive capabilities to identify what impact or events may arise in the future. 4) Prescriptive: when DT can decide actions based on predetermined objectives.

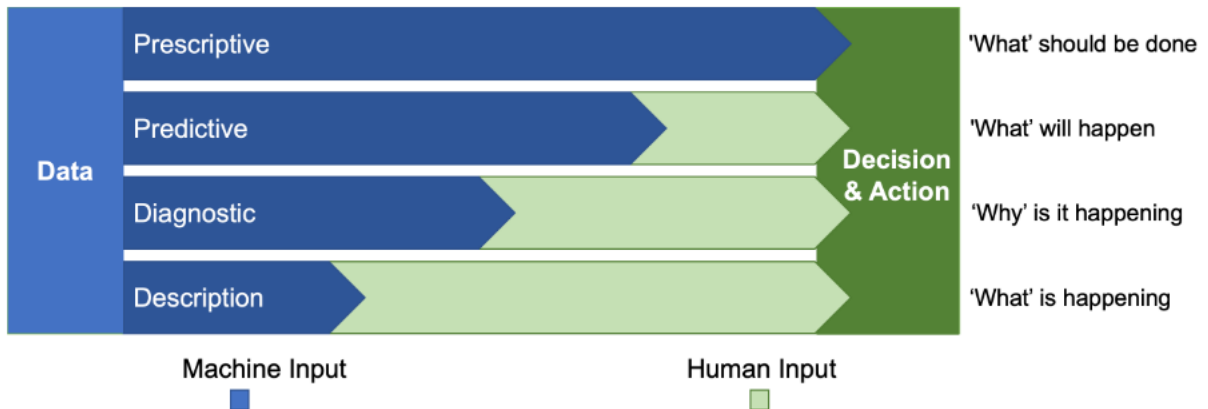


Figure 4.4. levels of analytical capabilities of DT systems (Agrawal, Fischer, et al., 2022)

In this study, the above-mentioned model was used to identify how DT was used in the literature to support decision-making process in the BE industry. **Figure 4.5** shows the analysis of the found case studies in the reviewed literature. The Figure shows that most of 39% of the cases reached the level of “Predictive” model. Which means that the developed DT systems in these studies were able to support the decision-making process to deliver what will happen. In turn, only 13% of the cases showed capabilities to present full autonomous DT systems, in which, decision-making can be fully supported to reach the level of what should happen. The figure also shows that the highest number of cases were for descriptive systems and the lowest was for diagnostic systems to explain the root causes of what is happening.

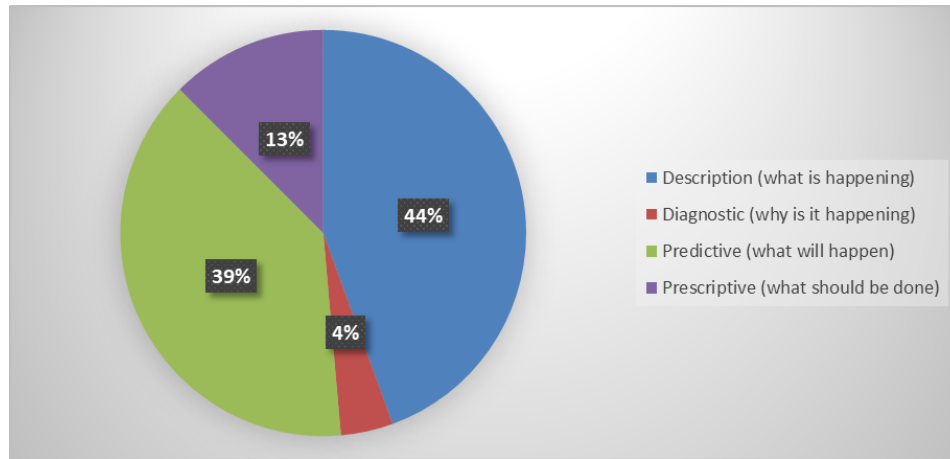


Figure 4.5. Analytical capabilities of DT systems in the reviewed literature

4.1.4 Discussion

DT is considered one of the emerging technologies these days. Reviewing 146 studies about DT in the built environment industry shows that DT can be applied in numerous ways in this industry. Its application can be helpful to revolutionize the industry by providing solutions to improve sustainable and environmental practices in built facilities, effectively and efficiently manage these facilities, enhance safety practices in the whole industry, support structural and architectural practices, and improve the way of constructing the built environment.

Nevertheless, the industry has still not benefited yet from the potentials of DT and its application. This might be due several reasons related to the lack of financial capabilities, lack of skills, resistance to change, reluctance to invest in innovation, contractual difficulties, difficulties with data and data management, and the insufficient knowledge of the concept of DT and its potentials (Agrawal, Fischer, et al., 2022; Ammar et al., 2022; Araújo et al., 2022; Feng et al., 2021; T. Salem & Dragomir, 2022; Shahzad et al., 2022; Xie & Pan, 2020). To mitigate the impact of the lack of knowledge of DT and its potentials, this review presented a definition for the DT concept and its potentials.

With regards to the links between DT and Lean thinking, the results of the review showed that the integration between the two concepts was found in different calls. Nevertheless, these calls have not yet translated into applications. Therefore, the following section aims to propose a way to integrate the two concepts.

4.2 Lean and Digital Twin in Brick Manufacturing

As mentioned in **Chapter 2**, the implementation of Lean and Industry 4.0 in the studied brick factory was based on two cases; the first one was about Lean and IoT integration to improve workflow in the factory, while the second is about proposing and initiating a framework that aims to benefit from the use of digital twin technology to support Lean implementation in the factory to improve the efficiency and eliminate the wastes in the production process.

4.2.1 The proposed framework

The proposed framework is based on the use of green-digitalized VSM. VSM is one of the most known Lean tools that help to visually analyze, document, and improve production processes (Hannis Ansah et al., 2016). Using VSM provides opportunities to identify production wastes and achieve improvement in the process. VSM can be also linked with environmental metrics to identify the existing problems that affect environmental performance (Nguyen & Sharmak, 2022). Normally, VSM is applied on levels; starting with the current VSM, which shows the current situation and the existing bottlenecks and wastes in the process, then the future VSM, which aims to integrate changes in the process to provide improvements and waste elimination, and then, the frequent (normally yearly) VSM that aims to evaluate the progress based on the recommendations of the future VSM. Nevertheless, many SMEs face difficulties in VSM implementation. These difficulties are a result of the reluctance to continuously invest in VSM as a static tool that requires continuous updates (Y. Lu et al., 2021). Therefore, the proposed framework aims to benefit from the advancement of DT and IoT to improve the implementation of VSM.

The selection of DT and IoT was firstly due to their ability to deliver real-time information and connectivity that help achieve continuous monitoring and rapid decision-making to make improvements and optimizations in energy consumption, materials management, process

management, and safety (Dardouri et al., 2022; Y. Lu et al., 2021). The second reason was due to the flexibility of DT systems that can facilitate the application of Lean thinking due to the ability to monitor the flow, eliminate waste, and provide visual and real-time access to the management and teams to ensure the continuous improvement and error proofing in the process (Barkokebas et al., 2022; Y. Lu et al., 2021). The third reason was due to the business need of the studied company to deploy DT; similar to what was described by Agrawal et al (2022) as the implementation of DT as a “need pull”.

As shown in **Figure 4.6**, the proposed framework is based on two main phases:

The first phase covers the identification of bottlenecks and wastes in the process. This is based on the use of different data collection methods such as interviews with workers or management staff, surveys, or observations, in addition to the possibility of the use of different types of sensors to collect data about workflow, temperature, humidity, and others. In this phase the current production process can be translated into current VSM using different measures such as cycle time (C/T), change over time (C/O), machine time (M/T), processing time (P/T), and others. Benefiting from the IoT measures like energy consumption and CO₂ emissions are also possible to be integrated into the VSM. The first phase results in building the virtual model using simulation or software.

Building the virtual model helps to create a flow of data from the physical model (the production process) to the virtual model. The latter is responsible for processing the data to produce useful information to improve production control and automate decision-making (Agrawal, Fischer, et al., 2022). By making this connection between the physical and virtual models, frequent testing and integration for scenarios and improvements are possible. It is worth mentioning that the second phase is not implemented once. It is continuously implemented aiming at achieving the principle of continuous improvement.

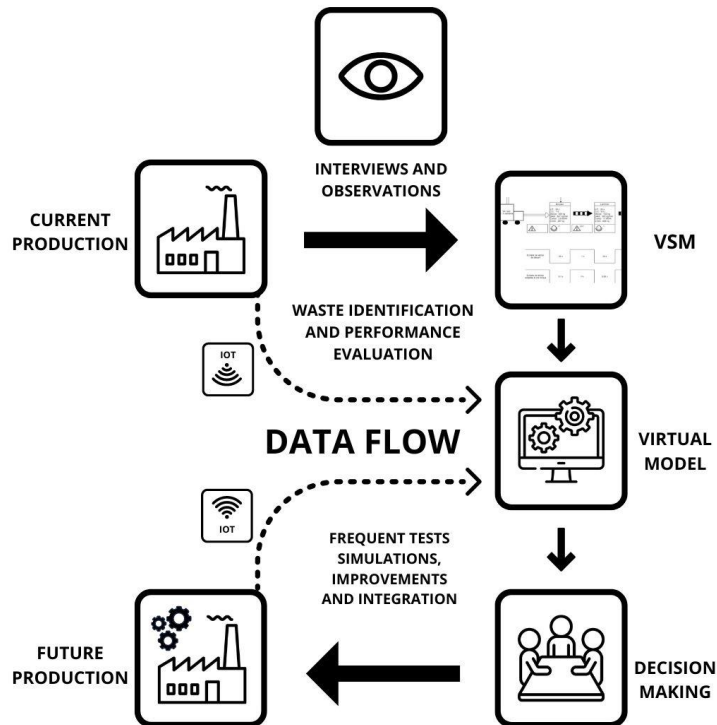
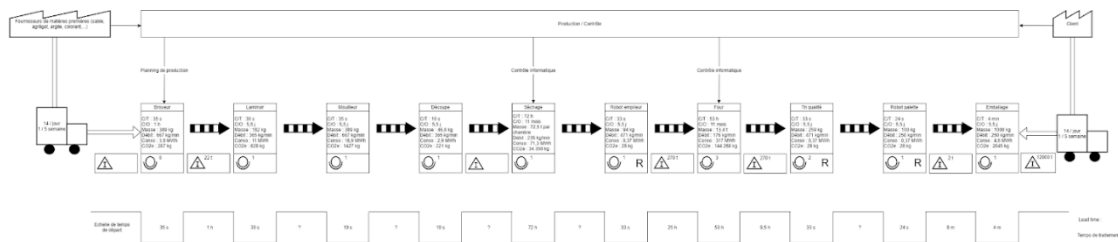


Figure 4.6. The proposed DT-based VSM framework

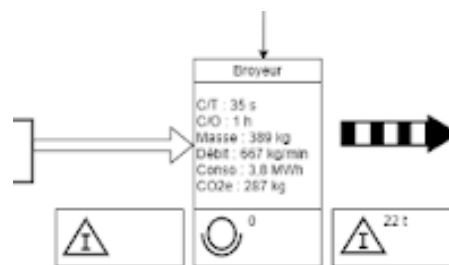
4.2.2 Current VSM and encountered bottlenecks

Based on observations and interviews with workers and management staff, the current VSM was developed (as shown in **Figure 4.7**). Based on the VSM, the total time of non-value-adding activities is 35.5 hours, constituting around 28.4% of the total time in the production process (starting with the arrival of the raw materials and ending with arrival to the storage area). Nevertheless, the efficiency is not optimal as the time spent in the kiln (72 hours) was considered a value-adding activity. This means that neglecting the time needed in the kiln, the percentage of waste in time can reach 67% of the overall process time. In addition to the visualization of the production process and identification of the wasted time, the use of VSM was also helpful to identify the current flow rates, consumed energy, and CO₂ emissions in each machine in the

process (as shown in **Figure 4.8**). This helped to identify the bottlenecks and problems in the process, which can be summarized in:



(a)

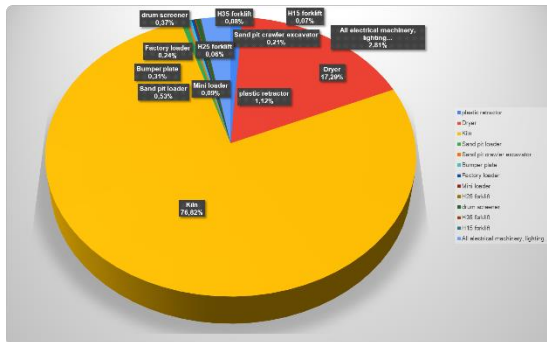


(b)

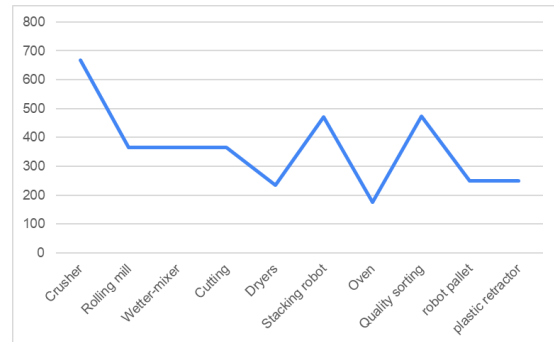
Figure 4.7. Current VSM: (a) full VSM, (b) used metrics.

- High levels of energy consumption and CO₂ emissions in the kiln (the kiln is responsible for more than 75% of CO₂ emissions and more than 70% of energy consumption).
- High levels of defects in different places along the process including for instance defects resulting from bricks falling after getting out from the kiln due to wrong positioning and bricks due to instability of the old wagons.
- Stoppages in the production line due to some reasons such as fallen bricks in the wagon path, problems in machines, and stoppages due to the cutting machine. The latter is responsible for a lot of stoppages (5-6 times per day) due to frequent failures in the cutting wires, which require their replacement.

- Levels work-in-progress (WIP), which affects the freedom of movement and creates problems in brick storage.



CO2 emissions per machine



The flow rate in each machine (Kg/min)

Figure 4.8. Performance measures in the process

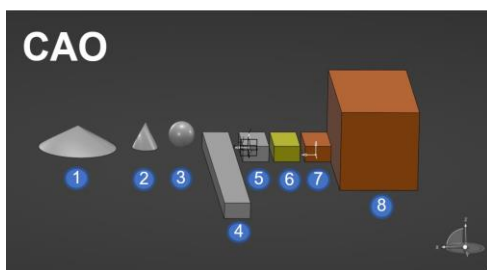
Accordingly, the proposed solutions include:

- Continuity of the process monitoring to identify the reasons for the wastes in the production process.
- Apply Lean principles and tools such as pull, Just-In-Time (JIT), 5S, and supermarket to eliminate wastes and reduce levels of WIP.
- Use of IoT to provide alerts when stoppages in the production line happen.
- Conduct numerical simulations and study the different placement of the bricks in the kiln (so that the heat reaches the brick in the middle of the bottom car faster) which will reduce the firing temperature and the firing time. As a result, trying to improve efficiency and reduce energy consumption and CO2 emissions.
- Implement predictive maintenance to predict future failures in machines and avoid machines breakdown that would cost productivity loss.

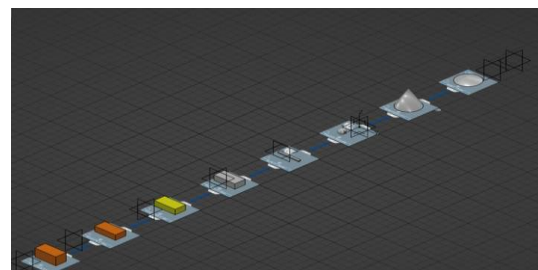
4.2.3 Building DT Model and Future Directions

Despite the role that VSM played in identifying problems in the production process, some limitations require the use of more dynamic and digitalized VSM. Firstly, the current VSM is static; therefore, with the stoppages in the production line, its results need to be updated frequently. Secondly, the current VSM was done for only one product in the factory. To apply the principle of leveling (i.e. Heijunka), there is a need for a flexible system that can integrate more than one product; such improvement can be done using DT as stated by Lu (2021). Thirdly, due to the changes in the production line (affected by the stoppages and unexpected events), it is not easy to identify improvements in efficiency and WIP reduction; especially with the presence of workers turnover (Y. Lu et al., 2021), which happens in the studied case. Finally, the use of an interactive model that links the physical process and the digitalized process can provide real-time data and updates about the effectiveness of the changes in the production process (e.g. due to repositioning of bricks in the kiln, changes of current wagons, and predictive maintenance implementation).

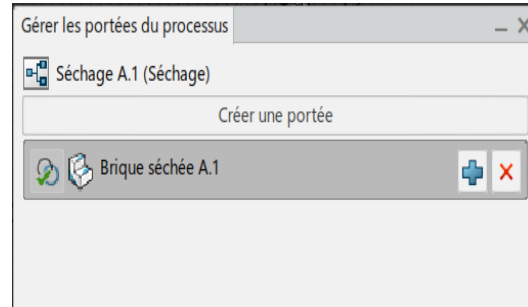
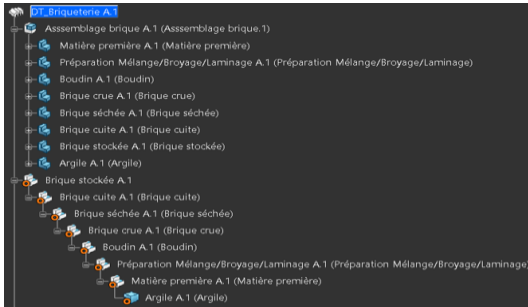
Therefore, the work started to build the digital twin model. So far, the team was able to build the 3D model and distribute a set of needed sensors linked with the IoT platform. The 3D model was built using “The 3DEXPERIENCE platform from Dassault Systèmes”. The current work covers:



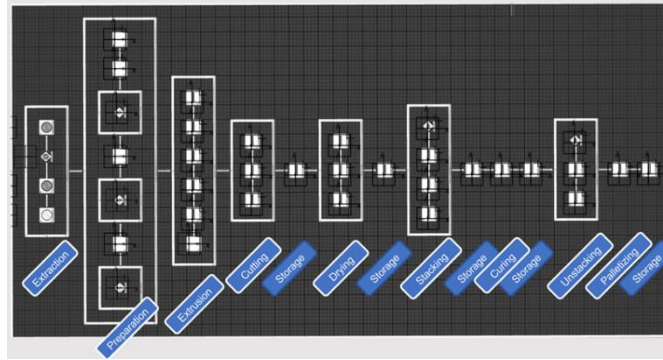
a) Modeling different states of the brick



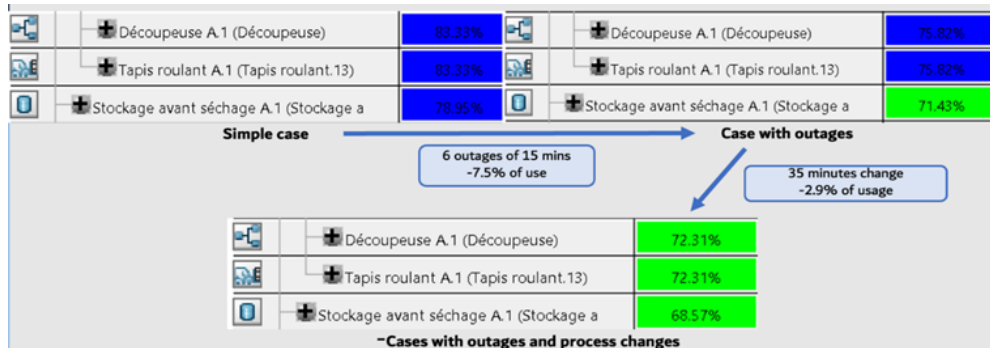
b) MBOM



c) Process planning and flow simulation.



d) Modeling of the production line



e) Example of scenario testing

Figure 4.9. Building the DT model

- Building the 3D design and modeling the brick in its different states (as shown in **Figure 4.9-a**). Each transformation of the brick corresponds to a visual of the brick, starting with the extracted earth, then the preparation of the earth, the molded, cut, dried, baked, and stored brick

- Building the Manufacturing Bill of Materials (MBOM) (**Figure 4.9-b**), which integrates the different 3D models of the brick in the logical order of the manufacturing process.
- Process planning and flow simulation (**Figure 4.9-c**), which covers creating workstations consistently with the flow in the original process and linking them to the two previous phases. This step also covers the creation of the workstations, which is a critical step as it allows the definition of the different workstations, the production line as well as the time that the brick spends at this station. In this step, several parameters are defined such as throughput, cycle time, estimated operation time, and the interval between failures and repair time.
- Scenarios testing and monitoring (**Figure 4.9-d, e**): as a result, the digital twin system, presents useful information in the shape of a Gantt Chart about the systems, operation, parts, and resources. The most important criterion is the utilization rate of the systems/machines. This enables checking how the systems are used in the production line, and if a change is made, observing the repercussions on the other systems, especially the storage areas, and checking if this affects the production downstream. An example of the testing of different scenarios was predicting the stoppages of the cutting machine, which as mentioned above, was one of the identified bottlenecks that affect the flow in the process based on the results from the VSM. The machine is made of steel wires that allow cutting the raw brick. However, the process must be stopped manually when the wires break. This leads to other problems that increase the workload and impact the productivity of the company. The digital twin can predict the breakage of a wire and automatically stop the process. For this, it is necessary to implement sensors on the machine (a noise sensor (a microphone), force, and proximity). Thus, the implementation of sensors and alarming system to provide alerts when the machine stopped. A complete digital twin should make it possible to do this work

for each machine of the brick factory and to show their impact on the production line in the event of a problem or modification.

The proposed framework is currently implemented in a French brick factory. While the implementation is still in its early phases, the framework has shown some potential to improve predictability, waste elimination, visibility, and decision-making in the factory. Nevertheless, further investigations are needed to validate the framework. Future works can be done based on case studies to modify and test the framework even in other industries. Other research works can investigate the impact of the model on performance, identify key performance indicators for the framework, or identify the barriers to implementing it.

4.3 Chapter Conclusions

The objective of this chapter was to explore the integration of Lean and DT. This chapter was based on two studies. The used methodology in the first study was SLR to define the concept of DT and its structure and applications in the BE industry. While the second was based on proposing a DT-based VSM framework as a way to integrate Lean and DT.

The results of the chapter can be summarized as follows:

- 1- DT structure was presented. Based on the reviewed studies, DT can be built in various ways; however, the defined structure in this study was based on four main layers; 1) physical layer that includes the physical component and the connected data acquisition and communication infrastructure, 2) digital layer that is based on data integration and modeling tools; in addition to data management applications, 3) application layer that defines the services of the DT system, 4) users layer.

- 2- DT can support the BE industry in numerous ways. Based on the reviewed studies, DT uses were classified into: 1) sustainability and environmental-related, 2) facility management-related, 3) safety, health, and risk management-related, 4) construction management-related, 5) structural performance-related, and 6) architectural and urban-related applications.
- 3- Digital twin implementation in the BE industry is still in its infancy. Many challenges can face its implementation. The challenges can be financial-related, data management and security-related, human capital-related, knowledge and awareness-related, and cultural-related challenges.
- 4- While DT can significantly support Lean implementation, the integration between the two concepts is still overlooked.
- 5- The use of the DT with VSM can help continuously visualize, monitor, and improve the flow, value creation, and waste elimination in brick production processes.

CHAPTER 5. LEAN CONSTRUCTION AND 3D PRINTING

Chapter 5. Lean Construction and 3D Printing

This chapter aims to present the integration between Lean Construction and digital tools for collaboration and integration in the design phase. This chapter is built over two cases; the first one is about the use of digital tools to improve planning for design activities during the pandemic of COVID-19, while the second is based on the integration of Lean and BIM and its impact on the performance in the design phase. The two works were conducted in France.

5.1 Review of Lean and 3D Printing

5.1.1 Construction 3D Printing

Three-dimensional printing (3D printing) and Additive Manufacturing are used interchangeably to refer to the “process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies” (ASTM, 2009). The term appeared firstly in the writings of the Japanese researcher Hideo Kodama and the first commercial 3D printing machine was developed by Charles Hull who invented the Stereolithography fabrication system. Since then, 3D printing has evolved from producing small prototypes to allowing the serial production of manufactured parts for different purposes and in different fields (Sini et al., 2020b).

Without using tools or fixtures, the successive process allows 3D printing to produce numerous on-demand complex structures and geometric shapes that are not easy to produce with other fabrication techniques (Ning et al., 2021). This has made 3D printing one of the trendiest innovative technologies in the last few years. In 2021, the global revenue of the 3D printing sector exceeded 10 billion US dollars with expectations of growing to more than 50 billion US dollars in 2030 (Molitch-Hou, 2020) as the sector is entering a growing level of maturity and receiving higher demand from many industries such as the automotive industry, healthcare, aerospace, and others;

in addition to its role in facing global logistics challenges appeared after the COVID-19 pandemic (Choong et al., 2020; Ishack & Lipner, 2020).

The construction industry, which is widely criticized due to the low levels of productivity, poor safety conditions, poor quality, delays, and poor environmental performance can benefit in numerous ways from 3D printing applications (Besklubova et al., 2021; Hou, Tan, et al., 2020; Lafhaj et al., 2022). One example of how 3D printing can be advantageous in architecture and design is its ability to create customized structures that are not always possible with conventional construction methods. The ability to fabricate complex structures is also accompanied by more design flexibility and an easier ability to cope with design changes even after the pre-planning phase (Hou, Tan, et al., 2020); in contrast to the traditional construction methods where design changes have a significant impact on the time, cost, and even relationships between stakeholders in the projects (Abdel –Rasheed et al., 2014; Assbeihat & Sweis, 2015; Sweis, Sweis, Abu Hammad, et al., 2008). Additionally, 3D printing contributes to saving a significant amount of time during the design and construction process, making it an ideal solution for constructing quick shelters in emergencies or wartime conditions (Schuldt et al., 2021b). In terms of the cost, despite the large capital needed for the initial investment due to the expensive 3D printing equipment, the overall cost of the projects can be decreased due to the saving in materials management (e.g. handling, delivery, acquiring), labor, framework, and costs resulted from design changes, overproduction, and human errors (Hou, Tan, et al., 2020). According to Mohd Tobi (Sini et al., 2020a), the use of 3D printing in housing construction can help in saving up to 35% of the total house price in the UK. In regards to the sustainable impact, 3D printing offers opportunities to reduce waste generation, use more eco-friendly materials, and reduce greenhouse gas emissions (GHG) resulting from several sources such as materials production and transportation and

machines use (Dixit, 2019; Romdhane, 2020). According to a report by market research company “Markets and Markets”, 30-60% of the generated waste during construction can be saved when using concrete 3D printing. Social sustainability factors such as the comfort of workers, safety, and healthy working conditions can also improve due to the use of 3D printing (Krimi et al., 2017; Lafhaj et al., 2019; Olsson et al., 2019; Romdhane, 2020; Schuldt et al., 2021b). Many researchers presented the principles (e.g. Lafhaj et al., 2018) that summarize the advantages of 3D printing based on three main categories as shown in **Figure 5.1**; input data, conversion process, and output data.

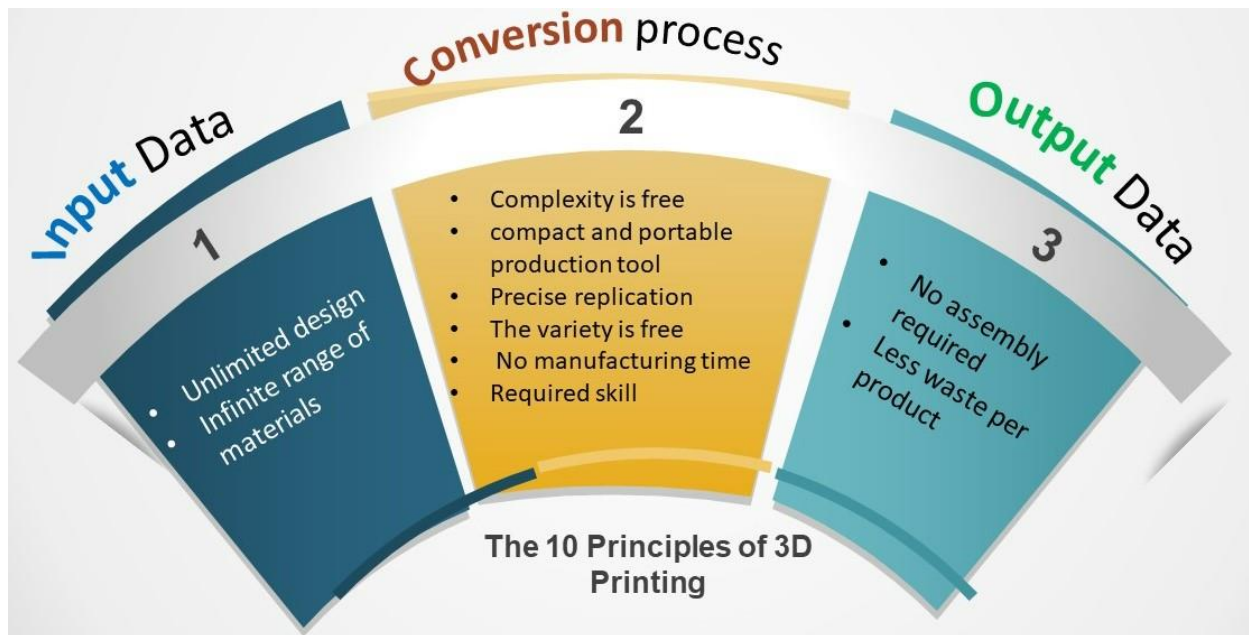


Figure 5.1. The 10 principles of 3D printing (Lafhaj & Dakhli, 2018)

The construction 3D printing process is based on software and hardware integration as shown in **Figure 5.2**. The software part is based firstly on the modeling of the object (using software such as AutoCAD, Solid Works, or others), then exporting the model to another software to identify the dimensions of the layers (slicing), and then generate a G-code program file to be read by the printer and print the object. The hardware part is composed of a printer (gantry or robotic) that is connected

to a material delivery system; this system includes a mixer, pump, and hose pipe to deliver the materials to the nozzle head to deliver the materials in the shape of additive layers. The hardware part also includes a controller to control the printer and pump according to the design (shape, size, etc.) of the printed object.

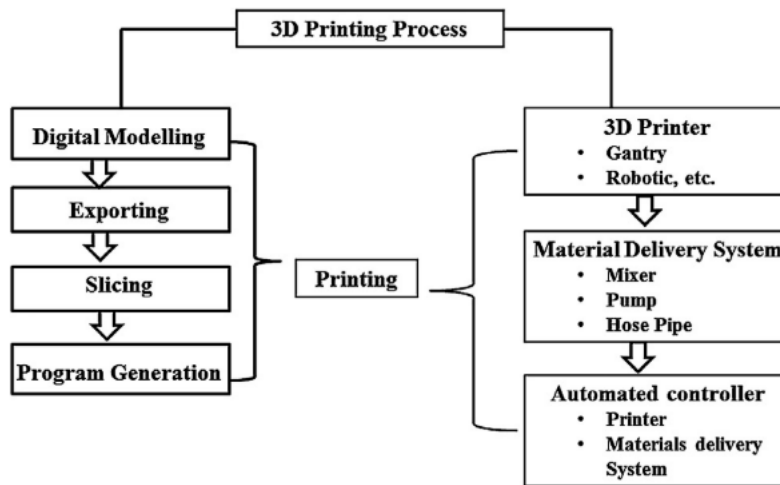


Figure 5.2. The process of 3D printing for the construction industry (Paul et al., 2018)

3D printing has not shown its full potential in the construction sector. Until now, it can be said that 3D printing is gaining more popularity in the sector, but it is still at the research and development level limited to a small number of teams and applied in small-scale projects (Dixit, 2019; Schuldt et al., 2021b). This is due to several challenges facing this technology in construction including, but not limited to, the printability buildability, scalability, ability to print large-size buildings, high investment cost, lack of skilled workers, low levels of standardization and redundancy, and cybersecurity risks (Olsson et al., 2019; Romdhane, 2020). One of the main reasons that this technology has not taken off more is the fact that there has been no corresponding change in the building system around it and there has not been enough work to link it with other managerial concepts and process optimization philosophies such as the philosophy of Lean.

The main principles of Lean are identifying the value, mapping the value stream, creating flow, establishing pull, and working for continuous improvement (Womack & Jones, 1996). The value that can be provided in the production system is a core concept in Lean thinking and it should govern all the practices in the system. Therefore, Lean researchers and practitioners stressed that Lean implementation should understand how the value streams between the different activities in any system and then improve the activities that add value and eliminate those that do not. This review uses the concept of value and the elimination of non-value-adding activities or wastes to study the synergies between Lean and 3D printing in construction. This is by understanding how 3D printing can contribute to the achievement of Lean principles in construction projects (i.e. delivering value and waste elimination) and how Lean in turn can help in improving 3D printing processes by identifying the wastes and eliminating them (as shown in **Figure 5.3**).

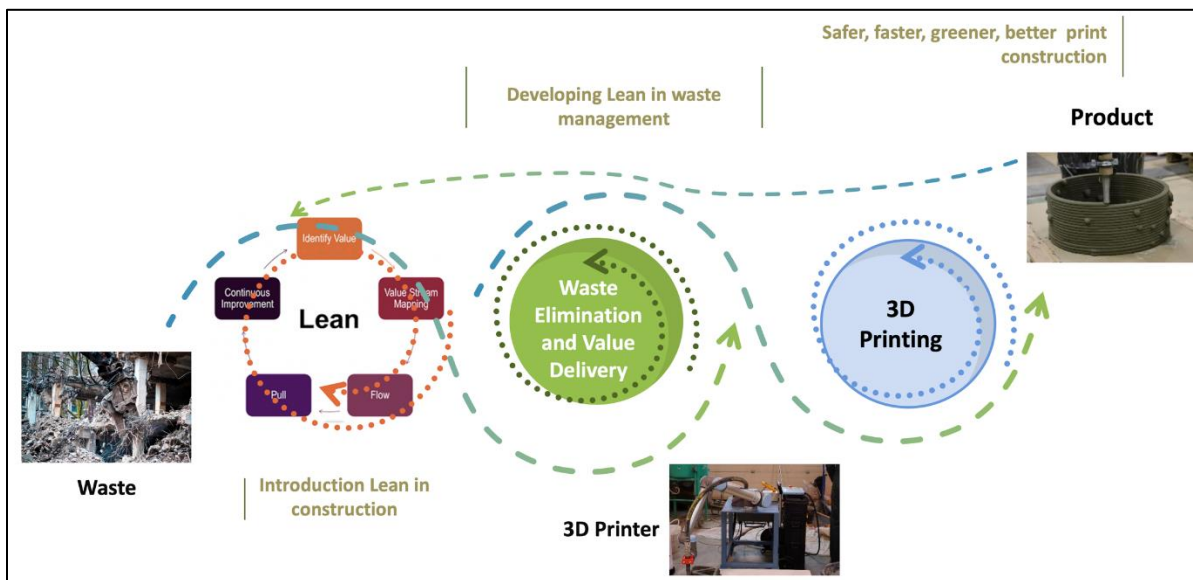


Figure 5.3. Synergies between Lean and 3D printing

To achieve this objective, a literature review was conducted, in which the search was using the following keywords: Lean AND (wastes OR waste OR “value-adding activities” OR “non-value adding activities”) AND (“3D printing” OR “3D print” OR “three-dimensional printing” OR “additive manufacturing” OR “additive construction”) AND (“construction” OR “building” OR “buildings” OR “built environment”). The results of the search showed that the main focus in the literature was on how 3D printing can eliminate Lean waste, and only a few studies covered the contribution of Lean to the improvement of 3D printing processes.

5.1.2 Synergies between Lean and 3D Printing in Construction

How 3D printing can eliminate Lean wastes

Many authors and researchers agree that 3D printing has a significant role in eliminating Lean wastes in construction when it is compared to conventional building methods (El sakka & Hamzeh, 2017; Ghobadian et al., 2020; Hamzeh et al., 2021; M. A. H. Khan & Leicht, 2022; Rouhana et al., 2014):

The first reason why 3D printing is “Leaner” than the conventional ways of construction is due to the differences in materials management in the two systems. 3D printing requires only a limited amount of materials that are necessary for the printing process and the materials move directly from the mixers to the hosepipe and the printed object. This means that there is no need for unnecessary inventory in the form of unnecessary areas for materials storage, work-in-progress, or storage areas for final products. This also helps to decrease the waiting time for materials handling and transportation and achieve JIT principles.

Waiting time is also reduced due to the reduction of inactive time needed for curing concrete, formwork time, setup time to produce different types of items, and supply lead time for materials and equipment delivery and transportation, in addition to the reduction of waiting for tools and

labors movement and intervention. **Figure 5.4** shows how 3D printing helps to avoid Lean wastes in general, and waiting wastes in particular due to the avoidance of logistics problems and the simplicity and stability of the production system social ecosystem.

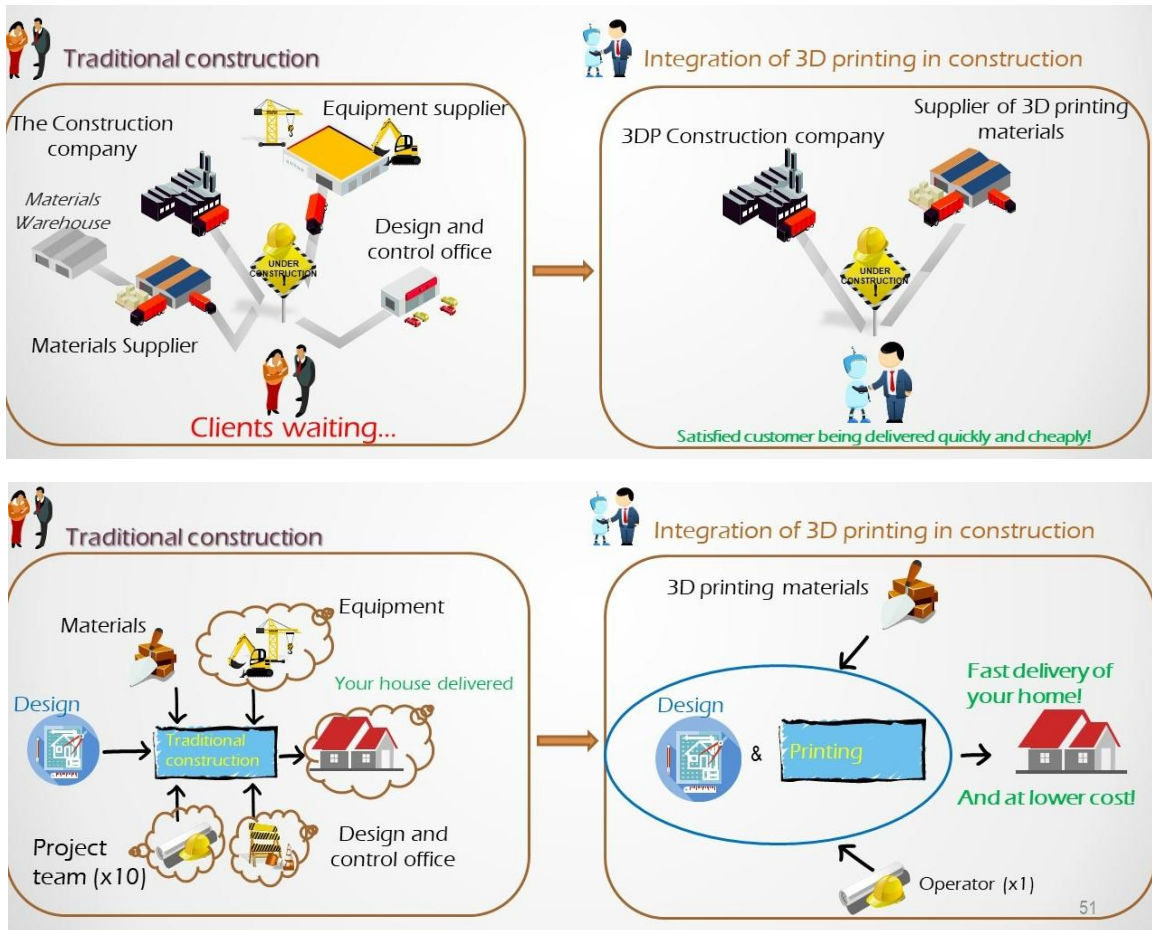


Figure 5.4. Impact of 3D printing on Lean wastes in construction (Lafhaj & Dakhli, 2018)

3D printing also offers opportunities for error-proofing applications and the removal of defects. This is due to the possibility of noticing the defects in an easier way than that in conventional construction where defects are invisible due to the forms. The detection of these defects helps to avoid wasted time for repair and rework.

Additionally, as 3D printing is done by one crew and one printer (in most cases), it helps to minimize the movement of labor, machines, materials, and equipment. Consequently, it helps to decrease transportation and motion wastes. Furthermore, due to automated production, 3D printing helps to decrease over-production and excess processing wastes. **Figure 5.5** summarizes some of the factors that help to eliminate waste in the 3D printing systems as found in the reviewed studies.



Figure 5.5. Factors help to reduce waste in 3D printing processes

Lean wastes in 3D printing processes

Although 3D printing can help in achieving Lean principles and delivering higher value to the client, many non-value-adding activities may occur in the 3D printing processes (Groneberg et al., 2021, 2022). The most apparent type of waste that can happen in 3D-printed buildings or building

components is defects. According to Sini et al (2020a), 3D printing is still immature to guarantee the quality of the final printed object and is still unable to eliminate the wastes of defects.

Many factors affect the quality of the printed object such as the materials' properties, print speed, layer thickness, layer time, print path, nozzle shape, size, and standoff distance (Schuldt et al., 2021b). For instance, regarding print speed, too-slow printing would result in reduced bonding between the layers, while too-quick printing would prevent the development of the layer's strength that is needed to carry the new layer.

Concerning the materials, despite the great focus on materials in the construction of 3D printing literature, there are still no codes or standards for the tests needed for 3D printing materials (Schuldt et al., 2021b). The lack of these codes raises some questions regarding the wasted materials, the number of defects, and even the safety of the 3D-printed buildings. So far, many characteristics affect the printability of the materials and differ from one place to another; for instance, what can be printable in hot areas may not be printable in very cold locations in the world. This increases also the risks of waiting wastes. Offsite printing might be one of the effective solutions to solve this problem, but it may present some limitations regarding the design and size of the printed object. In offsite printing, defects may also occur during the transportation and installation of the object.

Defects may also appear in the design model due to the lack of proper communication and collaboration (e.g. in the shape of rework) or just like any other design process in the shape of revisions, deviation from customer requirements and need, or damaged, lost, or incomplete files. Defects in the automated printer (robot or gantry) are another serious problem that may face the 3D printing process; especially when there is only one printer that cannot be easily fixed or repaired.

Waiting wastes are one of the most frequent wastes in conventional construction methods. Similarly, waiting in 3D printing can occur for many reasons, and normally it can be connected to defects. For instance, defects that may happen in the printer would result in waiting wastes for maintenance and spare parts. Knowing that 3D printing can be a suitable solution for remote areas and areas affected by unusual events such as wars and disasters (Schuldt et al., 2021b), the impact of waiting might be very serious.

Waiting wastes could occur due to the additive process when conducting quality measures and control. As mentioned above, defects during 3D printing are easier to detect than those in the conventional or manual construction methods; however, the occurrence of these defects requires hinders the continuity of the work. Repairs, measurements, and retesting would result in idle machines or crews and delays in the processes. Another example of waiting waste is the idle nozzle due to the concrete solidification in the pipeline (Rouhana et al., 2014).

Non-utilized talents can be noticed when there is a lack of expertise in dealing with the 3D printing system. This might result from the lack of standardized printers in the market and the lack of skilled workers. The robots that are currently on the market cannot be modified by the company that purchased them. To meet specific demands, the company must therefore call on another 3D printing company to subcontract or buy a new robot and train its staff to use it. The lack of standardization and redundancy in the work may also cause more waiting wastes.

Similar to any other production system, other types of wastes may appear in the 3D printing system due to several reasons. For instance, disputes between the different stakeholders can result in delays or defective design; a non-optimal printing path might be the reason for unnecessary motion and defects; and unreliable logistics system in the on-site and off-site printing (for raw materials, components, and final product...etc.) can produce inventory, overproduction, transportation, and

waiting wastes. **Figure 5.6** shows the categories for Lean waste sources in the 3D printing processes, and in **Table 5.1**, we show some examples of Lean wastes in these processes based on the definition provided by El Jazzar and Nassereddine (2021).

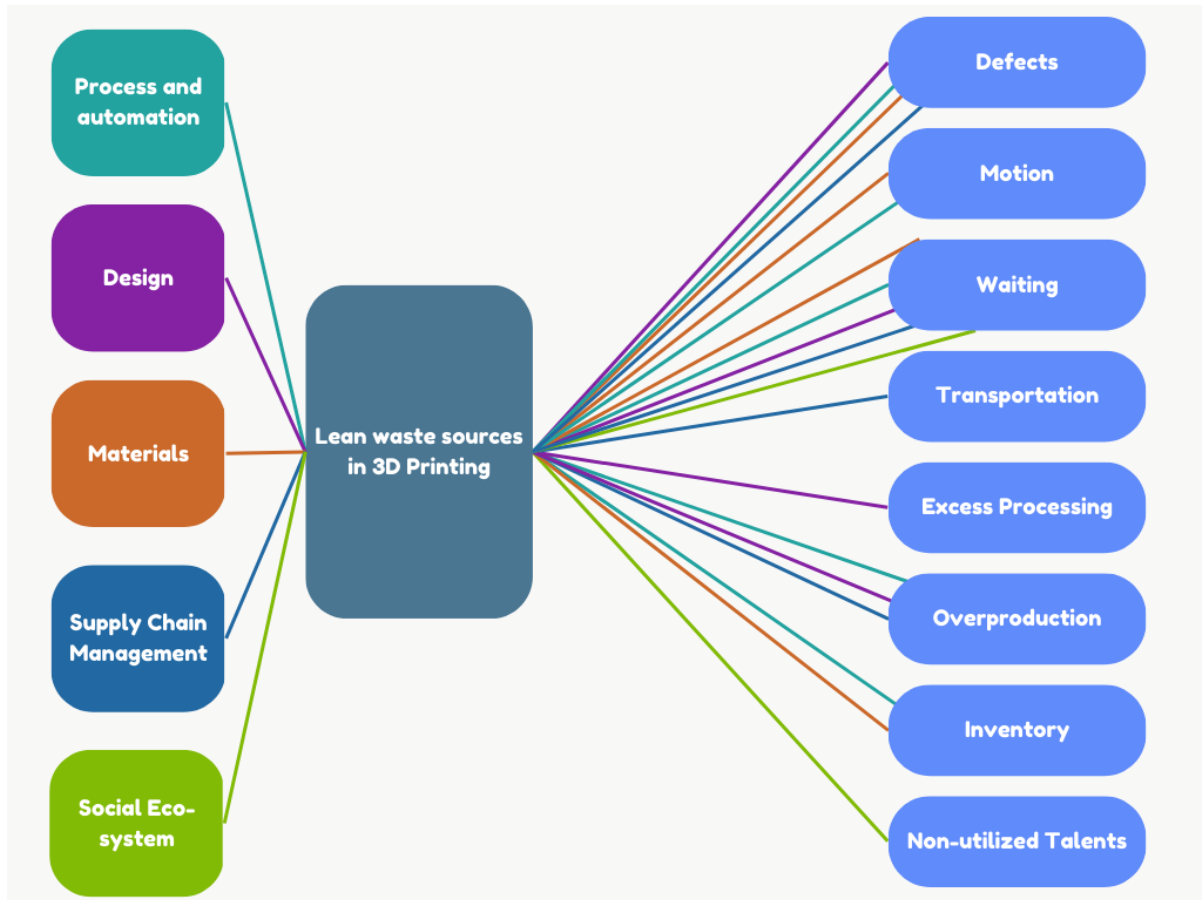


Figure 5.6. Categories for Lean waste sources in the 3D printing processes

Table 5.1. Examples of Lean wastes in 3D printing processes

Category	Definition (El Jazzar & Nassereddine, 2021)	Examples in Construction 3D Printing
Defects	Defective product, unacceptable quality, rework/repair/replacement is needed	Defective layer Defects while objects/parts transportation Design error/redesign Unprintable materials Defects in robot

Category	Definition (El Jazzar & Nassereddine, 2021)	Examples in Construction 3D Printing
Motion	The unnecessary movement that does not add value	Non-optimal path for printing
Waiting	Delays or wasted time while waiting for a machine, product, labor, action, decision, information...etc.	Waiting for maintenance Waiting for design information/decision Waiting for quality measurement Waiting for wearing personal protective equipment Idle machine/crew (e.g. due to concrete solidification in the pipeline) Meetings with no decisions
Transportation	Movement of materials or equipment that does not add value	Transportation of spare parts Sending components back and forth between different sites More components or workers need to be brought to the site
Excess Processing	Unnecessary steps in the production/ produce something is not valued or required by the client	Post-processing due to the defects
Overproduction	Producing too much or too early/ ordering too many materials	Overdesign Early preparation of mortar Pre-installation Too late/too early printing Too much flow through the printing head
Inventory	Excess storage of materials/WIP/unused tools	Lost files More mortar than needed
Non-Utilized Talents	Non-utilized crew and skills	Lack of skilled workers in the crew

The Lean theory has presented several tools to improve performance in construction processes and projects. In dealing with wastes, Hannis Ansah et al (2016) classifies Lean Construction tools into three main categories:

- Waste detection tools: such as VSM, construction process analysis, Muda walk, and spaghetti diagram
- Waste processing tools: such as 5 Why, Pareto analysis, and Fishbone diagram.
- Waste response tools: such as 5S, LPS, work standardization, check sheets, Just-in-time, A3 problem solving, VM, and others.

Companies and practitioners in the construction of 3D printing projects can use these tools to identify and remove the wastes. An example of the use of these tools is the integration between VSM, 5Why, and A3 problem solving; in which a current VSM can be used to map the value stream during the 3D printing processes, then based on the 5 Why and A3 problem solving, actions can be made to develop and apply future VSM to improve the performance in the processes.

5.2 Analysis of Lean Wastes in a 3D Printing Experiment

Apart from the above-presented review, during the work on this thesis, no other studies were found about the presence of Lean waste in construction 3D printing. To analyze the possible waste, a two-round lab investigation was conducted (as shown in **Figure 5.7**):

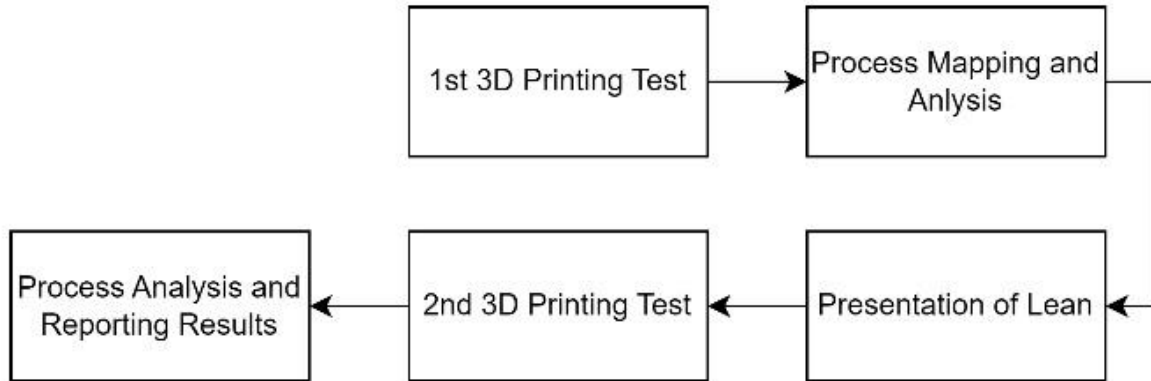


Figure 5.7. The used methodology to analyze Lean waste in 3D printing processes

Conducting the first 3D printing test

The printed object (**Figure 5.8**) has a plan that takes the shape of a hexagon at the bottom, then ends as a circle with the dimension: diameter and height of 45 cm, layer height of 1 cm, and layer thickness of 5cm. The overall printing time is supposed to be 15 minutes and 34 seconds and the overall volume of concrete is 132.32 Liters using wasted cement.



Figure 5.8. Printed object

Process Mapping and Analysis

Process mapping aims to understand and register all the process steps and sub-tasks to understand the value-adding activities (VA) and the non-value-adding activities (i.e. wastes or NVA) (Groneberg et al., 2022). The team divided the overall process based on 17 main steps starting from the preparation of the printing materials (following wearing personal protective equipment) to the end of the printing process.

Using video recording for the two tests, the process was mapped and analyzed in a standardized structure that is shown in **Table 5.1**. This structure was for the two parts of each test; the materials and robotic parts. Using the mapping and analysis structure, each task was decided if it is necessary (VA) or unnecessary (NVA). The time of each task was defined and each NVA task was assigned to the waste category it belongs to. Following the mapping of the tasks, the analysis was conducted to identify the overall wasted time and the percentage of each waste category.

Table 5.2. Process mapping and analysis structure

No.	Time	Task description	Type (VA/NVA)	Category (if NVA)
Task 1	t1	Searching for a tool	NVA	Motion
Task 2	t2

...
Task n	tn

5.2.1 Results

The first test

The analysis of the first test revealed that the overall time to print the selected object was 2785 seconds and the total wasted time was 678 seconds. In other words, 24.34% of the printing process was wasted on non-value-adding activities.

The analysis also showed (as shown in **Figure 5.9**) that 45% of the overall wasted time was due to the occurrence of waiting activities, 22% was due to transportation activities, and 19% was because of unnecessary movement or motion activities. For the robotics part, the percentage of the waiting activities was 55%, and then 14.53% and 13.70% for the transportation and motion activities, respectively. The highest percentage for the materials part was for the transportation activities (32.25%), then for waiting (29.22%), and then for motion (26.62%).

Examples of the NVA activities include waiting for information (waiting), searching for the design file (waiting), waiting due to technical error (waiting), searching for a tool (motion), searching for materials (motion), transportation of the mixer (transportation), redo weighing of materials (defects/rework).

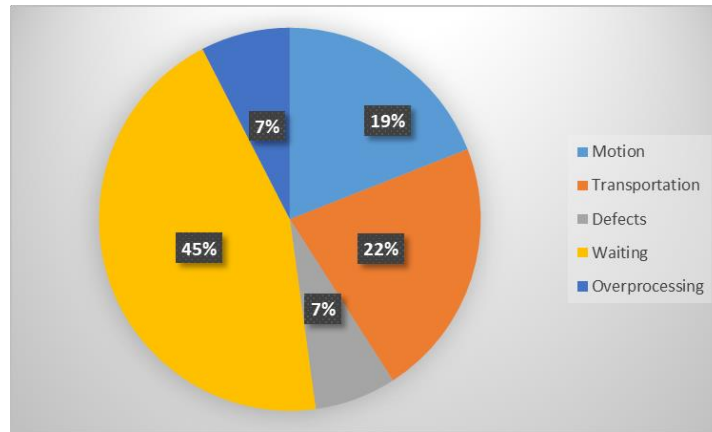


Figure 5.9. Percentages of waste categories activities to the overall NVA activities in the 1st test

Presentation of Lean

Following the analysis of the first test's results, Lean principles and tools were introduced to the team. The presentation included introducing the principles of Lean and Lean Construction and reviewing the wastes found in the first test. The presentation also covered some tools that can be helpful when trying to improve the 3D printing process and eliminate the found waste. The tools that were covered were:

- 5 Why: “is a systematic questioning process used to identify the root cause of a problem” (O’Connor & Swain, 2013). This tool was used to explain the occurrence of Lean wastes found in the first test.
- Value Stream Mapping (VSM): one of the main principles and tools of Lean, where the process is mapped and visualized to show the value flow along the different activities, and as a result, finding rooms for eliminating wastes and optimizing adding value activities (Hannis Ansah et al., 2016; O’Connor & Swain, 2013).
- 5S workplace organization: a structured method to achieve, maintain and improve workplace organization and standardization aiming to ensure having a safe work area and efficient processes with the least amount of waste (O’Connor & Swain, 2013). 5S is based

on five actions that start with the letter “S”, which are “Sort”, “Set”, “Shine”, “Standardize”, and “Sustain”.

- Plan-do-check-act for continuous improvement (PDCA): a four-step iterative structured method to achieve continuous improvement by testing gains in the process improvement when taking different actions. In this method, Plan refers to (set up a plan and expect results), Do refers to (execute the plan); Check refers to (verify anticipated result achieved); and Act (evaluate; do it again) (Hannis Ansah et al., 2016; O’Connor & Swain, 2013).

In addition to discussing some solutions such as the supermarket solution, VM, predictive maintenance, error-proofing, and parallel processing.

The second test

Following the Lean presentation, the team decided to take some measures to improve the 3D printing process such as the use of supermarket, workplace organization, and parallel processing. Other measures were decided to be adopted in the future due to the time limitation and the need to conduct more than one test to validate their use. Examples of these measures include visual management, error-proofing, and predictive maintenance.

The analysis of the results of the second test revealed that the total time was reduced by 152 seconds (total= 2633 seconds) in comparison to the first test. The total wasted time on NVA activities was 13.1% of the overall process time.

Figure 5.10 shows the percentages of the waste categories activities to the overall NVA activities. The figure shows that waiting activities remained to be the most frequent activities in the second test constituting 51% of the overall NVA. The percentage of the waiting wastes was mostly in the

robotics (65.77%), while in the materials part was 16.6%. Following the waiting activities, motion (23%) and transportation (15%) remained to be the highest.

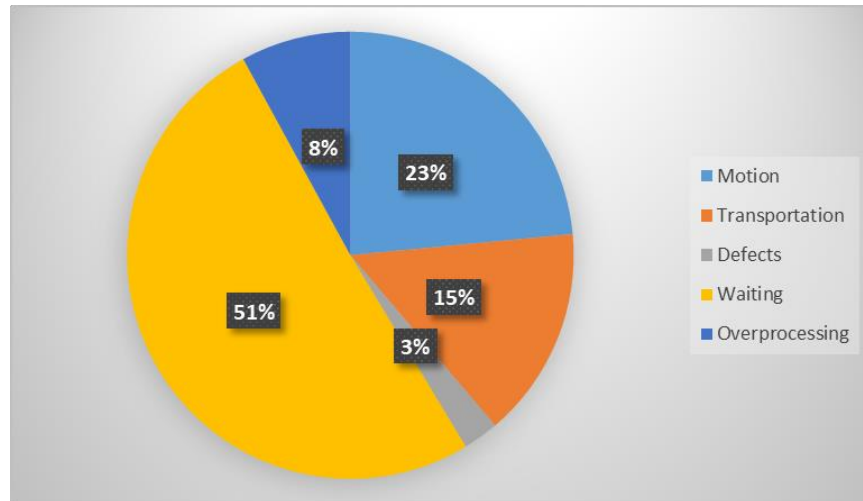


Figure 5.10. Percentages of waste categories activities to the overall NVA activities in the 2nd test

Figure 6 shows a comparison between the number of NVA activities in the two tests. The Figure shows a decrease in all categories. The highest change was in the transportation activities and the defects/rework activities. This might be attributed to the workplace organization and parallel processing work that helped the team to avoid doing too many transportation activities or doing the same thing twice.

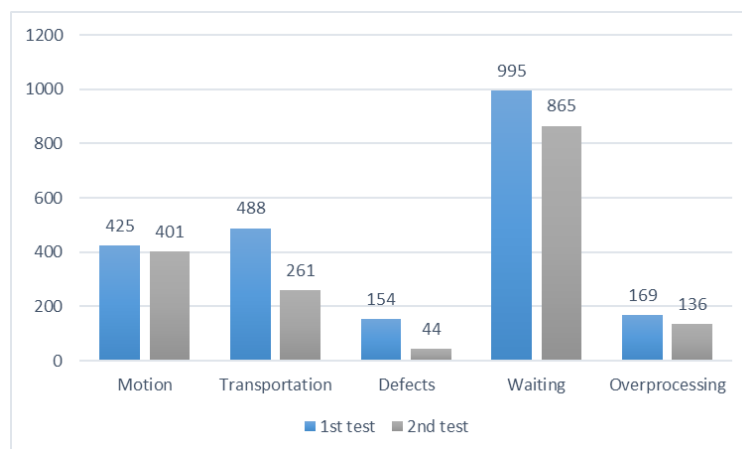


Figure 5.11. Percentages of waste categories activities to the overall NVA activities in the 2nd test

Despite the decrease in the waiting and motion activities, there is a need for more work to ensure achieving the continuous improvement goals, delivering higher value, and eliminating more waste. This might be done by improving the planning of the process and workplace, use of visual management, and improving the coordination work.

5.2.2 Discussion

The results of the first test showed that more than 24% of the 3D printing time was wasted on non-value-adding activities. According to Aziz and Hafez (Aziz & Hafez, 2013), the average wasted time in manufacturing operations is around 12%, while it is more than 57% in construction projects. Despite the need for many other investigations, the found ratio in this study may support the claim that 3D printing can help reduce wasted time in construction operations. However, this ratio is still high and calls the need for more thinking about possible ways to improve 3D printing operations' efficiency.

Following the presentation of Lean, the ratio of waste was reduced to 13.1%. This showed a possible opportunity to improve the time and even the cost of 3D printing systems while maintaining the quality or even improving it, which is the essence of Lean thinking.

In the two tests, the share of the waiting wastes was the highest among the non-value-adding activities. This is similar to the case reported in different cases in the traditional methods of construction (Bajjou et al., 2017; Sarhan et al., 2017). As a result, similar to the traditional construction methods, 3D printing systems should be built over a high level of coordination and can benefit from different Lean tools (e.g. JIT, VM, and pull planning) to eliminate as much waste as possible. It is worth mentioning here that as the current study was conducted in a laboratory environment with a known mixture and known test parameters, other sources of waste may appear while constructing a full-scale 3D printing building. One main example of these wastes is the

“defects”, which were not the highest in this study but according to Sini et al (Sini et al., 2020a), it is the main reason why 3D printing is still immature enough to guarantee the quality of the 3D printed products. Accordingly, it is recommended to conduct similar research to answer the same research questions in a real project environment, where other factors such as supply chain and logistics management can be covered.

In addition to the lab investigation, the section has the limitation of the number of tests. While continuous improvement is one of the core concepts of Lean, the current study builds its results over a short period of investigations. As a result, there is a need for a larger number of tests and a longer period to ensure achieving greater improvement and eliminating the possible wastes that may appear over time. Other research areas can cover investigating the Lean wastes or Lean adoption opportunities in onsite and offsite construction 3D printing systems, exploring the challenges that face this adoption, examining the impact of Lean on supply chain management and sustainability in the two types of systems, and using other Construction 4.0 practices side by side with Lean to improve the performance in 3D printing operations. Moreover, while this work tries to investigate the existing waste 3D printing processes, it is necessary to stress the impact of Lean on the overall performance in 3D printing projects in a wider way that considering only specific processes. This is because the concept of waste is situational-related. For example, various planning meetings included in LPS levels can be perceived by some as wasteful. However, in Lean philosophy, these meetings are essential to optimize the entire project timeline, minimize change orders and errors, and ensure continuous collaboration between all stakeholders. Accordingly, future work can focus on the entire 3D printing project lifecycle and the role of Lean on different context and situations.

This study tries to fill the gap in the literature that lies in the scarcity of resources about the Lean waste in 3D printing. It also serves as an example of how to analyze and identify wastes in 3D printing operations. As a result, this study tries to provide practitioners and researchers with a way to investigate how to improve efficiency in the construction of 3D printing.

5.3 Chapter Conclusions

The objective of this chapter was to explore the integration of Lean and 3D Printing. This chapter was based on two studies. The used methodology in the first study was a review for the literature to investigate the relationship between Lean and 3D Printing. While the second was based on lab investigations to analyze waste in 3D concrete printing.

The results of the chapter can be summarized as follows:

- 1- Both; Lean and 3D printing, can benefit from each other to improve the performance of construction projects.
- 2- Due to the way materials managed, automated system, additive process, and stable production system in 3D printing processes, the latter can help eliminate much of the expected waste when compared to conventional construction methods.
- 3- 3D printing processes are not immune to have waste. Waste in these processes can arise in design, materials, automated process, supply chain, and social eco-system. Lean Construction can affect 3D printing processes by providing opportunities for continuous improvement of these processes.
- 4- The analysis of laboratory-based 3D printing processes showed more than 24% of the time can be wasted on non-value-adding activities.

- 5- After introducing Lean principles, the waste ratio decreased to 13.1%, indicating a potential opportunity to enhance the efficiency and cost-effectiveness of 3D printing systems while preserving or even enhancing quality. This aligns with the core principles of Lean thinking.

**CHAPTER 6. LEAN CONSTRUCTION AND NEW
PROJECT MANAGEMENT METHODS: THE CASE OF
ADVANCED WORK PACKAGING (AWP)**

Chapter 6. Lean Construction and New Project Management

Methods: The Case of Advanced Work Packaging (AWP)

This chapter aims to present a comparison between Lean Construction and one of the new project management methods that are gaining popularity in the construction environment, which is Advanced Work Packaging (AWP).

6.1 Advanced Work Packaging (AWP)

Work packaging is among the essential concepts in the project management theory (Ponticelli et al., 2015). The concept that was coined in the US Department of Defense (DoD) when presenting the work breakdown structure (WBS) in the 1950s refers to breaking down the project into manageable and executable work packages (Halala, 2018). Each work packages includes a group of activities that constitute the work package and a set of identifications to complete these activities (i.e. cost, quality, allocated resources, safety requirements, and schedule) (Halala, 2018).

Following the development of WBS, the use of work packaging in project planning and control was recommended by various parties such as the Project Management Institute (PMI) and the Construction Industry Institute (CII) (Hamdi, 2013). however, the presentation of systematic approaches to govern the process of work packaging remained missing for years (J.-J. Kim & Ibbs, 1995).

In 2005, the Construction Owners Association of Alberta (COAA) considered workforce planning as a best practice among contractors (AlHamouri et al., 2021; Hamdi, 2013). The latter refers to the process of delivering and organizing all necessary elements for the work package before the work is started (CII & COAA, 2013a). Accordingly, reducing the project schedule and enabling

the craft workers to perform tasks safely, efficiently, and effectively (CII & COAA, 2013a; Hamdi, 2013).

In 2009, a joint research between CII and COAA (RT 272 Phase I) was initiated to review the used work packaging practices (including the workface planning) and develop an execution model for work packaging. In 2011, another phase of research started (RT 272 Phase II) and aimed at extending the development of the execution model and presenting the advanced work packaging (AWP).

AWP is a construction-driven project delivery process that begins with the end in mind, in which construction and engineering must collaborate during planning to create a constraint-free field environment. This collaboration ensures that the project is designed with a construction-friendly sequence and that the supply chain is sequenced accordingly by breaking down the project scope into Construction and Engineering Work Packages (Ponticelli et al., 2015). AWP was also designed to facilitate the planning process and reduce the burden while creating work packaging by removing any possible constraints as early as possible (Halala, 2018). Unlike traditional work packaging where planning is done only in the early phases of the project, AWP tries to provide a holistic approach to planning and execution of work packaging along the whole project life cycle as follows (Hamdi et al., 2013; Ponticelli et al., 2015):

1. The first stage of a project involves identifying critical planning elements to define work packaging deliverables. The project is divided into Construction Work Packages (CWPs) which align with the execution plan and Engineering Work Packages (EWPs).
2. The second stage is Detailed Engineering which refines the work from the first stage. Output includes detailed specifications for EWPs, a discipline-based schedule, and aligning plans to ensure consistency.

- The third stage is Construction, with detailed planning and execution of Installation Work Packages (IWPs). IWPs are issued 3 weeks before the start and are approved by frontline personnel. After execution, IWPs are controlled by owner representatives for quality checks and updates.

The Integrated Advanced Work Packaging Flow Chart is shown in **Figure 6.1**.

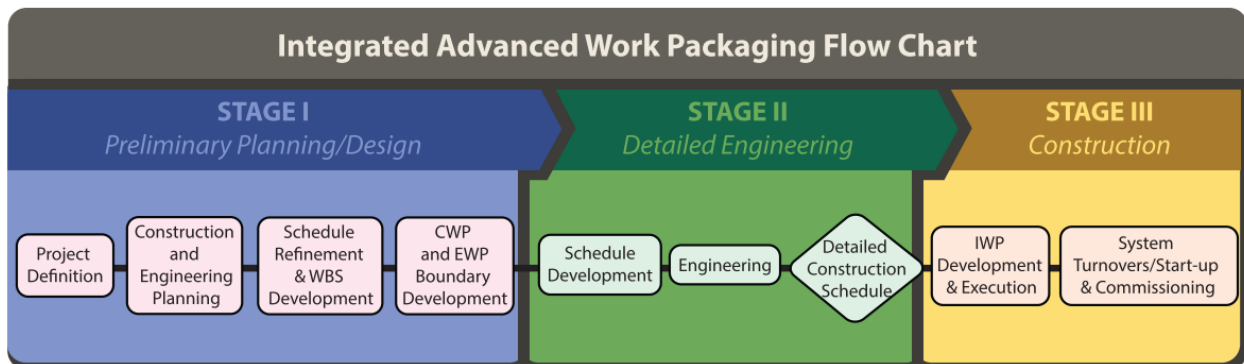


Figure 6.1. Integrated Advanced Work Packaging Flow Chart (CII & COAA, 2013a)

6.2 Lean Construction and AWP

While the implementation of Lean Construction has shown various improvements since it was presented in the early 1990s, AWP is still new. Though, the implementation of AWP showed some positive signs about its ability to improve performance in construction projects. For instance, a study that included 20 construction projects in the United States and Canada showed that the implementation of AWP helped to achieve better predictability and achieve improvements in productivity, cost, safety, and quality (Hamdi & Lafhaj, 2021; O'Brien et al., 2016). Some estimates showed that AWP can help achieve around 25% gain in productivity and 10% installation cost savings in construction projects (CII & COAA, 2013b; Rebai et al., 2022). Accordingly, research and interest in AWP are increasing.

Despite receiving some critics from the Lean community due to the expected impact on inventory growth, push orientation, and variability increase (Arbulu & Shenoy, 2021; Tommelein & Ballard, 2016), there have been several calls to integrate AWP and Lean Construction, especially by the CII and the Lean Construction Institute (LCI) (CII & LCI, 2022a, 2022b; CIIBuilds, 2022b, 2022a). The reason behind these calls can be explained by the shared goals to improve performance and productivity in construction projects. Despite these calls, it can be said that the link between them still needs further investigation. One main question that can be raised in this regard is how the two concepts can benefit from each other. To answer this question, this section, which is based on reviewing the existing literature aims to investigate the similarities and differences between AWP and Lean Construction.

6.2.1 Research methodology

The literature review was conducted using a search for the keywords: ((“advanced work packaging” OR AWP) OR (“workface planning” OR WFP)) AND (construction or building). The focus on AWP is due to the low number of publications about it in comparison to Lean. The search was done firstly on Google Scholar, Web of Science, and Scopus to cover the scientific articles about the studied topic. Then, it included other resources; especially those published by CII.

The total number of included studies in the literature was 29. Following the analysis of these studies, four main categories were studied, which are context and culture, project specification, roles in the project, and work approach. Due to the presence of different Lean tools, the fourth part, which is about the work approach provides a comparison between AWP and LPS as LPS is the most known planning and control tool in Lean thinking.

6.2.2 Results

Context and principles

Context includes the type of each concept, origin, orientation, and purpose as explained in the literature as summarized in **Table 6.1**. Concerning the type, it is agreed that Lean is not based on a specific tool or methodology; rather, it resulted from a set of principles that were first coined in the automotive industry and constitute what is called Lean thinking. Accordingly, Lean can be seen as a philosophy based on which different tools and methodologies were developed (Albalkhy & Sweis, 2021; CII & LCI, 2022a). On another hand, AWP is an approach or a methodology that was considered a best practice in work packaging to solve the problems facing construction in the oil and gas sector as explained by the (CII - RR272-11, 2013). In terms of orientation and purpose, AWP can be considered a task-oriented approach that aims to improve task management to increase predictability and productivity in projects (Halala, 2018). While Lean has evolved to be a human-centric approach that values workers' engagement and is based on collaboration to create value, flow, and continuous improvement (Santos et al., 2021). Orientation toward "respect for people" and collaboration made it possible for Lean to go beyond time, cost, and quality improvement to cover other aspects such as innovation and integration of workers' ideas, sustainability, and safety (CII & LCI, 2022a). This does not mean that AWP neglects the human factor. For instance, Path of Construction (POC), which is an essential practice in AWP should be jointly developed and aligned with respect to all stakeholders (CII & LCI, 2022b). Additionally, according to CII and LCI, a key value for AWP and Lean Construction is integrating the safety, health, and well-being of workers in the process design (CII & LCI, 2022a).

Table 6.1. AWP vs Lean- context

Context		
Criteria	AWP	Lean Construction
Type	Methodology	Philosophy
Origin	Oil & Gas Industry	Automotive Industry
Orientation	Task-oriented	People-oriented
Main Purpose	Increase productivity, predictability, and efficiency	Value creation, flow, and continuous improvement

Project Specification

AWP method was developed to respond to the increased complexity of capital construction projects (Halala, 2018). According to Hamdi (2022), the implementation of AWP in small projects is possible but not attractive as it fits more megaprojects. In contrast, Lean can be implemented in all types of projects (Albalkhy & Sweis, 2022). Concerning the contractual relationships and project delivery types, AWP considers early contracting a priority, in which the requirements for AWP and AWP language (plans, procedures, strategies, and responsibilities) should be clearly stated and included in the contract (Halala & Fayek, 2019). For Lean, Lean can be used with different types of contracting and project delivery methods. However, the Lean community has had a big role in the development and adoption of collaborative delivery methods such as Lean project delivery system (LPDS), integrated project delivery (IPD), target value delivery (TVD), and others (CII & LCI, 2022a; Koskela et al., 2002). Referring to the costing strategy, the AWP requires defining the initial conceptual model and estimate based on the work packages and then conducting formal cost-saving ideas, which results in the locking of the estimate (CIIBuilds, 2022b). For Lean, one of the most encouraged practices is the Target Value Design (TVD), which is based on keeping the design and costs aligned with the client's target cost defined in the early design phase (Ng & Hall, 2019). Regarding the project planning methods, AWP conducts interactive planning sessions, which

include all key stakeholders and are driven by the construction, until the preparation of the CWP (Construction work packages) with a push aspect in the CWP release matrix, but once on the site, the workforce planner changed the concept dealing with the IWP (Installation work packages) release plan in a pull concept but always conforming to the main plan and with the alignment to the POC (path of construction) (CIIBuilds, 2022b). On another hand, Lean Construction strictly focuses on pull planning and builds its plans using a collaborative planning method in the presence of all stakeholders and participants (CII & LCI, 2022a). **Table 6.2** presents the comparison between Lean and AWP based on the specifications of the project.

Table 6.2. AWP vs Lean- Project specifications

Project Specifications		
Criteria	AWP	Lean Construction
Suitability	Capital Projects	All types of Projects
Contracting and project delivery	Contracting strategy is a priority and needs to be defined	Different types of delivery but encouraging IPD
Costing/value	Initial conceptual model and estimate Conducting formal cost-saving ideas	Target value design (TVD)
Planning Principle	Push and interactive planning Pull in the site	Pull and collaborative planning

Roles in the project

As AWP is a structured approach, it has clear definitions for various roles, which is not the case in Lean. For instance, while in Lean clients are the main focus and their presence and participation is a key to success in all project phases, there is no strict definition of their representatives like that in AWP. AWP champions, who act as the voice of the client are responsible for the implementation of AWP procedures and standards throughout the project (Hamdi, 2022). Additionally, while the collaborative planning sessions require the attendance of all possible stakeholders in LPS, there is no strict requirement to make someone a facilitator. In contrast, AWP interactive sessions are

usually led by the Construction Manager (1st to 3rd levels of planning) and then workforce planners (4th and 5th levels of planning) (Hamdi, 2022). The workforce planners are responsible for IWPs definition and management on site to ensure the removal of constraints and the proper execution of the work (CII & LCI, 2022a). A clear definition of Lean roles can be found in the last planner which refers to the foreman or the frontline supervisor who has to engage in constraints management and removal (Porwal et al., 2010).

Work approach

AWP is a structured approach that has three main phases of work that are resulting in the CWPs, EWPs, and IWPs. The work in AWP usually starts with area-based decomposition by developing the construction work areas (CWAs) and then over the disciplines-based planning and control. As an approach with origins from the oil and gas sector, during the planning process, AWP focuses on aspects such as constructability, operability, maintainability, and constraint removal (CIIBuilds, 2022b). In turn, Lean practices in LPS adopt the short-range production planning levels (i.e. master schedule, phase or pull planning, look-ahead planning, weekly work planning, and daily huddle meetings and learning). Aligned with some practices such as takt planning, short-range planning in LPS aims to ensure the avoidance of overlapping between trades and remove variability sources that may hinder the flow of the work (CII & LCI, 2022a).

Concerning performance measurement, AWP relies on productivity measures for the CWP, and EWP, in addition to safety and delay indicators. It also uses the installation cost of IWPs and their conformity with the planned budget (Halala & Fayek, 2019; Hamdi, 2013; Rebai et al., 2022). In Lean, as stated earlier, the focus is on trying to achieve continuous improvement in all possible aspects (e.g. client satisfaction, safety, sustainability, time, cost, and quality). Specifically, in LPS, different measures are considered to cover different aspects including for instance the percent plan

complete (PPC), which helps to identify the deviation between what was planned and what was executed (Ballard, 2000). In addition to other measures such as cost reporting (CR), schedule variation (SV), quality reporting (QA/QC), Root-cause Analysis (RA), and Reason Summary for non-competition (RS) (España et al., 2012).

Regarding the learning process, AWP refers to knowledge management related to the IWP process and value chain (Hamdi, 2022). In Lean, the learning process is a fundamental concept that supports the continuous improvement goal. Therefore, many tools can be used to support the learning process in LPS such as the analysis of the frequency of plan failures, 5 Whys, Plan–Do–Check–Act (PDCA), Detect–Correct–Analyze–Prevent, variance analysis and the reason for variance (Hannis Ansah et al., 2016). **Table 6.3** summarizes the comparison between AWP and LPS.

Table 6.3. AWP vs Lean- Work approach

Work approach		
Criteria	AWP	Lean Construction (LPS)
Planning Structure	Milestone Planning L1 Planning (Areas) L2 Planning (Disciplines) L3 Planning (Work for a crew) CWA, CWP, EWP, IWP	Master Schedule Phase Scheduling Look-Ahead Planning Weekly Planning Daily huddle meetings and learning
Risk	Systemized risk analysis and constraints removal	Constraints removal throughout the whole project Error-proofing
Performance measurement	Productivity Safety Installation cost Delay	PPC, CR, SV, QA/QC, RA, RS, and others
Planning classification (colored stickers)	By areas and discipline	By trades
Learning	Knowledge management (IWP)	Analysis of Frequency of plan failures

Work approach		
Criteria	AWP	Lean Construction (LPS)
		5 Whys, Plan–Do–Check–Act, detect–Correct–Analyze–Prevent Variance analysis Reason for variance

6.2.3 Discussion

The analysis of the found studies showed that despite the differences in the approach, context and principles, type of projects, and structure and roles, the two concepts have many things in common. This shows room for mutual interaction and integration between the AWP and Lean Construction.

Figure 6.2 shows the possible integration chart between AWP and Lean Construction.

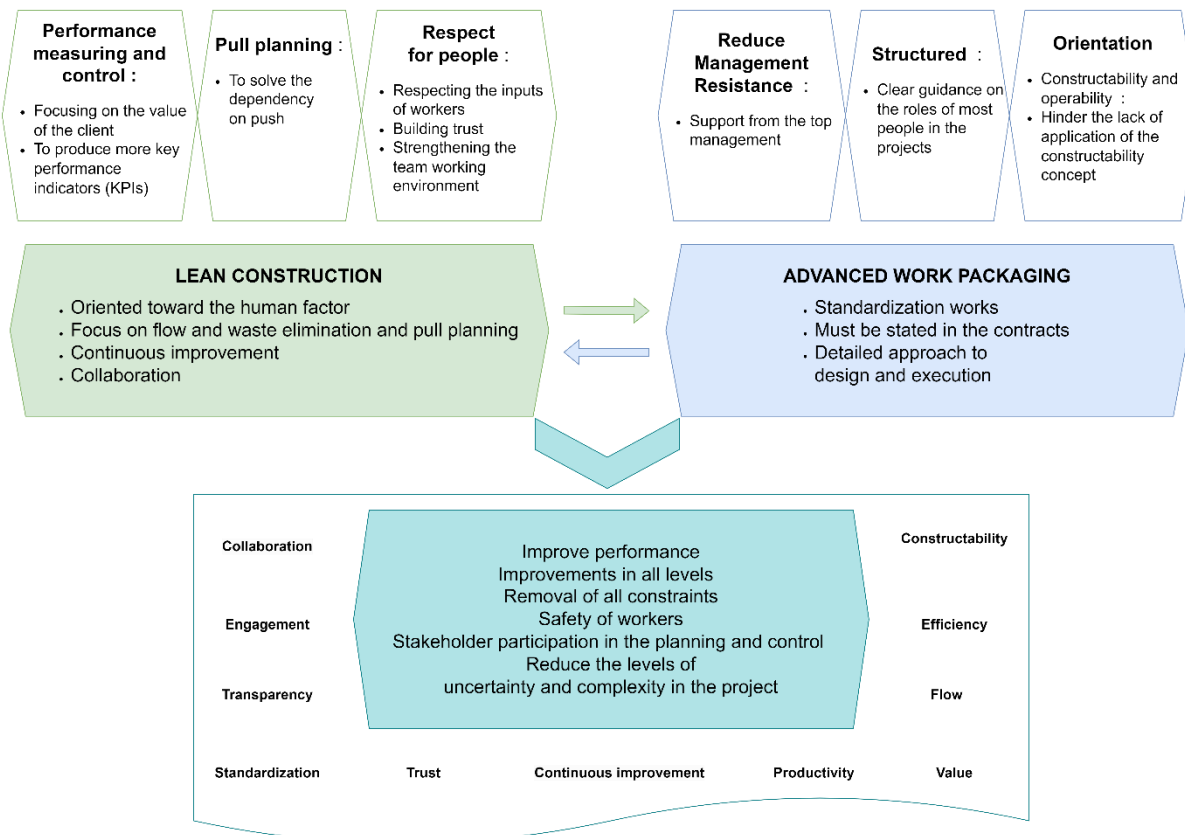


Figure 6.2. Possible integration chart between AWP and Lean Construction

More specifically, AWP and Lean Construction share the goals of creating improvements in productivity, quality, and efficiency in construction projects. Both focus as well on the removal of all constraints that may hinder the flow of work and affect efficiency. The safety of workers and stakeholder participation in the planning and control are also among the shared points between AWP and Lean Construction.

Concerning how AWP can benefit from Lean Construction, one of the primary focuses can be more oriented toward the human factor. In Lean Construction, respect for people is an essential principle that is reflected in most Lean tools; especially in the LPS. This principle requires respecting the inputs of workers, building trust, creating effective communication strategies, and strengthening the team working environment. More specifically, Lean Construction advocates a more "bottom-up" management style. This implies that managers encourage, reward, and disseminate improvement recommendations from workers on the ground. The motto "With every pair of hands comes a free brain" underscores the importance of involving workers in decision-making processes. This active engagement of workers using different ways foster a sense of ownership and value in their contributions. In Turn, AWP tends to follow a more "top-down" management approach. As a result, employees' sense of involvement in decision-making and enthusiasm for process improvement may not be as pronounced as in Lean Construction.

Additionally, AWP can benefit from other Lean principles such as the focus on flow and waste elimination and pull planning. This might help to solve the issues that may arise from the dependency on push such as shortages or excesses in materials. Moreover, while AWP has its tools to improve the learning process, there is still room to benefit from the continuous improvement experience in Lean thinking. Concerning performance measuring and control, focusing on the value

of the client may help to produce more key performance indicators (KPIs) that can help achieve better performance on different levels while implementing AWP. Finally, AWP can benefit from the integration with other concepts related to Lean such as TVD, IPD, and LPDS.

In turn, AWP can support the standardization works in Lean. With its structured way, AWP offers opportunities for easiness of implementation. This is supported by its clear guidance on the roles of most people in the projects. On one hand, this might be helpful to face the challenges of the reluctance of people to adopt Lean (Albalkhy et al., 2021; Albalkhy & Sweis, 2021). On the other hand, it is worth noticing that despite its contribution to clarity, this prioritization for standardization may pose challenges in adapting to dynamic environment and unforeseen circumstances. Accordingly, Lean Construction with its flexibility in response to changing conditions and encourages the use of individual judgment calls might be suitable for experienced workforces. In turn, AWP may be beneficial in situations requiring a structured approach, particularly with inexperienced teams that benefit from clear guidance but may face limitations in adapting to unexpected challenges.

Additionally, as AWP has to be clearly stated in the contracts, its adoption with Lean Construction may help to reduce the management resistance to change and the lack of support from the top management, which was considered in many studies among the most serious barriers facing the adoption of Lean (Albalkhy et al., 2021; Albalkhy & Sweis, 2021; Brien & Hamdi, 2016). Moreover, with its detailed approach to design and execution and its orientation toward constructability and operability, AWP adoption may hinder the lack of application of the constructability concept, which is another cited barrier that faces the adoption of Lean (Albalkhy et al., 2021). Finally, as a method that was specifically developed for a large-scale project, the

integration of AWP and Lean Construction can help to reduce the levels of uncertainty and complexity in the project.

The current section is based on the analysis of the literature. This comparison helps practitioners and researchers to identify the links and the differences between two concepts that can make improvements in the construction environment. It can serve as a reference to understand both concepts and integrate them. One main limitation is the low number of publications about AWP in comparison to Lean. Investigating possibilities, impacts, or challenges facing this integration between AWP and Lean Construction may require conducting further investigations that are based on case studies analysis or collecting perspectives via interviews, surveys, or any other data collection method. Another limitation of this study is that it does not focus on the detailed approach in AWP and a specific Lean tool such as LPS. Rather, it covers the main themes of the work. Future studies can provide a comparison on the base of details in each phase of the project.

6.3 Chapter Conclusions

This chapter presented a comparison between Lean Construction and AWP and their use for construction project management. The used methodology in this study was SLR to review studies about both concepts and their possible interaction.

The results of the chapter can be summarized as follows:

- 1- Lean Construction and AWP differ in four main ways. The first is related to the general context of the two concepts. While Lean Construction is a people-oriented philosophy with a set of tools and methodologies to improve performance and efficiency, AWP is a methodology that is task-oriented.
- 2- The second main difference is related to project specifications. Lean is applicable in many types of project, while AWP is suitable for capital projects.

- 3- The third main difference is related to the roles in projects. Unlike AWP, Lean and its different tools are not strictly defining the roles of people in project.
- 4- The fourth difference lies in the work approach of the two concepts. In comparison to AWP, Lean Construction covers more performance measures and gives higher focus on learning processes.
- 5- Despite the differences between Lean Construction-AWP, their integration may result in creating an environment that incorporates collaboration, engagement, transparency, trust, standardization, constructability, productivity and efficiency improvement, flow, value, and continuous improvement.

GENERAL CONCLUSIONS

Conclusions

The construction industry is the backbone of the economy of every country. Worldwide, construction projects are employing more than 7% of the global working population (Business Wire, 2022; McKinsey, 2020) and provide the necessary shelters for people and infrastructure to support their daily life activities. Nevertheless, the industry is characterized as a wasteful and susceptible industry, suffering from being easily affected by the external environment, poor quality, delays, poor safety, low profitability, and low productivity (Aziz & Hafez, 2013; Koskela, 1992). Therefore, many researchers, academics, and practitioners have called for the need to create change in the practices and methods of management in the industry.

Similar to what has happened in other industries (e.g. automobile industry), the construction industry has the opportunity to benefit from the principles and practices of Lean philosophy and the use of advanced technologies under the umbrella of the fourth industrial revolution in construction; Construction 4.0.

Aiming at benefiting from the two concepts, and with a focus on the French construction sector, this thesis covered the integration between Lean Construction and Construction 4.0 as follows:

Chapter 1 defined the philosophy of Lean and reviewed the historical evolution of Lean Construction and its different tools and practices. It also presented the concepts of Industry 4.0 and Construction 4.0. The chapter identified the opportunities of Lean Construction 4.0 and the barriers that may face its adoption.

Chapter 2 aimed to investigate the relationship between Lean Construction and IoT. To do so, the chapter was based on a review study using SLR methodology and two proposed frameworks in the material production phase and prefabrication. The results of the chapter showed that IoT with its different functionalities (monitoring, control, autonomy, data transfer, data storage, data analytics, and integration) can support Lean Construction implementation and help to improve flow, value generation, problem-solving, continuous improvement, and collaboration between partners.

Chapter 3 covered the relationship between Lean Construction and the integration and collaboration of digital tools (including BIM) in the design phase. The chapter that was built on two cases from France showed that the integration between Lean Construction and digital tools can help improve the performance of the design, deliver the design on time, improve collaboration, and achieve customer satisfaction. The first case in the chapter showed that this integration can be very effective in times of uncertainty as found during the COVID-19 pandemic. Nevertheless, the results of the second case showed that French design firms do not fully benefit from this integration as they do not have high levels of Lean adoption or support Lean training (94% of the companies do not provide training on Lean for their employees).

Chapter 4 explored the concept of digital twin in the construction sector and its integration with Lean Construction. The chapter showed that despite the challenges the digital twin adoption may face, the latter is expected to improve the performance in the construction industry and solve different problems related to safety conditions, productivity loss, and poor environmental performance. The integration of digital twin with green-based VSM was explored in this chapter. The integration is expected to support the visualization of the process, efficiency, CO₂ emissions reduction, and scenario testing.

Chapter 5 aimed to investigate the integration of Lean Construction and 3D printing. The chapter presented a review of the dual relationship between Lean and 3D printing and explored how the two concepts can work together to improve performance, decrease levels of waste and carbon impact, and improve efficiency. The chapter also presented a case study based on lab investigations. The results of the study showed that Lean Construction can help decrease waste in the 3D printing process. The study was based on two phases, the reduction of wastes in the second phase was 11%.

Chapter 6 presented a comparison between Lean Construction and AWP. Based on reviewing the related literature, the chapter summarized similarities and differences between Lean and AWP based on four categories; context and principles, project specification, roles in the project, and work approach. The chapter showed that despite the differences between the two concepts, Lean-AWP integration can be helpful to mitigate the impact of the challenges facing the adoption of the two concepts by enhancing collaboration, transparency, standardization, and continuous improvement.

The presented work in this thesis can be seen from two perspectives:

- The relationship between Lean Construction and Construction 4.0 technologies: which was studied based on three main directions (as depicted in *Figure 1* in the introduction): Construction 4.0 as an enabler for Lean Construction, Lean Construction as an enabler for Construction 4.0, and the correlation between the two concepts. The first direction can be seen in the use of IoT and digital twin as enablers for Lean in the material production phase in sections **2.2**, **2.3**, and **4.2** and the use of integration and collaboration tools as enablers for Lean planning in the time of COVID-19 pandemic in Section **3.2**. The second direction can be seen in the use of Lean to support waste elimination and improve the efficiency of 3D printing processes in Section **5.2**. In turn, the third direction can be seen in the rest.

- Lean Construction 4.0 along the main life cycle phases of the building: **Figure 3** shows that this thesis covered the integration between Lean Construction and Construction 4.0 along different phases. Lean Construction 4.0 was presented based on two cases in the material production phase, two cases in the design and planning phases, one case in the offsite production phase, and one case in the construction or on-site production phase. Future work can investigate the integration in the operation and use, renovation, end-of-life, or deconstruction phases.

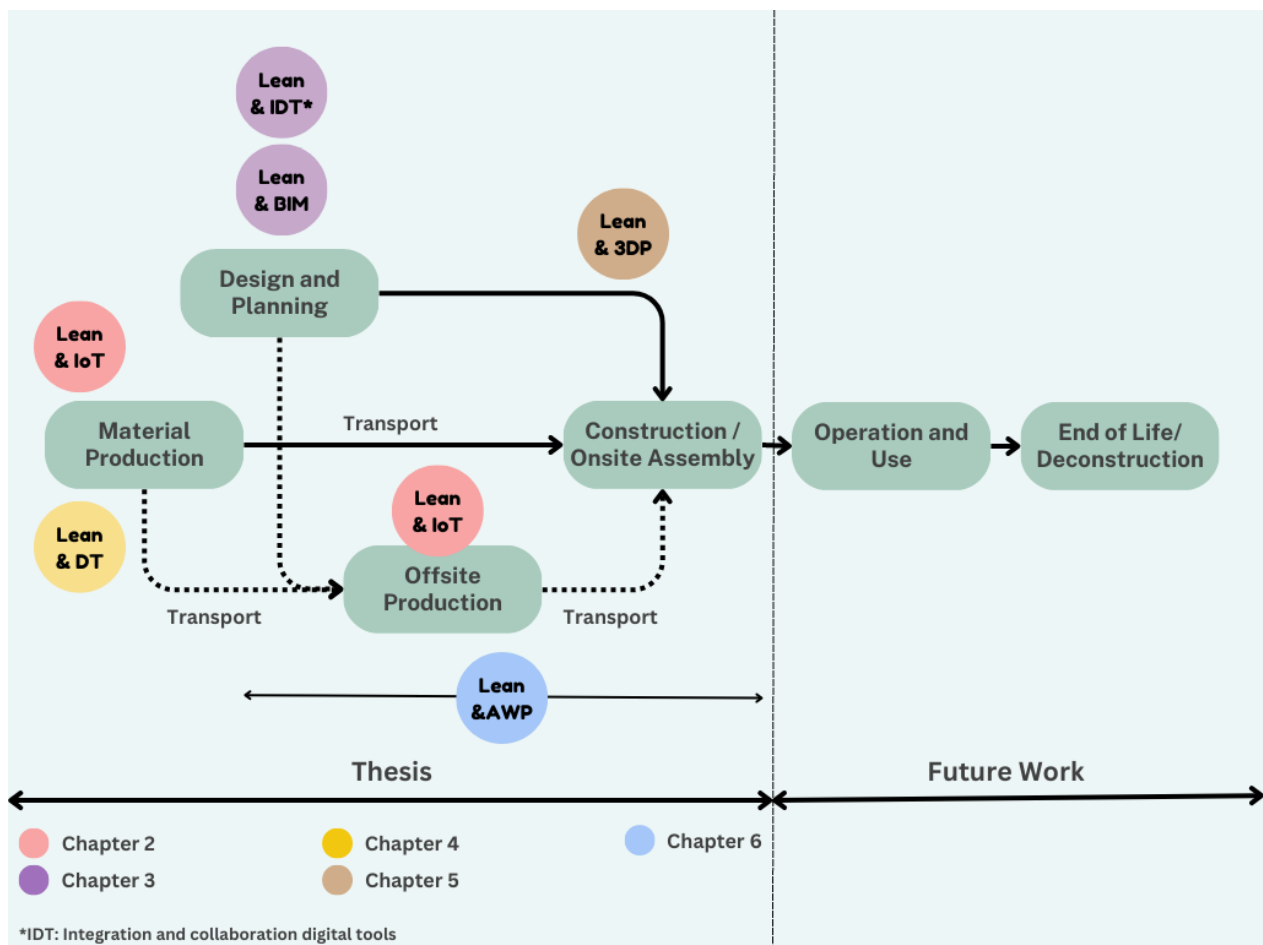


Figure 3. Lean Construction 4.0 along the main life cycle phases of the building

Perspectives and Future Directions

The general perspectives and future directions of research can be summarized as follows:

- 1) The results of this thesis show that Lean Construction 4.0 can create a construction environment where performance improvement, people consideration, collaboration, efficiency, and productivity can be respected and achieved.
- 2) Lean Construction 4.0 is not easy to implement. During its implementation, both social and technological challenges have to be considered. Strategies to balance between technological adoption, efficiency goals, and respect for people are needed to ensure mitigating the impact of the faced challenges. Gradual implementation to gain continuous improvement and reduce resistance to change can be a critical success factor to implement Lean Construction 4.0.
- 3) This thesis aims to present the potentials and ontologies of the concept of Lean Construction 4.0. Therefore, the thesis does not deal with a specific case of Lean Construction 4.0 implementation. Future studies can focus on a specific application (e.g. Lean and IoT) for one or multiple projects and identify the different factors affecting this implementation.
- 4) Due to the time limitations and difficulty of data collection (especially during the COVID-19 pandemic), this thesis did not study the implementation of a specific case along all project life cycle phases. Future research directions can investigate the implementation of a specific case and compare the results gathered in different phases.
- 5) While this thesis tries to promote Lean Construction 4.0 by proposing more than one framework, the performance of the proposed frameworks has not yet fully investigated due to the time limitation (despite being put in practice). Further investigations are needed to

evaluate the performance of these frameworks and identify the effectiveness of them and the challenges that may encounter.

- 6) This thesis explored the integration between Lean and three main categories of Construction 4.0 technologies; industrial production and construction (3D printing and prefabrication), cyber-physical systems (IoT), and digital technologies (DT, BIM, and integration and collaboration digital tools). The selection of these technologies was based on the accessibility to the cases/data or the needs of the collaborators. Future works can cover other technologies such as VR, drones, AI...etc.
- 7) The current study does not investigate the perspectives of professionals or academics about the topic of Lean Construction 4.0. These perspectives can be the direction of future works.

Thesis Contributions

The academic contribution of this thesis lies in:

- 1) Contributing to the existing knowledge about Lean Construction 4.0 globally and in France.
- 2) Exploring theoretical bases and synergies between Lean principles and Construction 4.0.
- 3) A new endeavor to understand the nature of the relationship between high-tech solutions and human-centric approaches.

In turn, the practical contribution is understand based on the following:

- 1) Exploring the potential of Lean Construction 4.0 and increasing awareness of this concept.
- 2) Providing replicable and usable frameworks and tools to respond to existing problems and challenges.

- 3) Increasing the likelihood of fulfilling stakeholders' requirements and improving performance in the construction industry.
- 4) Supporting digital transformation in the construction sector.

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ANNEXES

Annex 1

Lean-IoT Matrix Statements

No	Statement	Reference
1	The implementation of IoT will shrink the time gap between data capture and decision-making, empowering supply chains to respond to real-time changes with an unprecedented level of agility and responsiveness	(Ben-Daya et al., 2019)
2	IoT facilitates the remote management of supply chain operations, enhances coordination with partners, and furnishes more precise information to bolster more effective decision-making	
3	When smart objects emit data that is collected, analyzed, and transformed into meaningful information, it can provide unparalleled visibility into every facet of the supply chain. This not only offers early warnings of situations, both internal and external, that necessitate remedial action but also enhances overall situational awareness	
4	IoT elevates supply chain communications to a new standard, introducing the potential for communication between humans and connected devices, as well as autonomous coordination among these devices. This applies whether they are stored in a facility or in transit between different entities within the supply chain	
5	IoT facilitates the virtualization of supply chains, offering buyers virtual control to track and trace goods as they traverse through the supply chain. This capability extends to performing advanced quality control and planning with enhanced precision	
6	The utilization of cloud computing, combined with smart communication devices, has the potential to minimize the time delay between placing an order and shipping building materials	(A. Kumar & Shoghli, 2018)
7	Smart sensing devices such as RFID tags can be applied to tag the inventory at construction sites or warehouses. These devices not only keep track of the available stock but also can initiate a replenishment request when the inventory falls below predefined levels	
8	In an era where customer satisfaction is of utmost importance, organizations can employ big data services to identify potential customers and tailor their products and marketing strategies based on customer needs	
9	Leveraging IoT enables the tracking of construction equipment such as machinery, excavators, scrapers, drilling machines, cranes, and booms. This system manages resource allocation and strategically positions equipment on job sites	
10	IoT helps technicians to remotely operate machinery, enhancing safety. Wireless networking enables work execution through remote-operated machines and robots, ensuring efficiency and risk reduction	
11	Smart sensing devices enhance safety standards onsite. Employing technologies such as smart locating, imaging, laser sensors, and hawk-eye-vision cameras ensures the well-being of on-site personnel	
12	RFID tags are used in the shipping process to provide essential information about materials (e.g. manufacturer, product quality, and specifications), benefiting professionals such as buyers, project managers, and truck drivers. RFID acts like a price tag, particularly for large construction components, ensuring accurate tracking	

No	Statement	Reference
	when combined with technologies such as Global Positioning System (GPS) and Geographic Information System (GIS)	
13	Effective inventory management is crucial in construction for a seamless process. RFID technology enhances this by placing RFID readers in storage areas. This allows for easy maintenance of inventory, as the readers automatically update the inventory by reading RFID tags attached to materials	
14	Leveraging cloud computing and big data allows for the operation, recording, and storage of information from machines, software, sensors, and individuals. This data, housed in the cloud, can be accessed via various devices, unrestricted by physical location or time constraints	
15	Employing IoT alongside intelligent sensing devices enhances communication and material tracking with precision, eliminating issues like human error, workforce shortages, budget constraints, adverse weather, and environmental factors	
16	IoT allows for the management of ready-mix concrete operations by tracking the position of trucks and monitoring the real-time motion and status of concrete conveyances	
17	The tracking of labor, materials, and equipment in complex construction sites can be optimized with the use of sensors such as Bluetooth Low Energy and motion sensors. These systems integrated BIM models to visualize movement paths, facilitating the monitoring of resource status and labor behavior	(Tang et al., 2019)
18	The monitoring of construction performance and progress can benefit significantly from IoT devices and BIM. Sensors capture reality data, incorporating actual performance, project status, construction activity, and real-time project information. When integrated with BIM, these data can effectively monitor the construction process and facilitate timely updates to construction schedules	
19	Health and safety training systems can employ BIM and Ultra-Wideband (UWB) sensors. In these systems, the location of trainers, trainees, materials, and equipment during the training can be tracked. Collected sensor data and BIM models are utilized for safety and productivity analysis, offering real-time and post-event visualization via a VR environment	
20	Implementations of on-site health and safety (H&S) monitoring involve the integration of sensors and BIM for enhanced safety. IoT devices are integrated with BIM tools, facilitating real-time data query, risk identification, and visualization over BIM models. This approach, incorporating sensor networks and BIM models, mitigates risks in complex and confined construction sites. Structure monitoring sensors, RFID tags, and BIM enable visualization for structural health monitoring, complemented by surrounding environment monitoring and portable warning devices for early hazard warnings during work.	
21	Integrating IoT, computer vision, and resource positioning into design and planning, supported by AI, enhances visual management. Real-time processing provides workers prompt answers, while digitalization ensures automatic exposure to pertinent information, streamlining task execution without the need for active information-seeking	
22	“Through multi-agents and IoT framework and a pull-based production system, the products will themselves “know” when the next operation that needs to be performed on them and the related schedule. Hence, a product would “call” for delivery from a manufacturer or a supplier when it is ready to be shipped to the site”	(Dave et al., 2015)

No	Statement	Reference
23	Upon arrival at the site, the product communicates its location and alerts the worker when it's ready for installation. This production logic extends across the entire product lifecycle, encompassing design and operational phases	
24	Wireless sensors and the auto-ID system network provide real-time awareness of environmental and structural conditions, identity, time, activity type, location, and reasons. This aligns seamlessly with the generic objectives of the visual management strategy by embedding information into processes, facilitating information flow, and enhancing workplace autonomy through increased process transparency	(Tezel & Aziz, 2017)
25	Leveraging IoT in tools and machinery automates the generation of performance data on visual boards in construction. Supervisors, equipped with mobile devices, can provide immediate feedback across expansive construction areas on various performance aspects, including 5S audits or the health and safety conditions of specific work units or locations. In turn, Construction units receive customized performance information and standardized operation procedures based on their trade, location, work requirements (e.g., plans, health and safety, quality), and work times (day or night).	
26	Extending BIM-based Kanban systems to mobile devices is viable. Mobile devices, acting as RFID tag readers/writers through AutoID technologies, facilitate Kanban signals among work units, conveying visualization information. Additionally, IoT enables inanimate objects to independently generate Kanban signals for purposes such as material replenishment, machinery/tool safety checks, and monitoring machinery utilization status (idle, stopping, working, etc.)	
27	Drones and RFID readers can play an effective role in managing on-site materials on large construction sites. Their use in visual controls enables effective tracking of stocked materials, automating "pull" signals. This streamlines production and replenishment through an ERP system, aligning with Just-in-Time delivery practices. Which in turn, guarantees optimal inventory levels and work-in-progress based on external/internal demands	
28	In construction logistics, real-time monitoring and visualization of the entire supply chain, from design to demolition, is attainable through RFID and Near Field Communication (NFC) technologies. This enables operating with minimal safety stocks and ensures a dependable Just-in-Time delivery system	
29	Immediate access to supply chain information enhances workforce awareness and maintains stock levels at their optimal points	
30	In warehouses, sensors visually monitor atmospheric conditions, environmental factors, material quantities, consumables, and tool possession information in real-time on-site	
31	On-site stocked materials and tools can be effortlessly located and monitored by the workforce, minimizing material losses and reducing the time spent searching for them	
32	Visual control and real-time tracking can diminish on-site theft, site restriction violations, and misuse of materials, equipment, or plants by monitoring whether they have been moved from restricted areas without permission	
33	Sensors play a crucial role in monitoring and visualizing both structural conditions, such as soil or concrete strain, and environmental conditions, including temperature, moisture, rainfall, specific gas levels, and wind speed. This is essential for safety and quality management purposes	
34	Utilizing IoT, the illumination on a construction site can be automatically tailored to daylight conditions, averting accidents and errors associated with visibility issues	

No	Statement	Reference
35	Integrating BIM with IoT addresses challenges in construction projects, mitigating the lack of updated information and information silos. This fusion enables communication between systems and humans, with the primary objective of capturing data at the right moment and delivering it to the appropriate individual promptly	(Reinbold et al., 2019)
36	The envision of automated tracking and monitoring of labor efficiency by Lean managers aligns with a scientific optimization approach through the PDCA framework	(Teizer, Golovina, et al., 2020)
37	Utilizing LoRa architecture in construction, along with embedded GNSS sensors, expedited material searches for apprentices. This demonstrated the technology's superiority in handling and analyzing the vast amount of data prevalent in construction processes, surpassing human capabilities	
38	Construction companies can cut management and coordination costs by utilizing an IoT-based platform. This approach minimizes paperwork as information becomes easily accessible and shareable on the platform.	(G. Xu et al., 2018)
39	The reliance on phone calls can be decreased, as a substantial portion of communication can be transitioned to IoT platforms. This shift brings additional benefits, including enhanced clarity, accuracy, and timeliness	
40	Utilizing IoT, the integration of internal and external data is summarized on a supply chain management platform. It delivers perceptive information promptly to each node enterprise, encompassing product, enterprise, and supply chain knowledge. Timely and effective communication understands customer requirements, facilitating orderly interaction between internal and external management	(L. Y. Wang, 2016)
41	Construction enterprises can achieve real-time sharing of material planning and inventory with suppliers, enhancing visibility into enterprise demand. By aligning with procurement planning and order processes on the IoT platform, accuracy and timeliness are improved, enabling the goal of Lean procurement with precise, timely deliveries	
42	In pursuit of Lean inventory management, construction enterprises aim to minimize inventory, mitigating the "bullwhip effect" in the supply chain. This necessitates suppliers to accurately grasp the inventory status. Leveraging an IoT-based platform, timely material deliveries are realized, and transport routes are optimized, addressing these challenges. The platform facilitates real-time information exchange between construction enterprises and suppliers, enabling suppliers to strategically allocate and distribute materials, monitor transportation in real-time, and optimize distribution routes, achieving the objective of Lean inventory	
43	In the competitive construction market, Customer Relationship Management (CRM) is essential for enhancing customer service. Construction enterprises can adopt an IoT Customer Management Platform to understand and address personalized customer needs, fostering loyalty and retention. This platform enables real-time perception of customer information, facilitating prompt responses to complaints and suggestions, ultimately improving building quality and maximizing customer value	
44	Leveraging a fusion of IoT technologies, ERP, and BPR breaks down internal departmental self-interests. This transformation in the production model is facilitated by direct communication of things to things. EPC technology plays a crucial role in delivering precise inventory information, thereby minimizing internal waste and elevating overall efficiency	(L. Y. Wang, 2012)
45	Integrating IoT technologies with ERP and BPR optimizes business processes, fosters extensive information sharing with suppliers, and tracks product composition and	

No	Statement	Reference
	sources. This enhances construction product quality and allows for personalized product design to meet customer demands, fostering long-term customer relationships	
46	“Accurate resource tracking is crucial for efficient production management, particularly in managing the flow aspect. IoT messaging standard O-MI (Open Messaging Interface) and O-DF (Open Data Format) enables the integration of advanced tracking tools such as RFID, Quick Response (QR) codes, and GPS systems. This integration allows for comprehensive resource tracking at every stage of the construction process, providing visibility from placing an order for structural steel to its journey from the supplier to the site and designated storage areas”	(Dave et al., 2016)
47	The production team can precisely plan tasks based on both the resources within the order and the available resources. O-MI/O-DF will be employed to "push" this information to pre-assigned recipients and devices, such as smartphones for the site supervisor or project manager	
48	In field operations, real-time updates of production information can reduce waiting times for workers and enhance responsiveness when work is halted. IoT can facilitate a fully automated system utilizing electronic communication where workers equipped with smartphones can easily access planned task information and update task status (e.g., started, stopped, completed)	
49	By employing Electronic Product Code (EPC) and RFID, each building material can be assigned a labeled tag containing comprehensive interoperability information. This allows for the tracing of the building material's composition, processing history, and source, ensuring quality and minimizing waste	
50	IoT is effective in managing supplier information. Based on performance, suppliers can be categorized for effective management and selection of strategic partners, fostering long-term relationships	
51	By utilizing IoT and CRM, enterprises can gain a thorough understanding of customer demands through the acquisition, recording, and analysis of relevant information. This facilitates the delivery of customized services	(L. Y. Wang, 2012)
52	Utilizing IoT in construction machinery, materials, tools, and devices enables programming them to send critical information to mobile devices, acting as safety and quality poka-yokes. For instance, sensors in plants and work helmets can communicate, providing warnings to work units about potential hazards. This allows the creation of customized poka-yoke systems for different work teams facing various conditions and constraints	(Tezel & Aziz, 2017)
53	Wireless data transfer in IoT usually occurs without human intervention. Collected data is analyzed in cloud spaces, enabling convenient access and evaluation through smart, user-oriented applications, including building information systems and services	(Teizer, Golovina, et al., 2020)
54	Effectively managing and promptly updating information from the field ensures up-to-date actionable insights. Instantly relaying this information to all on-site personnel enhances downstream task reliability, promoting safety and quality in future assignments. This, in turn, improves predictability, boosting production unit efficiency and minimizing waste linked to poor productivity. Transmitting this information from field personnel supports safety and quality in production teams, fostering efficiency and reducing waste in the field. All stakeholders can review and identify successes and areas for improvement.	(McHugh, Dave, & Koskela, 2022b)

Annex 2



Impact of Lean and Building Information Modeling (BIM) Integration on Construction Design Performance

Survey

Dear Madam/Sir,

We would like to seek your kind cooperation in participating in this survey. The survey aims to identify the level of Lean-BIM implementation in the French construction design and studies offices.

Your participation in this survey is strictly voluntary and you may withdraw at any time. The questionnaire will take roughly 5-10 minutes to complete. We assure you that the results of this study will only be used for academic purposes and your response will be confidential. While completing this survey, you will not be asked to add any information about your identity or the identity of the company (no need to put names or contact details).

If you have any questions regarding your rights as a participant, please do not hesitate to contact us. Your response is very important and we appreciate all your time and effort in completing this survey.

Thank you very much.

PAGE 1: General Information

Participant Profile:

- Participant's number of years of experience: *(please tick (✓). On the box)*
 - Less than 3 years
 - 3-5 years
 - 5-10 years
 - More than 10 years.

- Participant's position:

Company Profile:

- Company/Office years of experience in construction design: *(please tick (✓). On the box)*
 - Less than 3 years
 - 3-5 years
 - 5-10 years
 - More than 10 years.

- Type of projects the company is involved in their design:

- Company Size: *(please tick (✓). On the box)*

- Less than 10 employees 10-50 employees 50-100 employees
- More the 100 employees.

PAGE 2: BIM

- How long the company/office has been using BIM: *(please tick (✓). On the box)*
 - BIM is not used in the company Less than 1 year 1-5 years
 - 6-10 years More than 10 years

- Does the company provide training on BIM: *(please tick (✓). On the box)*
 - Yes No

- What are the disciplines the company uses BIM in: *(please tick (✓). On the box: more than one choice is possible)*
 - Architecture Structure Electrical and alarm systems Mechanical systems
 - Plumbing Fire protection

- Kindly, using a scale (from Never to Always), indicate the uses of BIM in the design phase of the projects of your company:

Dimension	Item	Never	Rarely	Sometimes	Often	Always
Cost Estimation	Specialist designers are involved during the early stages of the project					
4D Planning	A 4D BIM model is utilized to effectively plan, especially spatial planning, including spatial clashes and paths					
Site Analysis Space	BIM/GIS is used to select and evaluate a site location and to select a building position on the site					
Space Programming Design	A BIM model is used to design and analyze the project spaces and rooms and to assign each space use and its measurements					
Design Review	Stakeholders interact with a BIM model and provide their feedback to validate multiple design aspects					
Code Validation	The model parameters are checked against project-specific design or construction codes or norm					
Sustainability Evaluation	The sustainability of a facility is evaluated and tracked using a sustainability metric system					

Dimension	Item	Never	Rarely	Sometimes	Often	Always
Engineering Analysis	A BIM model and specialized software are used to identify the most efficient method or design					
Design Authoring	A project is designed in a BIM model, where the typical iterations of a project are made, and everything is built directly in the BIM software					
3D Coordination	A 3D coordination software is used to identify 3D geometric conflicts by comparing 3D models of building systems.					

PAGE 3: Lean and Lean-BIM

- How long the company/office has been adopting Lean: (*please tick (✓). On the box*)
 - Lean is not adopted in the company
 - Less than 1 year
 - 1-5 years
 - 6-10 years
 - More than 10 years
- Does the company provide training on Lean: (*please tick (✓). On the box*)
 - Yes
 - No
- Kindly, using a scale (from Never to Always), indicate the uses of the following in the design phase of the projects of your company

Dimension	Item	Never	Rarely	Sometimes	Often	Always
Client value	Instead of one brief of requirements by the client, the early design is developed in an iterative way. In each iteration, the requirements of the client are evaluated and the design is refined.					
	BIM models are used to develop the early design to help evaluate the requirements of the client					
Set-based strategy	Designers consider sets of alternatives from the start of the design process rather than developing one alternative at the beginning					
	BIM is used to enable rapid visual creation, communication and assessment of project alternatives					
Early involvement of stakeholders	Major project stakeholders (e.g. contractors, suppliers...) are involving early in the design process					
	BIM models are used in the design phase to help stakeholders to virtually plan and construct the building					

Dimension	Item	Never	Rarely	Sometimes	Often	Always
Collaborative Design	BIM models for all design teams can be combined periodically for collaborative working and analysis					
	The client is participated in the meetings regularly to support decision-making and problems resolution					

- Kindly, indicate if you use any of the following tools in the design phase of the projects of your company:

A3 Problem solving	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Target Value Design (TVD)	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Integrated Project Delivery (IPD)	<input type="checkbox"/> Yes	<input type="checkbox"/> No
5S	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Value Stream Mapping (VSM)	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Design Workshop /Big Room (co-location)/ iRoom	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Plan-do-check-act (PDCA)	<input type="checkbox"/> Yes	<input type="checkbox"/> No
Design structure Matrix	<input type="checkbox"/> Yes	<input type="checkbox"/> No

PAGE 4: Design Performance

Please rate the following statements based on the performance in your projects on a scale starts from strongly disagree to strongly agree

In our projects:

Item	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
We are able to understand clients' needs and requirements					
The definition of the scope of work is quick					
Delivery of design is usually on-time					
Design errors and reworks are minimal					
Change orders are minimal					
Dealing with change orders is easy					
Clashes and are minimal					
Disputes are minimal					
Clients are generally satisfied					
Decisions are taken flexibly					
Stakeholders are engaged easily					
Design process is delivered with the expected budget					

Annex 3

Digital Twin Definitions in the Literature and Industry

No	Definition	Reference
1	“A digital twin is a realistic digital representation of assets, processes or systems in the built or natural environment. What distinguishes a digital twin from any other digital model is its connection to the physical twin. Based on data from the physical asset or system, a digital twin unlocks value principally by supporting improved decision making which creates the opportunity for positive feedback into the physical twin”	(Sacks et al., 2020)
2	“A digital twin (DT) - also referred to as digital shadow, digital replica or digital mirror - is a digital representation of a physical asset. Linked to each other, the physical and digital twin regularly exchange data throughout the PBOD lifecycle and use phase. Technology like AI, machine learning, sensors and IoT allow for dynamic data gathering and right-time data exchange to take place”	(Building Smart International, 2020)
3	“A digital twin is a mirror image of a physical process that is articulated alongside the process in question, usually matching exactly the operation of the physical process which takes place in real time”	(Batty, 2018)
4	“The digital twin is a hierarchical system of mathematical models, software services, and computational methods, which facilitates real-time synchronization between a real-world model (physical model) and its virtual copy for improved monitoring to the efficiency of the equipment.”	(David et al., 2018)
5	“A Digital Twin is an integrated Multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin.”	(Glaessgen & Stargel, 2012)
6	“A digital twin is a computerized model of a physical device or system that represents all functional features and links with the working elements.”	(Yubao Chen, 2017)
7	“The digital twin is actually a living model of the physical asset or system, which continually adapts to operational changes based on the collected online data, information, and can forecast the future of the corresponding physical counterpart.”	(Q. Qi & Tao, 2018)
8	“A digital twin is a virtual instance of a physical system (twin) that is continually updated with the latter’s performance, maintenance, and health status data throughout the physical system’s lifecycle.”	(Madni et al., 2019)
9	“Digital twin is a set of virtual information that fully describes a potential or actual physical production from the micro atomic level to the macro geometrical level.”	(Y. Zheng et al., 2019)
10	“There are five levels of digital twins depending on the level of development and characteristics of the digital twin: a level 1 digital twin is the conventional prototype produced for engineering purposes and supports early decision making at the concept stage. A level 2 digital twin can incorporate historical data, maintenance data, and operational performance from the physical twin. A level 3 digital twin is the adaptive digital twin that contains an adaptive user interface for the digital and physical twins; it can learn the priorities and preferences of the operator in various contexts and is continuously updated based on the information received from the physical part in real time. A level 4 digital twin is an intelligent model that includes the functionalities of level 3 and is capable of self-learning without any supervision. Finally, a level 5 model is receptive to the data provided by external sources and processes the data for analysis in a situational context”	(Madni et al., 2019)
11	“An interconnected ecosystem of digital twins, each modeling a component, a system, or a system of systems of buildings and infrastructure, connected via securely shared data—reflects the view of the nature of digital twins in the built environment”	(Sacks et al., 2020)
12	“Digital twin a digital replica of physical assets, processes and systems that can be used in real-time for control and decision purpose”	(Vatn, 2018)

No	Definition	Reference
13	“Digital twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level and any information that could be obtained from inspecting a physical manufactured product can be obtained from its digital twin”	(Grieves & Vickers, 2016)
14	“Digital twin refers to a virtual representation of manufacturing elements, a living model that continuously updates and changes as the physical counterpart changes to represent status, working conditions, product geometries and resource states in a synchronous manner”	(Dai et al., 2021)
15	“It is a virtual mapping of the real world through modeling, providing data support for relevant personnel to evaluate the physical world”	(Songchun Wang et al., 2021)
16	“Digital twinning is a process of simulating multiple physical quantities, scales and probabilities by making full use of physical models, updating sensors and running historical data, and reflecting all information in the whole life cycle of physical equipment”	(Songchun Wang et al., 2021)
17	“A realistic digital representation of assets, processes, or systems in the built or natural environment”	(Bolton et al., 2018)
18	“A model of the physical object or system, which connects digital and physical assets, transmits data in at least one direction, and monitors the physical system in real time. In addition, it also should support analytics, control, and simulation functions”	(High Value Manufacturing Catapult Visualisation and VR Forum, 2018)
19	“An integrated software solution to manage static and dynamic information of a built asset across its lifecycle phases. It usually provides a realistic digital representation of the physical asset, generated by enriching the geometric or graphical data with support from building automation systems (BAS), sensors, internet of things (IoT) components, and other feedback systems informing about the asset, its occupants, or its environment”	(Camposano et al., 2021)
20	“A physical entity, a virtual counterpart, a connection between a physical and a virtual counterpart, data, and service are the components of a complete Digital Twin”	(Tao et al., 2018)
21	“A cyber-physical system consists of a physical entity and a cyber entity in the form of a Digital Twin”	(Autiosalo et al., 2020)
22	“The Digital Twin of a physical entity involves layers of data consisting of the product itself, the processes, and the resources in the environment where it functions”	(Demkovich et al., 2018)
23	“The Digital Twin is a digital counterpart of a physical object”	(Kritzinger et al., 2018)
24	“The Digital Twin is a virtual representation of a production system that can be synchronized with the production system by means of sensed real-time data obtained via connected smart devices”	(Negri et al., 2017)
25	The Digital Twin refers to a virtual representation of a component, product, or system that may be useful throughout the entity’s lifecycle	(Boschert & Rosen, 2016)
26	“Digital twin refers to digitally creating a virtual model of a physical entity, which is a perfect mapping of the entity, not only simulating the entity’s behavior in the real environment with the help of data but also making command operations on the entity, making the production process run under the guidance of the plan”	(Y Liu et al., 2021)
27	“A digital comprehensive physical and functional description of a component, product or system together with all available operational data useful in all the current and subsequent lifecycle phases”	(Boschert & Rosen, 2016)
28	“A Digital Twin of a certain product is defined as a virtual representation of its real-world counterpart, which (1) contains all essential elements, such as all geometrical components and material properties; (2) simulates accurately and realistically all relevant processes and their kinetics throughout the product’s life- cycle; and (3) is	(Defraeye et al., 2021)

No	Definition	Reference
	connected to the real-world product and processes by sensor data, which is preferably continuously updated in real-time”	
29	“Digital Twin of a construction project is the concept where a digital model related to either an existing, on-going, or future construction project is created and is linked throughout its lifecycle. When the project is existing or on-going, the digital model is a replica of the physical project and the two aspects (i.e., virtual and physical) have a bi-directional relationship enabled through advanced technologies including IoT, CPS, AI, and sensors. In the case of a future project, the digital models built from historical projects feed into the realization of the future project creating a one-directional relationship, which becomes bi-directional when the future project is in construction mode. Through this bi-directional relationship, the digital model is enriched in real-time with layers of up-to-date semantic data such as geometric, specifications, drawings, schedules, and financial reports that builds up through every phase of the construction project lifecycle and is an accurate representation of the project at a time t. This digital model is translated into information that construction stakeholders can use at time t and in the future”	(Ammar et al., 2022)
30	<p>“A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity.</p> <ul style="list-style-type: none"> • Digital twin systems transform business by accelerating holistic understanding, optimal decision-making, and effective action. • Digital twins use real-time and historical data to represent the past and present and simulate predicted futures. • Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT/OT systems.” 	(Digital Twin Consortium, 2020)
31	“A digital twin is an exact digital replica of a physical asset—an up-to-date thread of information for every component of a project. It brings together design, construction, and operational data to improve efficiencies and help reduce the total cost of ownership for your customers”	(Autodesk, 2023)
32	“The virtual twin is both the digital replica of the product itself and of its history and evolution.”	(Dassault Systèmes, 2023)
33	<p>“A digital twin is a virtual representation of a physical product or process, used to understand and predict the physical counterpart’s performance characteristics. Digital twins are used throughout the product lifecycle to simulate, predict, and optimize the product and production system before investing in physical prototypes and assets. By incorporating multi-physics simulation, data analytics, and machine learning capabilities, digital twins are able to demonstrate the impact of design changes, usage scenarios, environmental conditions, and other endless variables – eliminating the need for physical prototypes, reducing development time, and improving quality of the finalized product or process.”</p>	(Siemens Software, 2023)
34	“A realistic and dynamic digital representation of a physical asset, system or city”	(Bentley Systems Software, 2023)

FRENCH EXTENDED ABSTRACT

L'industrie de la construction est l'une des principales industries qui emploie plus de 180 millions de travailleurs dans le monde. Cependant, elle est confrontée à de nombreux défis tels que le faible niveau d'adoption de la technologie, le manque de main-d'œuvre qualifiée, le manque de collaboration, la faible productivité et la résistance au changement. La France n'est pas à l'abri de ces défis, comme en témoignent les statistiques sur les problèmes de rentabilité, les retards, la faible qualité, les conditions de sécurité médiocres, les quantités importantes de déchets et les faibles niveaux de dépenses en R&D dans le secteur.

Pour relever ces défis, les chercheurs proposent des stratégies telles que la Lean Construction et la Construction 4.0, collectivement appelées Lean Construction 4.0. La Lean Construction, basée sur le système de production de Toyota, met l'accent sur des principes tels que la génération de valeur, l'élimination des déchets, le flux continu et l'amélioration continue. À son tour, la Construction 4.0 s'aligne sur la quatrième révolution industrielle (Industrie 4.0), intégrant des technologies intelligentes telles que la modélisation des informations du bâtiment (BIM), le jumeau numérique, l'intelligence artificielle (IA), l'internet des objets (IoT), les drones et l'informatique en nuage pour améliorer les performances des processus de construction.

Motivée par des études montrant l'efficacité de la Lean Construction et de la Construction 4.0 dans l'amélioration de l'innovation, de la durabilité, de l'efficacité des coûts et des gains de temps, la thèse se concentre sur l'intégration des deux concepts. Une telle intégration est utile pour tirer parti des deux concepts et éviter toute mise en œuvre inappropriée. Par exemple, il est largement conçu que parfois, lorsque la technologie est utilisée, les personnes peuvent se sentir démunies en raison de la suraccentuation de la technologie. D'autre part, à l'ère de la technologie avancée, la

Construction 4.0 peut aider la Lean à réduire la complexité et à améliorer la visualisation, l'inclusion, la détection des besoins des clients et le partage d'informations. Néanmoins, malgré l'importance de cette intégration, elle est encore négligée.

En étudiant cette intégration, différents manques de recherche ont été identifiés, et sur cette base, les objectifs de la recherche ont été définis. Le premier objectif est de passer en revue les synergies entre la Lean Construction et les technologies de la construction 4.0. Cela était dû au faible nombre de revues sur ce sujet. Le deuxième objectif concerne la mise en œuvre des deux concepts en France. Cet objectif a été fixé en raison de la rareté d'études à leur sujet en France. De plus, comme le sujet de la Lean Construction 4.0 est encore nouveau, il est nécessaire de proposer des cadres pour soutenir la mise en œuvre de la Lean Construction 4.0 (le troisième objectif) le long des principales phases des projets de construction (le quatrième objectif). Le dernier objectif était d'analyser la relation entre la Lean Construction et les nouvelles méthodes de gestion de projet. À cette fin, l'exemple de l'Advanced Work Packaging (AWP) a été pris. En conséquence, le travail de thèse a été organisé en 5 parties principales : Lean et IoT, Lean et outils numériques pour la conception, Lean et jumeau numérique, Lean et impression 3D, et Lean et AWP.

Lean Construction et IoT

L'intégration de la Lean Construction et de l'Internet des objets (IoT) est abordée à travers trois études dans cette thèse. Dans la première étude, une revue exhaustive de la littérature a exploré l'intégration des principes de la Lean Construction avec les fonctionnalités de l'Internet des objets (IoT). En analysant 268 études sur l'IoT et 43 études sur la Lean Construction, la revue a identifié cinq principales fonctionnalités de l'IoT : la surveillance, le contrôle, le support aux opérations autonomes, la gestion des données et l'intégration de différents systèmes. Les résultats ont révélé

que l'IoT, à travers ces fonctionnalités, peut soutenir tous les principes de la Lean, avec un accent particulier sur l'amélioration du flux grâce au transfert de données et au partage d'informations.

La deuxième étude s'est concentrée sur la mise en œuvre pratique de l'IoT dans une entreprise de fabrication de briques en France. Face à des défis tels que le gaspillage et les retards, l'entreprise a adopté des stratégies de l'Industrie 4.0, installant un système IoT pour surveiller le flux de travail. Le système, tout en étant efficace pour identifier les produits gaspillés, a rencontré des défis liés à l'acceptation des travailleurs et à la responsabilité, soulignant l'importance de prendre en compte le facteur humain dans la mise en œuvre de la technologie.

La troisième étude visait à améliorer la synchronisation du flux dans les projets de préfabrication en utilisant un cadre combinant les méthodologies Lean et l'IoT. Le cadre proposé, basé sur l'étude d'une entreprise de préfabrication canadienne, intègre le système Last Planner (LPS), la planification pull et les systèmes de suivi IoT pour améliorer les processus de livraison et réduire la variabilité du flux. Les résultats initiaux ont démontré la capacité à suivre la livraison et l'installation de composants en acier préfabriqués.

Lean Construction et outils numériques pour la gestion de la conception

Motivée par les avantages potentiels de cette intégration et une lacune de connaissances en France concernant l'impact de la Lean Construction 4.0 sur la gestion de la conception, la deuxième partie couvre l'intégration entre la Lean Construction et les outils numériques pour la gestion de la conception en France à travers deux études.

La première étude a examiné l'influence de la Lean Construction et des outils numériques sur la planification des activités de conception en France. Les outils Lean et numériques ont été mis en œuvre dans deux projets français, l'un préparant les Jeux olympiques de Paris et l'autre étant un

campus de bureaux et d'entreprises, en utilisant le LPS et des tableaux Kanban numériques. Les résultats de l'enquête ont indiqué que la mise en œuvre de la Lean améliorerait la livraison de la conception, la collaboration et la réactivité aux changements. Les outils numériques, en particulier la planification à court terme à travers des réunions fréquentes et des plateformes collaboratives, se sont révélés efficaces pour améliorer la gestion de la conception, en particulier pendant les défis imposés par la pandémie de COVID-19.

La deuxième étude s'est concentrée sur les niveaux d'adoption de la Lean et du BIM dans les bureaux de conception français et leur impact sur la performance de la conception. Plus de 75% des entreprises avaient plus de 5 ans d'implémentation du BIM, tandis que l'adoption de la Lean était notablement plus faible, seulement deux entreprises fournissant une formation et la majorité n'adoptant pas les principes Lean. L'enquête a révélé des niveaux modérés d'intégration Lean-BIM, indiquant l'utilisation intentionnelle ou non intentionnelle de modèles BIM pour atteindre les principes Lean. La performance de la conception a été positivement impactée par l'intégration Lean-BIM.

Lean Construction et jumeau numérique

La troisième partie de la thèse, basée sur deux études, se concentre sur l'intégration des principes Lean et de la technologie du jumeau numérique. La motivation découle de la nouveauté de cette intégration et du potentiel du jumeau numérique à relier les environnements virtuels et physiques, à synchroniser les données en temps réel et à améliorer la prise de décision basée sur les données.

La première étude a réalisé une revue systématique de la littérature pour identifier les applications et les structures du jumeau numérique dans l'industrie du bâtiment. La revue a couvert 228 études et a proposé une structure en quatre couches pour les systèmes de jumeaux numériques : physique,

numérique, application et utilisateur. Six catégories d'applications potentielles du jumeau numérique dans l'industrie du bâtiment ont été identifiées, notamment la durabilité, la gestion des installations, la sécurité, la santé, la gestion des risques, la performance structurelle, la gestion de la construction et les applications architecturales/urbaines. Les défis de la mise en œuvre du jumeau numérique ont été catégorisés comme des défis liés à l'industrie, sociaux/organisationnels, techniques, économiques et juridiques/gouvernementaux.

La deuxième étude visait à proposer un cadre intégrant les principes Lean et le jumeau numérique pour améliorer le flux et éliminer les déchets. Le cadre utilisait la cartographie de la chaîne de valeur (VSM), un outil Lean, et les systèmes de jumeaux numériques. Le cadre proposé en deux phases implique la compréhension du processus, la collecte de données pour cartographier le processus actuel et la construction d'un jumeau numérique dans la deuxième phase. Le jumeau numérique facilite la surveillance continue, les tests de nouvelles solutions et la prise de décision. La mise en œuvre continue de ce cadre a le potentiel de soutenir la transformation numérique dans les petites et moyennes entreprises (PME) en améliorant les processus, le flux et en permettant l'amélioration continue grâce à l'accès en temps réel et aux tests de scénarios.

Lean Construction et impression 3D

La quatrième partie de la thèse explore la synergie entre la Lean construction et l'impression 3D. L'intégration de la Lean et de l'impression 3D est motivée par leurs objectifs communs d'atteindre une construction plus rapide, plus respectueuse de l'environnement dans un environnement plus sûr.

La première étude de cette partie porte sur une revue de la littérature pour comprendre comment l'impression 3D contribue à l'élimination des déchets par rapport aux méthodes de construction

conventionnelles et quels déchets peuvent être trouvés dans les processus d'impression 3D. L'étude présente différents exemples de ces déchets et de leurs causes fondamentales.

La deuxième étude mène des expériences en laboratoire en deux rounds pour analyser les déchets dans un processus d'impression 3D. Le premier round identifie les activités non génératrices de valeur, révélant que 24,34 % du temps est gaspillé dans des activités telles que l'attente d'informations, la recherche de fichiers ou d'outils et les erreurs techniques. Des principes et outils Lean, tels que 5S, VSM, Plan-Do-Check-Act (PDCA), la gestion visuelle, la maintenance prédictive et la protection contre les erreurs, sont proposés. Après la mise en œuvre des interventions Lean, le deuxième round montre des réductions significatives dans divers types de déchets et une réduction du temps d'impression. L'étude conclut que la Lean Construction et l'impression 3D peuvent être employées de manière synergique pour améliorer les performances dans l'industrie de la construction, les principes Lean offrant des opportunités pour améliorer le temps, les coûts et la qualité dans les processus d'impression 3D.

Lean Construction et AWP

Motivée par le potentiel de l'AWP pour stimuler la productivité, la sécurité et la rentabilité, la cinquième partie de la thèse explore la relation entre la Lean construction et l'AWP dans les projets de construction. L'analyse révèle des différences entre la Lean et l'AWP, notamment leurs origines, leur orientation, leur adaptabilité aux types de projets, leurs principes de planification et leurs approches de l'apprentissage et de l'amélioration. Malgré des distinctions, les deux partagent des objectifs communs, et leur intégration peut améliorer la productivité, la qualité, l'efficacité, la sécurité et l'engagement des parties prenantes dans les projets de construction, offrant des avantages mutuels et réduisant la résistance au changement.

Conclusions

La thèse explore le concept de Lean Construction 4.0 (LC4.0) sous deux perspectives : comme une relation mutuellement facilitante entre la Lean Construction et la Construction 4.0 et comme un concept applicable à différentes phases de projets de construction. L'applicabilité de la LC4.0 s'étend sur les phases de production de matériaux, de conception, de planification, de production sur site/hors site, de planification et de construction. Malgré son potentiel à favoriser un environnement d'amélioration des performances, de la collaboration, de l'efficacité, de la sécurité et de la productivité, l'adoption de la LC4.0 en France est encore insuffisante, avec plusieurs défis à relever. Une mise en œuvre progressive, la résolution des obstacles et l'exploration des liens entre la Lean et d'autres technologies de la Construction 4.0 sont suggérées pour les travaux futurs. La thèse contribue académiquement en élargissant les connaissances sur la LC4.0 à l'échelle mondiale et en France, en explorant ses bases théoriques et en comprenant la relation entre les solutions haute technologie et les approches centrées sur l'humain. Pratiquement, elle accroît la sensibilisation à la LC4.0, propose des cadres et des outils reproductibles, et soutient la transformation numérique dans le secteur de la construction. L'encouragement du gouvernement, les programmes de sensibilisation, les légalisations, les incitations et les initiatives de financement sont essentiels pour la mise en œuvre réussie de la LC4.0.

The Ontology of Lean Construction 4.0 in the Construction Industry

Abstract

This thesis focuses on the concept of “Lean Construction 4.0” and its applicability to solve the different challenges facing the construction industry in France and globally. The concept is resulted from the integration of Lean Construction and Construction 4.0. Lean Construction emphasize value generation, waste elimination, continuous and reliable flow, collaboration, and continuous improvement. In turn, Construction 4.0 aligns with the fourth industrial revolution (Industry 4.0) and aims to integrate smart technologies and practices to improve performance in the construction industry. The research presented in this thesis is based on the use of different methodologies including the systematic literature review approach, surveys, experimental work, and case studies in the French construction sector to study the concept of Lean Construction 4.0. The thesis unfolds across five main parts, exploring Lean integration with the Internet of Things (IoT), digital tools for design, digital twin, 3D printing, and Advanced Work Packaging (AWP). In each part, studies reveal substantial insights. For instance, Lean Construction and IoT integration enhance flow and integration of project’s stakeholders, while Lean and digital tools positively impact design delivery and quality. Integration with digital twin technology and 3D printing illustrates potential improvements in flow, waste reduction, and overall performance. Analyzing the relationship between Lean Construction and AWP identifies differences but emphasizes shared goals, suggesting their integration can enhance productivity, quality, efficiency, safety, and stakeholder engagement. The conclusion highlights Lean Construction 4.0's potential across construction phases but underscores its insufficient adoption in France.

Keywords: Lean Construction 4.0, Lean Construction, Construction 4.0, Industry 4.0, Construction, Internet of Things (IoT), Digital Twin (DT), Building Information Modeling (BIM), Three-Dimensional Printing (3D Printing), Advanced Work Packaging (AWP), France.

L'ontologie du Lean Construction 4.0 dans l'industrie de la construction

Résumé

Cette thèse se concentre sur le concept de "Lean Construction 4.0" et sa pertinence pour résoudre les différents défis auxquels est confrontée l'industrie de la construction en France et dans le monde. Le concept découle de l'intégration du Lean Construction et de la Construction 4.0. Lean Construction met l'accent sur la génération de valeur, l'élimination des déchets, le flux continu et fiable, la collaboration et l'amélioration continue. À son tour, la Construction 4.0 s'aligne sur la quatrième révolution industrielle (Industrie 4.0) et vise à intégrer des technologies et des pratiques intelligentes pour améliorer les performances de l'industrie de la construction. La recherche présentée dans cette thèse est basée sur l'utilisation de différentes méthodologies, notamment l'approche de la revue systématique de la littérature, des enquêtes, des travaux expérimentaux et des études de cas dans le secteur de la construction en France pour étudier le concept de Lean Construction 4.0. La thèse se déploie en cinq parties principales, explorant l'intégration du Lean avec l'Internet des objets (IoT), les outils numériques pour la conception, le jumeau numérique, l'impression 3D et l'Advanced Work Packaging (AWP). Dans chaque partie, les études révèlent des informations substantielles. Par exemple, l'intégration du Lean Construction et de l'IoT améliore le flux et l'intégration des parties prenantes du projet, tandis que le Lean et les outils numériques impactent positivement la livraison et la qualité de la conception. L'intégration avec la technologie du jumeau numérique et de l'impression 3D illustre des améliorations potentielles dans le flux, la réduction des déchets et les performances globales. L'analyse de la relation entre le Lean Construction et l'AWP identifie des différences mais met l'accent sur des objectifs partagés, suggérant que leur intégration peut améliorer la productivité, la qualité, l'efficacité, la sécurité et l'engagement des parties prenantes. La conclusion souligne le potentiel du Lean Construction 4.0 à travers les phases de construction mais souligne son adoption insuffisante en France.

Mots-clés : Lean Construction 4.0, Lean Construction, Construction 4.0, Industrie 4.0, Construction, Internet des objets (IoT), jumeau numérique, modélisation des informations du bâtiment (BIM), Advanced Work Packaging (AWP), France.