Application of Lean Management to Modular Off-site Construction: Impact on the Sustainable Development Dimensions

by

Helia RASOULI

MANUSCRIPT-BASED THESIS PRESENTED TO ÉCOLE DE TECHNOLOGIE SUPÉRIEURE IN PARTIAL FULFILLEMENT FOR A MASTER'S DEGREE IN CONSTRUCTION ENGINEERING
M. A. SC.

MONTREAL, AUGUST 07, 2025

ÉCOLE DE TECHNOLOGIE SUPÉRIEURE
UNIVERSITÉ DU QUÉBEC

BOARD OF EXAMINERS (THESIS M.Sc.A.)

THIS THESIS HAS BEEN EVALUATED

BY THE FOLLOWING BOARD OF EXAMINERS

Mr. Silvio Melhado, Thesis Supervisor
Department of Construction Engineering, at École de technologie supérieure

Mrs. Ivanka Iordanova, Thesis Co-supervisor
Department of Construction Engineering, at École de technologie supérieure

Mr. Gabriel Lefebvre, President of the Board of Examiners
Department of Construction Engineering, at École de technologie supérieure

Mr. Adel Francis, Member of the jury
Department of Construction Engineering, at École de technologie supérieure

THIS THESIS WAS PRENSENTED AND DEFENDED

IN THE PRESENCE OF A BOARD OF EXAMINERS AND PUBLIC

ON AUGUST 01,2025

AT ÉCOLE DE TECHNOLOGIE SUPÉRIEURE

ACKNOWLEDGMENTS

This thesis marks the culmination of a meaningful journey, one that would not have been possible without the support, encouragement, and kindness of many remarkable individuals who have walked alongside me.

First and foremost, I would like to express my sincere gratitude to my supervisor, Professor Silvio Melhado, and my co-supervisor, Professor Ivanka Iordanova. Their mentorship and encouragement have been invaluable throughout this process.

To the GRIDD team, thank you for creating a welcoming environment. I extend my appreciation to all the researchers and colleagues who contributed to meaningful discussions and supported me along the way.

To my beloved parents, although thousands of kilometers separated us during this journey, your love was always present stronger than any distance. Your quiet sacrifices, unwavering belief in me, and the warmth of your prayers have carried me through the most challenging times. There hasn’t been a single day when I didn’t feel your presence beside me. This achievement is as much yours as it is mine.

To my partner, Mehdi, thank you for your endless patience, encouragement, and love. You have been my anchor through the highs and lows, always lifting me up and reminding me of my purpose.

To my dear uncle and aunt, Homayoun and Javle, your kindness, support, and presence made this road possible. You gave me a sense of family and belonging when I needed it most in this country.

A heartfelt thank you goes to Sima Zarghami, who introduced me to one of the most important people in my academic life Amirhossein Mehdipoor. Special thanks to Amirhossein, whose constant support, insightful discussions, and encouraging presence have made a significant difference throughout this process. Your friendship, motivation, and sincerity meant more than words can express.

To all those whether mentioned by name or silently supporting me along the way thank you. Your presence made this journey not only achievable but meaningful.

Application du lean management à la construction modulaire hors site: impact sur les dimensions du développement durable

Helia RASOULI

RÉSUMÉ

La construction modulaire et hors site (MOC) est de plus en plus présentée comme une alternative durable aux méthodes traditionnelles de construction sur site. Le Lean Management (LM), avec son accent sur la réduction des gaspillages, l'efficacité et l'amélioration continue, présente un fort potentiel pour soutenir les objectifs de durabilité dans la MOC. Cependant, les études existantes se concentrent souvent uniquement sur les bénéfices du Lean, sans explorer systématiquement ses limites ou ses impacts duals sur les différentes dimensions du développement durable. Cette thèse, structurée sous forme d'articles, examine le rôle des pratiques Lean dans l'avancement du développement durable (DD) dans le contexte de la MOC, à travers une approche méthodologique mixte combinant une revue systématique de la littérature (RSL), des entretiens avec des experts et le développement d'un cadre conceptuel. Une matrice a été élaborée pour évaluer les effets positifs et négatifs de 14 outils Lean sur 16 indicateurs de durabilité, regroupés selon les dimensions économique, environnementale et sociale. Le cadre a ensuite été validé à l'aide de la méthodologie de recherche en science de la conception (DSR) par des évaluations d'experts. Les résultats montrent que les impacts positifs des pratiques Lean sur les trois piliers du développement durable — économique, environnemental et social — l'emportent largement sur les effets négatifs. Des outils comme le Juste-à-Temps (JAT), les stratégies Pull et la gestion visuelle sont largement utilisés pour améliorer significativement la productivité, optimiser l'utilisation des matériaux et réduire les coûts. Toutefois, une application prudente est nécessaire, notamment pour des outils comme le JAT, car la fréquence des livraisons dans un contexte modulaire peut entraîner une augmentation de la consommation d'énergie et des émissions, si elle n'est pas correctement gérée. Ces résultats soulignent l'importance d'une mise en œuvre contextuelle afin de maximiser les bénéfices tout en évitant les compromis indésirables. Le cadre conceptuel final met en évidence ces effets duals, offrant un guide nuancé aux praticiens et aux décideurs souhaitant appliquer les principes du Lean dans une optique de durabilité au sein de la MOC. Cette thèse apporte ainsi une contribution à la fois académique et pratique en proposant une approche équilibrée et fondée sur des preuves pour l'intégration du Lean et du DD dans la construction modulaire.

Mots-clés : Construction Modulaire Hors Site (MOC), Lean Management, Développement Durable (DD), Assemblage sur site, Fabrication dans la Construction

Application of lean management to modular off-site construction: impact on the sustainable development dimensions

Helia RASOULI

ABSTRACT

Modular and Off-site Construction (MOC) is increasingly promoted as a sustainable alternative to traditional on-site building methods. Lean Management (LM), with its emphasis on waste reduction, efficiency, and continuous improvement, offers strong potential to support sustainability goals in MOC. However, existing studies often focus narrowly on Lean's benefits, without systematically exploring its potential drawbacks or dual impacts across sustainability dimensions. This article-based thesis investigates the role of Lean practices in advancing Sustainable Development (SD) within MOC, using a mixed-method approach combining Systematic Literature Review (SLR), expert interviews, and conceptual framework development. A matrix was developed to assess the positive and negative impacts of 14 Lean tools across 16 sustainability metrics, grouped under economic, environmental, and social dimensions. The framework was then validated through expert evaluations using Design Science Research (DSR) methodology. Overall, the results indicate that the positive impacts of Lean practices on the three pillars of sustainable development—economic, environmental, and social—clearly outweigh the negative ones. Tools such as Just-in-Time (JIT), Pull Strategies, and Visual Management are widely used to significantly enhance productivity, optimize material use, and reduce costs. However, caution is needed when applying certain tools like JIT in modular or off-site contexts, as the frequent deliveries required can lead to increased energy consumption and emissions if not carefully managed. These findings underline the importance of contextual implementation to maximize benefits and avoid unintended trade-offs. The final conceptual framework captures these dual effects, offering a nuanced guide for practitioners and policymakers aiming to apply Lean in a sustainability-oriented MOC context. This thesis contributes to both academic research and construction management practice by proposing a balanced, evidence-based approach to Lean-SD integration in modular construction.

Keywords: Modular Off-site Construction (MOC), Lean Management, Sustainable Development (SD), On-site Assembly, Manufacturing in Construction

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Page

LIST OF ABREVIATIONS

AI	Artificial Intelligence
BIM	Building Information Modeling
CBA	Choosing by Advantage
CPM	Critical Path Method
DSR	Design Science Research
GIRDD	Groupe de recherche en integration et développement durable
IPD	Integrated Project Delivery
JIT	Just-in-Time
Kaizen	Continuous improvement
LEI	Lean Enterprise Institute
LM	Lean Management
MEC	Manufacturing Execution & Control
MMC	Modern Methods of Construction
MOC	Modular and Off-site Construction
MS	Mean Score
OSM/OSC	Off-Site Manufacturing/Construction
PCMAT	Plan Conditions and Work Environment in the Construction Industry
PERT	Program Evaluation and Review Technique
SD	Sustainable Development
SLR	Systematic Literature Review
TBL	Triple Bottom Line
TPM	Total Preventative Maintenance

TQM	Total Quality Management
TPS	Toyota Production System
VSM	Value Stream Mapping
5S	Sort, Set in order, Shine, Standardize, Sustain

LIST OF SYMBOLS

α	Internal consistency
K	Number of groups or categories
Σ	Sum over a set of values
$\Sigma s^2 y$	Sum of each variable variance
$s^2 x$	Variance of a sum of variable value
s	sample standard deviation
N	number of observations
xi	observed values of a sample item
$\bar{x}$	mean value of the observations

INTRODUCTION

Over the past decades, global industries have faced mounting pressure to align growth with sustainable practices due to rising environmental concerns, increasing social expectations, and resource limitations (Carvajal-Arango et al., 2019; Naeemah & Wong, 2022). The construction sector, in particular, has been heavily scrutinized for its fragmented operations, inefficiencies, and high environmental impact. Despite its contribution to global economic development, construction remains one of the least productive sectors, with significant waste and limited value-added activities (Demirkesen & Bayhan, 2022). The Construction Industry Institute (CII) highlights this gap by estimating that only 10% of construction activities add value, while 57% result in waste (Aziz & Hafez, 2013). This inefficiency is even more evident when compared to manufacturing industries, which have long embraced systematic and lean-driven process improvements.

To address these systemic inefficiencies and meet sustainability expectations, Modular and Off-Site Construction (MOC) has gained prominence as a transformative solution. MOC involves the prefabrication of components in controlled factory settings followed by on-site assembly, offering reduced material waste, better quality control, shortened construction timelines, and improved safety outcomes (Innella et al., 2019; Moghadam & Al-Hussein, 2013).

However, the potential of MOC to drive sustainable outcomes is not automatically realized. Challenges related to coordination, digital maturity, upfront investment, and fragmented implementation continue to limit its impact (Du et al., 2023; Khodeir & Othman, 2018). Moreover, research shows that the integration of sustainability within MOC remains uneven, with particular neglect toward social indicators such as worker well-being, stakeholder collaboration, and inclusivity (Li et al., 2022; Moradi & Sormunen, 2023). Although the environmental and economic aspects of sustainable development have received relatively greater attention, the social dimension remains significantly underrepresented in both theory and practice.

At the same time, Lean Management (LM) originating from the Toyota Production System has emerged as a powerful philosophy aimed at maximizing value while minimizing waste (Koskela, 1993; Ohno & Ohno, 2008). In the construction sector, Lean principles such as Value Stream Mapping (VSM), Just-in-Time (JIT), and Kaizen have been employed to improve process flow, reduce delays, and increase productivity (Fuenzalida et al., 2016; Meng, 2019). Recent studies suggest that Lean practices also hold potential to positively influence sustainability by reducing emissions, improving safety conditions, and optimizing resource use (Francis & Thomas, 2019; Naeemah & Wong, 2022). Nevertheless, many construction firms lack awareness of the long-term benefits of Lean, viewing it primarily as a productivity tool rather than a pathway to holistic sustainability (Demirkesen & Bayhan, 2022).

Furthermore, research linking Lean practices with sustainability outcomes in MOC, particularly during the production and on-site assembly phases, remains scarce and fragmented. Most existing studies explore Lean tools or sustainable strategies independently, without addressing how Lean can support the Triple Bottom Line (TBL) economic, environmental, and social dimensions within modular workflows (Carvajal-Arango et al., 2019; Li et al., 2022; Moradi & Kähkönen, 2022). This gap limits the industry's ability to standardize effective practices and inhibits the full integration of Lean thinking into sustainable construction systems.

Some studies have begun to explore this relationship. For instance, Khodeir & Othman (2018) emphasize the need for holistic frameworks that simultaneously consider Lean tools and sustainability metrics. Du et al. (2023) call for a re-evaluation of Lean integration across all stages of MOC including production line planning, site layout, and waste management highlighting its potential in process control and cost optimization. Still, most current efforts remain focused on isolated dimensions or high-level concepts, without concrete strategies or validated frameworks to guide implementation across modular construction phases.

Given these gaps, this thesis aims to bridge Lean Management and Sustainable Development within Modular Off-Site Construction by focusing on both the production and assembly stages, two-phases that are critical yet, often underexplored. Building on the foundations laid by scholars like (Carvajal-Arango et al., 2019; Moradi & Kähkönen, 2022; Naeemah & Wong, 2022), this research develops and validates a conceptual framework that maps Lean tools to sustainability metrics across economic, environmental, and social dimensions. In doing so, it provides a structured pathway for stakeholders to implement Lean in a way that aligns with sustainability goals and addresses the sector's ongoing inefficiencies.

By applying a Design Science Research (DSR) methodology and adopting a mixed-method approach that includes a systematic literature review, thematic coding, and expert validation, the study contributes both theoretically and practically. It not only responds to current research gaps but also equips industry practitioners with tools and insights to navigate the complex realities of delivering sustainable, lean-based modular construction projects.

The thesis comprises four chapters, including two standalone papers: one based on a systematic literature review and the other on the development and validation of a lean-sustainability framework. Together, these chapters provide a cohesive narrative that advances academic understanding while offering practical insights for improving sustainability outcomes in Modular Off-Site Construction through Lean implementation. Finally, a general discussion and conclusion chapter completes the thesis, providing a comprehensive overview of the research findings and their implications

CHAPTER 1

LITERATURE REVIEW

1.1 Modular and Off-Site Construction (MOC)

Modular and Off-site Construction (MOC) is a modern advancement that significantly improves efficiency in the construction industry (McDermott et al., 2023). OSM and modularization involve the pre-assembly of building components in controlled environments before their on-site installation (Durdyev & Ismail, 2019). These techniques streamline construction operations, enhancing value and optimizing resource utilization (Peltokorpi et al., 2018).

1.1.1 Definition and key characteristics

As proposed by Koskela (1993) construction comprises of three core activities: moving materials, exchanging information, and creating value. He argued that principles from manufacturing systems could be applied to improve construction operations. In parallel, Modern Methods of Construction (MMC) including Off-Site Manufacturing (OSM) and on-site production innovations have been introduced as practical responses to productivity and sustainability challenges in the industry (Mostafa et al., 2016). Separately, Koskela's Transformation-Flow-Value (TFV) theory provided a theoretical foundation for rethinking construction through Lean principles (Koskela, 1993). Although MMC and TFV both seek to enhance efficiency, they emerged independently and should be regarded as distinct yet potentially complementary approaches (Mostafa et al., 2016). Off-site component assembly involves fabricating and combining building elements in a controlled environment before transporting them to the construction site for installation. These components typically include both structural and non-structural elements such as roof trusses, concrete columns, beams, plumbing systems, and staircases (Boyd et al., 2013).

Panel-based systems utilize prefabricated frameworks that are transported and permanently installed on-site. These systems often incorporate pre-fitted components such as doors, windows, exterior cladding, and insulation materials (Boyd et al., 2013). Modular constructs, similar to pods, typically consist of multiple rooms and range from single-unit residential houses to large multi-unit apartment complexes. These modules are fully factory-built, including electrical and plumbing systems, before being transported for permanent installation on a predefined foundation (N. Lu & Liska, 2008). Hybrid configurations, also known as "pods," are fully prefabricated building units that include all finishes and furnishings. These units are manufactured in a controlled environment and then transported to the site for permanent installation (N. Lu & Liska, 2008).

The modular manufacturing process varies by facility. In some factories, human labor is responsible for all stages of production Figure 1.1, while in others, industrial automation is utilized for various manufacturing tasks Figure 1.2 (Moghadam, 2014).

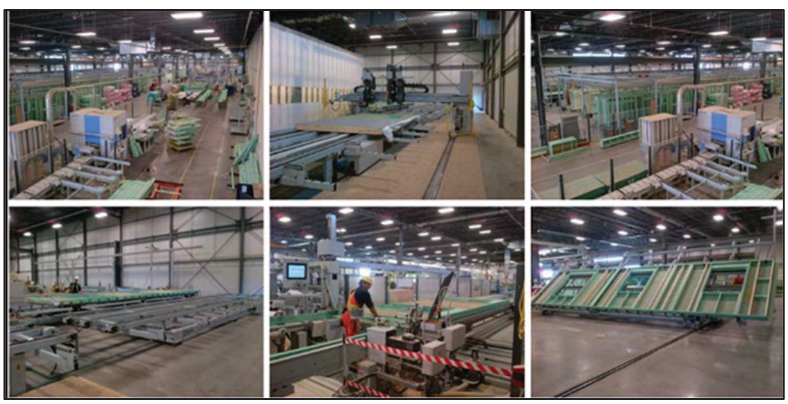

Figure 1.1 Semi-automated modular factory production line[1]
Taken from Moghadam, (2014)

Regardless of the approach, the ultimate goal in both manual and automated production environments is workload balance along the production line to boost efficiency (Moghadam, 2014). To optimize productivity, some strategies proposed such as allocating less workload to

[1] *Source of the example: Moghadam, (2014)*

central stations while increasing the load on stations at the beginning and end of the line. These workload distribution techniques are particularly relevant in modular construction, where streamlined processes and efficient labor allocation are crucial for achieving higher production efficiency (Das et al., 2010).

Figure 1.2 Modular factory human-performed tasks[2]
Taken from Moghadam, (2014)

1.1.2 Key benefits and challenges

According to the literature, MOC has the potential to offer significant time and cost savings by enabling prefabrication in a controlled environment, reducing on-site assembly time and enhancing overall project efficiency. Clients can customize designs or select from existing templates, ensuring flexibility while maintaining production efficiency. Additionally, waste reduction, improved safety, and enhanced quality control are key drivers for adopting MOC (Boyd et al., 2013). The use of sustainable materials in off-site manufacturing further reduces resource waste and inventory losses, supporting eco-friendly construction (Nahmens & Ikuma, 2012).

[2] *Source of the example: Moghadam, (2014)*

However, MOC also faces challenges that limit its widespread adoption. The lack of standardized design codes and regulations, coupled with limited quality control tools, creates inconsistencies in project execution (Enshassi et al., 2019). Additionally, shortages of skilled contractors and prolonged lead-in times during the engineering and design phase can delay project schedules. The high upfront investment required to establish manufacturing facilities, alongside transportation costs and logistics complexities, further impact cost-effectiveness (Mandala & Nayaka, 2023). Moreover, the fragmented nature of contractual agreements in modular construction complicates coordination among stakeholders, potentially affecting project delivery timelines (Enshassi et al., 2019). While MOC offers efficiency, sustainability, and cost advantages, addressing regulatory, logistical, and financial barriers is essential for broader industry adoption.

1.2 Lean management and manufacturing

Lean Management (LM) originated in Japan’s post-war automotive sector with the development of the Toyota Production System (TPS) (Ohno & Ohno, 2008). To provide a comprehensive understanding of modern LM theory, its key principles must be examined. The TPS serves as a foundational example, emphasizing two core objectives: achieving zero-defect production and minimizing waste, both of which are central to Lean Manufacturing. In this context, waste referred to as Muda in Japanese is identified as a critical factor in optimizing production efficiency. Waste reduction focuses on four primary sources: (1) excessive production resources, (2) overproduction, (3) surplus inventory, and (4) unnecessary capital investment, all of which can hinder operational effectiveness and increase costs. Over the years, LM has continued to evolve, attracting significant research interest as scholars explore its impact across various industries (Innella et al., 2019). The Lean Enterprise Institute (LEI) defines Lean as a management approach focused on maximizing customer value while minimizing waste. The rise of lean manufacturing can be attributed to two primary factors: the advancement of production techniques and the increasing expectations of customers (Jasti & Kodali, 2016). Since its introduction in the manufacturing sector, Lean principles have gained widespread recognition as an effective management system that enhances an organization's overall efficiency, productivity, and performance (Meng, 2019).

1.2.1 Lean Construction

Lean construction is the adaptation of Toyota Production System (TPS) principles to the construction industry, aiming to enhance efficiency and productivity. Similar to TPS, lean construction prioritizes waste reduction, value creation for the customer, and continuous improvement. While several lean principles and tools from TPS can be directly applied to construction, the sector also incorporates unique methodologies and practices tailored to its specific challenges and workflows (Sacks et al., 2010).

1.2.2 Lean manufacturing and construction principles

Various scholars have outlined Lean principles across different fields, including Lean production (Liker & Choi, 2004; Womack & Jones, 1997) and Lean construction (Koskela, 1993). Additionally, Deming's 14 Points, which emphasize a quality-driven approach, have also contributed to the development of Lean thinking (Deming, 1994). When identifying key Lean principles, specific selection criteria were applied. Liker (2003) categorizes these principles into four distinct areas: Philosophy, Process, People & Partners, and Problem Solving. The following Table 1.1 presents these principles as structured by (Sacks et al., 2010), providing a comprehensive overview of their application in Lean systems.

Table 1.1 List of lean categories and principles[3]

N	Category	N	Principle
1	Philosophy	1	Base decisions on long-term philosophy even at the expense of short-term financial goals.
2	Process	2	Create continuous process flow to bring problems to the surface.
		3	Use 'Pull' systems to avoid overproduction.
		4	Level out the workload.
		5	Build a culture of stopping to fix problems to get quality right the first time.
		6	Standardized tasks are the foundation for continuous improvement and employee empowerment.
		7	Use visual control so no problems are hidden.
		8	Use only reliable, thoroughly tested technology that serves people and processes.
3	People & Partners	9	Grow leaders who thoroughly understand the work, live the philosophy, and teach it to others.
		10	Develop exceptional people and teams who follow your company's philosophy.
		11	Respect your extended network of partners and suppliers by challenging them and helping them improve.
4	Problem Solving	12	Go and see for yourself to thoroughly understand the situation.
		13	Make decisions slowly by consensus, thoroughly considering all options; implement rapidly.
		14	Become a learning organization through relentless reflection and continuous improvement.

[3] *Source of the example: Sacks et al., (2010)*

1.2.3 Lean tools and techniques

Lean manufacturing introduces a set of tools and techniques aimed at eliminating non-value-adding activities while improving overall process flow and efficiency. As described by Abdulmalek & Rajgopal (2007) tools such as Value Stream Mapping (VSM), 5S, cellular manufacturing, Total Productive Maintenance (TPM), and Just-in-Time (JIT) are commonly used to identify inefficiencies and restructure processes. These tools have been successfully adapted from traditional manufacturing to other industries, including construction, where the goal is to streamline operations, reduce delays, and minimize resource waste. Table 1.2 presents a summary of these Lean tools, highlighting their intended functions and associated benefits in process improvement (Abdulmalek & Rajgopal, 2007):

Table 1.2 Tools found in scholarly works on lean manufacturing[4]

Lean Tools	Description
Cellular manufacturing	Groups all of the necessary machines, equipment, and operators into a group (or ‘cell") for a certain product or comparable items. Cell resources are organized to make all processes as simple as possible.
Just-in-time (JIT)	A system in which a client initiates demand, which is subsequently relayed backward from the final assembly all the way to raw material, "pulling’ all requirements just when they are needed.
Kanban	Kanbans are a signaling system used to execute JIT production.
Total preventative maintenance (TPM)	Workers do routine equipment maintenance in order to discover any irregularities. The emphasis has shifted from repairing faults to preventing them. Because operators are closest to the machinery, they are involved in maintenance and monitoring activities to avoid and warn of failures.

[4] *Source of the example: Abdulmalek & Rajgopal, (2007)*

Table 1.2 Tools found in scholarly works on lean manufacturing[4] (cont'd)

Lean Tools	Description
Total quality management (TQM)	A system of continual improvement based on participative management and customer needs. Employee involvement and training, problem-solving teams, statistical tools, long-term goals, and realization that inefficiencies are caused by the system, not people, are critical components.
Setup time reduction	Constantly strive to reduce setup time on a computer.
5S	Emphasizes excellent workplace organization and standardization of work practices.
Kaizen	It involves making small, incremental changes to processes, products, or services over time. This approach fosters a culture of ongoing learning and innovation, encouraging employees at all levels to contribute to the organization's efficiency and effectiveness.
Value Stream Mapping (VSM)	Is a visual tool used to map the entire production process, from raw materials to the delivery of the final product. It helps identify waste, inefficiencies, and bottlenecks, enabling organizations to streamline processes and optimize the overall delivery of value to customers.

In construction, workflow reliability and labor flow have traditionally been considered the key determinants of project efficiency. However, Lean Construction has redefined this perspective by shifting the focus from merely viewing projects as transformational processes to emphasizing flow efficiency and value generation. This approach aligns with the core objectives of Lean Production, such as reducing cycle time, eliminating waste, and minimizing variability. The implementation of Lean Construction is guided by principles like continuous improvement, pull-based production control, and uninterrupted workflow, ensuring greater efficiency and adaptability in project execution (Sacks et al., 2010). Based on Sacks et al. (2010) lean construction is composed of the following techniques :

Table 1.3 lean construction technique[5]

Technique	Description
Concurrent Engineering	Parallel execution of tasks by multidisciplinary teams to enhance functionality, quality, and productivity. Improves scheduling through network analysis (CPM, PERT) and overlapping activities.
Last Planner	Responsible for production unit control, ensuring workflow efficiency in supply, design, and installation. Uses look-ahead scheduling (2-6 weeks) to break master schedules into smaller packages.
Daily Huddle Meetings	Provides a platform for team members to share progress, discuss issues, and collaborate in problem-solving during daily production processes.

[5] *Source of the example: Aziz & Hafez, (2013)*

Table 1.3 lean construction technique[5] (cont'd)

Technique	Description
The Kanban System	Just-In-Time inventory strategy using kanban signals (bins, request forms) to regulate material flow between suppliers, warehouses, and site operations.
Plan Conditions and Work Environment in the Construction Industry (PCMAT)	Integrates health and safety planning into project execution. Ensures safety measures are incorporated into short-term planning with feedback from workers and subcontractors.
Quality Management Tools	Focuses on proactive quality management at the source rather than corrective actions. Uses point systems to evaluate adherence to planned quality controls.
Visual Inspection	Uses visual tools for material, workflow, and information flow. Helps in identifying materials quickly, reducing errors, and improving process efficiency.

1.2.4 Challenges and barriers

Adopting Lean production requires a significant initial investment in employee training and organizational change. This financial expense might discourage some businesses from implementing Lean techniques (Hallam et al., 2018). Furthermore, the cultural roots of the Toyota Production System, which serves as the foundation for Lean, provide hurdles to worldwide adaption (Meng, 2019). The effectiveness of Lean in industries requiring continuous production, such as petrochemicals and pharmaceuticals, is widely debated

(Abdulmalek & Rajgopal, 2007). Furthermore, the academic literature has yet to discuss how to effectively combine various Lean methodologies (D. Lee & Lee, 2021).

1.3 Integration of lean management in Modular and Off-site construction (MOC)

The modular building industry shares many similarities with traditional manufacturing. However, implementing Lean principles in modular construction presents unique challenges, including the need for greater flexibility in product customization, fluctuating market demand, and a more intricate supply chain compared to the manufacturing sector (Innella et al., 2019). Unlike conventional manufacturing, the modular construction process involves multiple distinct phases, including design, fabrication, transportation, and on-site assembly, making process integration more complex. Before addressing these modular-specific challenges, it is essential to refer to the Lean Project Delivery System (LPDS), a framework developed by Ballard & Howell (2003) that structures Lean implementation across all project stages from concept through design, construction, and commissioning. The LPDS emphasizes maximizing value while minimizing waste, encouraging collaboration among stakeholders, and enhancing workflow reliability (Ballard & Howell, 2003).This system provides a foundational lens through which Lean can be adapted for modular contexts. Building on this framework, Lean methodologies have been applied across the modular construction lifecycle to enhance efficiency and productivity. These stages in Figure 1.3 include: Lean Design Management, Lean Supply Chain Management, Lean Production Management, Lean Transportation Management, Lean Site-Assembly Management. The integration of Lean principles across these areas has demonstrated varying degrees of success in improving construction efficiency and project outcomes, reinforcing the value of Lean implementation in modular construction (Innella et al., 2019).

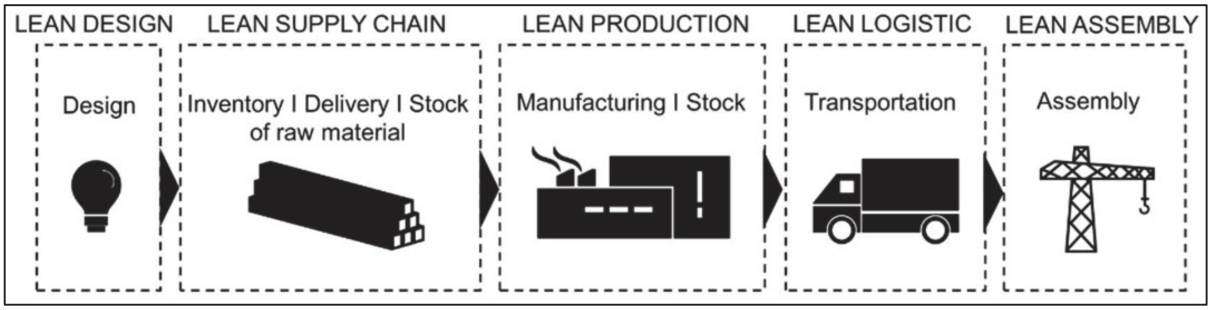

Figure 1.3 Production flow for modular construction[6]

Taken from Innella et al., (2019)

1.3.1 Identified gaps and research themes

The integration of prefabrication and Lean principles has emerged as a promising research area for improving construction efficiency. However, existing systematic analyses remain limited, lacking clarity in defining dominant research themes and structuring the key subfields (Du et al., 2023). Additionally, resistance to Lean adoption is prevalent worldwide, often influenced by past failures in off-site manufacturing (OSM) (Kong et al., 2018). To address these challenges, Blismas & Wakefield (2009) highlight the importance of applying manufacturing principles to enhance OSM processes. By improving process efficiency, significant cost savings can be achieved, helping to mitigate concerns over high initial investments and making OSM a more viable and attractive option for construction firms (Goh & Goh, 2019). Further, Jang et al. (2021) identified key areas for advancing Off-Site Construction (OSC), including the integration of OSC principles from the early stages to improve planning and efficiency, streamlining production schedules to reduce delays, enhancing material logistics and tracking for better coordination, leveraging Building Information Modeling (BIM) for improved decision-making and collaboration, and promoting OSC benefits to stakeholders to encourage wider adoption. By focusing on these areas, research can refine OSC implementation, optimize processes, and drive broader adoption across the construction industry.

[6] *Source of the example: Innella et al., (2019)*

1.4 Intersection of Lean Principles and Sustainable development in Modular Construction

In the home construction sector, Lean Construction provides an effective framework for promoting sustainability across economic, social, and environmental dimensions. By optimizing modular home construction, Lean principles help streamline processes, improving efficiency and resource utilization. As illustrated in Figure 1.4 Lean methodologies support sustainable practices by minimizing waste in various forms, including materials, energy, labor, and time, ultimately contributing to a more efficient and environmentally responsible construction approach (Nahmens & Ikuma, 2012).

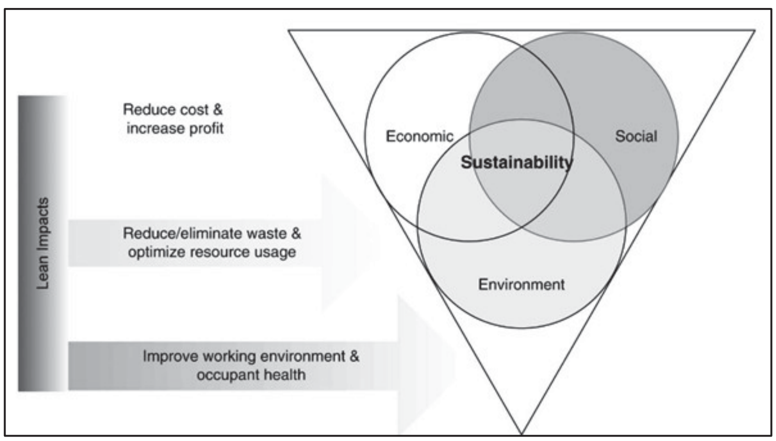

Figure 1.4 Effect of lean on sustainability[7]
Taken from Nahmens & Ikuma, (2012)

1.4.1 Gaps and research theme

While Lean Management (LM) tools have been extensively studied, their impact on the three pillars of sustainability environmental, economic, and social remains underexplored (Naeemah & Wong, 2022). Research on the synergies and conflicts between Lean strategies and sustainability goals is still in its early stages, with limited studies providing a comprehensive

[7] *Source of the example: Nahmens & Ikuma, (2012)*

framework for integrating these concepts effectively. Sustainability is traditionally categorized into three dimensions, often referred to as the Triple Bottom Line (TBL). The environmental dimension focuses on minimizing a building's lifecycle impact, reducing resource consumption, and lowering emissions. The economic dimension considers the affordability of construction projects, ensuring financial viability over time while adapting to market fluctuations and lifecycle costs (Kamali et al., 2018). The social dimension, which remains underexplored, involves workforce well-being, user comfort, and social equity in construction (Caiado et al., 2018).

Despite the recognized benefits of Lean Construction, its focus has been predominantly on efficiency and waste reduction, often neglecting its social implications. The absence of buffers and continuous production flow, two key characteristics of Lean, can lead to increased worker stress, time pressure, and reduced adaptability (Minh et al., 2019). Critiques Lean for its tendency to limit flexibility, making it difficult to respond to changing conditions and unforeseen disruptions. Furthermore, Lean principles have yet to be effectively tailored to the unique demands of MOC , where achieving a balance between operational efficiency, design flexibility, and sustainability objectives remains a critical challenge (Francis & Thomas, 2019). While prior research has highlighted the effectiveness and applicability of Lean Construction techniques, Francis & Thomas (2019) argue that further exploration is necessary to incorporate social and environmental considerations alongside economic factors. Expanding the scope of research beyond cost efficiency can provide a more holistic understanding of Lean Construction's role in promoting sustainability and long-term industry resilience.

A major research gap exists in optimizing Lean principles within MOC to better support sustainability objectives (Du et al., 2023). The integration of Lean into off-site construction (OSC) requires a refined approach to enhance workflow efficiency, adaptability, and long-term sustainability. Moreover, the role of algorithm-driven optimization, such as data analytics, artificial intelligence, and Building Information Modeling (BIM), in improving Lean Construction processes remains insufficiently explored. The development of a holistic framework that balances Lean efficiency with economic, environmental, and social sustainability in MOC projects is essential (Caiado et al., 2018).

1.5 Conclusion of the literature review

The integration of Lean principles, Sustainable Development (SD), and Modular Off-Site Construction (MOC) presents a significant opportunity for improving efficiency, reducing waste, and promoting sustainability in the construction industry. Lean Construction, derived from the Toyota Production System, has demonstrated its effectiveness in enhancing workflow reliability, reducing cycle time, and eliminating waste. However, its application in modular construction remains challenging due to issues such as customization flexibility, supply chain complexities, and the lack of standardized frameworks. Despite these challenges, Lean-driven MOC has been recognized for its potential to improve cost efficiency, environmental performance, and construction quality while streamlining design, production, and on-site assembly processes.

A key challenge in integrating Lean with MOC is the trade-off between efficiency and flexibility. Lean's focus on continuous flow and just-in-time production can lead to reduced adaptability, increased worker stress, and higher upfront investment costs, making its widespread adoption in modular construction more complex. Additionally, while the Triple Bottom Line (TBL) of sustainability environmental, economic, and social has been widely acknowledged, the social dimension remains the least explored, particularly in terms of its impact on workforce well-being, stakeholder collaboration, and user satisfaction. Research also indicates that algorithm-driven optimization and digital technologies such as Building Information Modeling (BIM) and Artificial Intelligence (AI) could play a crucial role in enhancing Lean-MOC integration by improving decision-making, supply chain management, and lifecycle efficiency.

While progress has been made in aligning Lean principles with modular construction, critical research gaps remain, particularly in standardizing implementation strategies, balancing efficiency with sustainability, and leveraging technological advancements for process optimization. Addressing these gaps will be essential for enhancing the viability of Lean-driven MOC, fostering innovation, and ensuring its successful adoption across the construction industry.

1.6 Potential areas for future research

Future research should focus on bridging the gaps between Lean, Sustainable Development, and Modular Off-Site Construction (MOC) by addressing the following key areas:

Integration of Lean and Sustainability in MOC – Developing comprehensive frameworks that align Lean principles with environmental, economic, and social sustainability while ensuring adaptability to market fluctuations and customization demands.

Digitalization and Data-Driven Optimization – Investigating how Building Information Modeling (BIM), Artificial Intelligence (AI), and predictive analytics can enhance workflow efficiency, material tracking, and lifecycle cost management in MOC.

Algorithm-Driven Process Optimization – Exploring the potential of automated scheduling, logistics planning, and real-time monitoring to enhance Lean efficiency in modular prefabrication and assembly.

Workforce Well-Being and Social Sustainability – Assessing the impact of Lean practices on worker stress, job satisfaction, and ergonomic risks, while developing strategies to balance efficiency with workforce safety and productivity in modular construction.

Economic Feasibility and Investment Strategies – Conducting cost-benefit analyses to evaluate the financial viability of Lean-driven MOC, identifying key investment models, procurement strategies, and policy incentives to encourage adoption.

Standardization and Scalability of MOC – Investigating how Lean principles can support the standardization of modular construction practices while maintaining flexibility, quality, and scalability across different project types and industry sectors.

Sustainable Lean Supply Chain Management – Exploring methods to optimize material procurement, minimize waste, and enhance logistics coordination in Lean-modular supply chains, ensuring just-in-time (JIT) delivery and sustainable resource sourcing.

Stakeholder Collaboration and Policy Support – Examining how regulatory frameworks, industry partnerships, and Lean-based procurement policies can facilitate the widespread adoption of sustainable modular construction.

Future research should bridge the gap between Lean, sustainability, and off-site construction by developing methodologies that ensure resource efficiency, adaptability, and long-term sustainability in modern construction practices. By prioritizing Lean-MOC integration as a core research focus, future studies will contribute to closing a significant gap in current knowledge and practice. This emphasis does not diminish the importance of other challenges; rather, it highlights the necessity of a foundational transformation in the construction industry. A systematic shift towards innovation, efficiency, and sustainability can only be realized by tackling the complexities of Lean adoption in Modular Off-Site Construction and ensuring its alignment with broader sustainability objectives.

CHAPTER 2

RESEARCH OBJECTIVES AND METHODOLOGY

2.1 Introduction

To generate meaningful insights and contribute to both theory and practice, this study employs an exploratory research strategy aimed at understanding how Lean management principles can be effectively integrated into Modular Off-Site Construction (MOC) to optimize sustainability. Given the interdependence between Lean efficiency, modular construction workflows, and the goals of Sustainable Development (SD), a multi-phase, mixed-method approach ensures a structured and in-depth investigation.

This research follows a Design Science Research (DSR) methodology, which facilitates the systematic development of a conceptual framework by integrating theoretical insights with empirical findings. The study aims to evaluate and refine the application of Lean tools and best practices in MOC, ensuring they align with economic, environmental, and social sustainability dimensions. By incorporating both qualitative and quantitative methods, the research provides practical recommendations that help industry professionals optimize Lean Production and Lean Assembly processes on-site.

The adoption of mixed-methods research has gained significant recognition due to its ability to offer a comprehensive and nuanced exploration of complex research problems (Heyvaert et al., 2013). This study integrates both qualitative and quantitative research techniques to enhance the validity and applicability of findings. The quantitative component enables the identification of generalizable patterns in Lean-MOC implementation, while the qualitative component provides in-depth, context-specific insights, helping to interpret the practical implications of Lean tools within the sustainability dimension framework.

This section begins by defining the research methodology and its alignment with the study's objectives. It then explores the motivations driving this research, emphasizing the need to bridge the gap between Lean management, modular construction, and sustainability. The research questions and objectives are outlined, focusing on assessing the effectiveness of Lean tools in optimizing Lean Production and Lean Assembly within MOC. Finally, the study develops an artifact (a conceptual framework) that integrates Lean principles with sustainability goals, which is then demonstrated and validated through expert feedback and industry application. The section concludes with a discussion on the contributions of this research to both academic literature and professional practice, reinforcing its relevance and potential impact on the construction industry.

2.2 Design Science Research (DSR) methodology

Design Science Research (DSR) is a problem-solving methodology that aims to advance human knowledge through the development of innovative artifacts (Vom Brocke et al., 2020). It serves as a structured approach for generating design knowledge (DK) by creating practical solutions to real-world challenges (Hevner et al., 2004).

The DSR process follows a systematic, iterative structure comprising six key stages: Problem Identification and Motivation, Definition of Objectives for a Solution, Design and Development, Demonstration, Evaluation, Communication. In this study, each step of the DSR process is explained in detail within the context of this research, demonstrating how it contributes to enhancing the efficiency, sustainability, and overall effectiveness of Lean-MOC integration.

2.2.1 Research motivation

The construction industry has long struggled with inefficiencies, lagging behind other sectors, particularly manufacturing, in terms of value-added activities. According to the Construction Industry Institute (CII), while 62% of activities in manufacturing contribute directly to value creation, only 10% of construction activities generate value, with an overwhelming 57% categorized as waste (Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019). This disparity highlights the urgent need for improving efficiency in construction by eliminating non-value-added activities, a strategy that has been successfully implemented in manufacturing through Lean management principles (Aziz & Hafez, 2013; Demirkesen, Wachter, Oprach, & Haghsheno, 2019).

In response to this challenge, Modular Off-Site Construction (MOC) has emerged as a transformative approach, offering reduced construction timelines, enhanced quality control, and minimizing material waste. However, despite its advantages, MOC has yet to achieve its full potential, particularly in aligning with Sustainable Development (SD) goals. Traditional construction methods remain resource-intensive and environmentally unsustainable, making it essential to adopt structured frameworks that enhance modular construction efficiency while addressing sustainability concerns.

Lean management principles are widely recognized for their ability to eliminate waste, optimize productivity, and improve process efficiency. However, their application in MOC remains underexplored, especially in terms of their impact on cost reduction, time optimization, waste minimization, quality enhancement, and social well-being. The lack of structured implementation strategies has made it challenging for construction stakeholders to integrate Lean tools effectively into modular workflows, limiting the industry's ability to fully leverage Lean methodologies as a pathway to sustainability.

This research is motivated by the need to bridge this gap by developing a conceptual framework that provides a systematic approach for applying Lean management in MOC. By offering practical guidance on optimizing Lean Production and Lean Assembly processes, this study ensures that industry professionals can adopt Lean practices in ways that enhance economic, environmental, and social sustainability.

Furthermore, a review of existing literature and industry practices reveals that while Lean methods have been extensively applied in manufacturing and conventional construction, their adaptation to MOC remains fragmented and lacks a unified methodology. Addressing this limitation is crucial to support industry professionals in making informed decisions, enabling them to effectively integrate Lean strategies into modular construction projects while ensuring long-term sustainability.

By undertaking this research, the study aims to develop a structured, evidence-based framework that will not only advance theoretical knowledge but also provide practical insights for industry stakeholders. The proposed framework will serve as a valuable tool for optimizing modular construction processes, ultimately contributing to a more sustainable, efficient, and resilient construction industry.

2.2.2 Problem statement, research questions

Although Lean management principles have been extensively implemented in manufacturing and traditional construction, their systematic adaptation to Modular Off-Site Construction (MOC) remains underexplored in current literature. Despite the recognized advantages of MOC in improving efficiency, quality control, and sustainability, the integration of Lean methodologies into modular workflows lacks a structured approach that maximizes economic, environmental, and social benefits.

One of the key challenges is the absence of clear implementation strategies for applying Lean tools specifically to MOC processes, particularly in Lean Production and Lean Assembly on-site. Without a comprehensive framework, construction professionals face difficulties in optimizing efficiency, minimizing waste, and fully leveraging Lean principles to enhance sustainability outcomes. Furthermore, while existing studies discuss Lean tools, they often lack a detailed evaluation of their effectiveness in MOC, limiting the industry's ability to make data-driven, informed decisions regarding Lean adoption.

To address these gaps, this research aims to develop a conceptual framework that integrates Lean management principles into MOC, offering practical implementation strategies to improve cost-effectiveness, time efficiency, waste reduction, and overall sustainability.

Based on the problems identified in the industry and by the existing body of knowledge, we have developed two research questions, which are as follows:

1. How do Lean management principles impact the economic, environmental, and social dimensions of Sustainable Development in Modular Off-Site Construction (MOC)?

This question explores the role of Lean methodologies in advancing sustainability within MOC, assessing their influence on economic efficiency, environmental responsibility, and social well-being. It seeks to identify both the benefits and challenges associated with Lean implementation in modular construction.

2. What are the most effective Lean tools and best practices for optimizing Lean Production and Lean Assembly in Modular Off-Site Construction?

This question focuses on identifying and evaluating the most effective Lean tools and best practices that contribute to enhanced efficiency, waste reduction, and sustainability in modular production and on-site assembly. It aims to determine which specific strategies deliver the greatest impact on cost, time, quality, and workforce well-being.

To address the first research question, a systematic literature review (SLR) was conducted to establish the current state of Lean tools and best practices in MOC. This review includes an extensive analysis of scholarly publications to assess the application of Lean methodologies in modular construction and their implications for sustainable development dimensions. A bibliometric analysis was carried out to explore the interrelationships between Lean management, MOC, and sustainability, highlighting research gaps particularly the limited evaluation of both the positive and negative impacts of Lean tools on sustainability goals. The findings of this comprehensive literature review are detailed in Chapter 3, providing insights into key Lean-MOC trends, sustainability outcomes, and recommendations for research and practice.

To answer the second research question, the study builds upon the findings of the literature review to develop, refine, and validate a conceptual framework that identifies Lean tools and best practices that are most effective in MOC. This framework is analyzed through empirical studies to assess its impact on sustainability dimensions, particularly in the manufacturing and on-site phases of modular construction projects. The framework development and its validation process are presented in Chapter 4.

The statement of the problem, research questions, and hypotheses ultimately lead to the definition of the research objectives, which form the second step within the Design Science Research (DSR) methodology. Through this structured approach, the study contributes to both theoretical advancements and practical applications, offering a systematic framework that guides industry professionals in leveraging Lean management for sustainable modular construction.

2.2.3 Research objectives

The primary objective of this research is to develop a comprehensive and actionable conceptual framework that integrates Lean management principles with Sustainable Development (SD) dimensions within Modular Off-Site Construction (MOC). By aligning Lean methodologies with economic, environmental, and social sustainability objectives, this study seeks to enhance the efficiency, sustainability, and overall performance of MOC projects.

To achieve this overarching goal, the study is guided by the following specific objectives:

1. Evaluate the impact of Lean management principles on the economic, environmental, and social dimensions of Sustainable Development in MOC.

This objective aims to systematically analyze how Lean principles influence key sustainability aspects in MOC, including cost efficiency, project timelines, productivity, quality, risk management, waste reduction, resource consumption, and workforce well-being. By identifying the specific benefits and challenges of Lean implementation, this study provides insights into how MOC can effectively align with SD goals.

2. Identify and recommend the most effective Lean tools and best practices for optimizing Lean Production and Lean Assembly on-site in MOC.

This objective seeks to determine which Lean tools, and best practices yield the greatest impact on efficiency, sustainability, and waste reduction in MOC. Through empirical studies and industry case analyses, the study evaluates the practical application of Lean strategies in both manufacturing and on-site assembly phases of MOC. The findings will offer industry professionals clear guidance on implementing Lean methodologies to enhance sustainability and operational performance in modular construction. By addressing these objectives, this research aims to provide a structured approach for integrating Lean principles into MOC, ensuring that industry professionals and researchers can adopt evidence-based strategies to improve the efficiency, quality, and sustainability of modular construction projects.

2.2.4 Artifact development

To establish a comprehensive understanding of Lean management's role in Modular Off-Site Construction (MOC) and its impact on Sustainable Development (SD), this study began with a systematic literature review (SLR) of 71 scholarly publications, which is detailed in Chapter 3 (dedicated to the conference paper). The literature review provided a broad analysis of Lean applications in MOC, identifying key trends, methodologies, and gaps in current research.

A major research gap identified through the SLR was the lack of studies examining the dual impact of Lean principles on sustainability across different stages of MOC. While numerous studies discuss Lean benefits, few explore both positive and negative effects at various stages of modular construction, particularly in relation to economic, environmental, and social sustainability metrics.

To address this, the study developed a framework mapping Lean impacts on sustainability metrics, which is extensively discussed in Chapter 4 (second paper). This framework serves as a foundational structure for assessing how Lean principles influence different sustainability dimensions within MOC processes. The framework was refined and validated through expert interviews, ensuring its applicability to real-world construction projects. The interview phase, also detailed in Chapter 4, was the final step in developing the conceptual framework, integrating insights from both the reviewed literature and identified research gaps.

The rationale for focusing on production and on-site assembly stems from the findings of the 71 reviewed papers, where the majority of Lean-MOC studies concentrated on manufacturing, while on-site assembly remained largely overlooked. As illustrated in Table 2.1, modular construction involves multiple stages, including design, supply chain management, production, logistics, and on-site assembly. However, coding analysis revealed that on-site assembly was one of the least studied phases in prior research despite its crucial role in MOC project execution and sustainability outcomes.

By systematically developing, refining, and evaluating proposed framework, this research provides a structured methodology for integrating Lean management into MOC, ensuring its alignment with sustainability goals and addressing previously neglected aspects of modular workflows.

Table 2.1 Table of different stages of MOC and number of coding process

Theme	Categories	Number of coding	Reference
MOC Process	Design	3	(Demirkesen & Bayhan, 2022) (Khodeir & Othman, 2018) (S. Lee et al., 2023)
	Supply Chain	5	(Demirkesen & Bayhan, 2022) (Du et al., 2023) (Abdulmalek & Rajgopal, 2007) (Arashpour et al., 2017) (Hussein et al., 2021)
	Production	17	(Salama & Said, 2023) (Gao et al., 2020) (Demirkesen & Bayhan, 2022) (Bertelsen & Koskela, 2004) (Du et al., 2023) (Abdulmalek & Rajgopal, 2007) (Arashpour et al., 2017) (Carvajal-Arango et al., 2019) (Hussein et al., 2021) (Caldarelli et al., 2022) (Khodeir & Othman, 2018) (McDermott et al., 2023) (Yu et al., 2009) (S. Lee et al., 2023) (Jang et al., 2021) (Yu et al., 2013) (Mostafa et al., 2016)

Table 2.1 Table of different stages of MOC and number of coding process (cont'd)

Theme	Categories	Number of coding	Reference
MOC Process	Logistic	5	(Demirkesen & Bayhan, 2022) (Du et al., 2023) (Carvajal-Arango et al., 2019) (Caldarelli et al., 2022) (Jang et al., 2021)
	On-site Assembly	6	(Salama & Said, 2023) (Gao et al., 2020) (Demirkesen & Bayhan, 2022) (Khodeir & Othman, 2018) (S. Lee et al., 2023) (Jang et al., 2021)

2.2.5 Evaluation

While the primary focus of this research was the development of a conceptual framework for integrating Lean management principles into Modular Off-Site Construction (MOC) with a sustainability perspective, the evaluation phase remains a crucial component of the Design Science Research (DSR) methodology. Ensuring the framework's validity, applicability, and impact is essential for both academic rigor and practical implementation.

Part of our results were indeed assessed for internal consistency using Cronbach's Alpha, providing preliminary validation of our findings. This statistical measure ensured that the framework maintains internal reliability, reinforcing the coherence and alignment of its components in evaluating Lean, MOC, and Sustainable Development (SD) objectives.

Beyond this initial validation, future research could incorporate additional evaluation methodologies to further test and refine the framework:

Case Study Implementations: Applying the framework to real-world MOC projects, assessing its effectiveness in optimizing Lean Production and Lean Assembly processes, and measuring its impact on economic, environmental, and social sustainability dimensions.

Expert Reviews: Engaging industry professionals and academic researchers to provide critical feedback on the framework’s structure, applicability, and relevance within modular construction practices.

Simulation-Based Evaluations: Conducting controlled testing using simulation models to assess the framework's predictive accuracy, its influence on cost efficiency, waste reduction, and workflow optimization, and its adaptability to different modular construction settings.

By incorporating these evaluation approaches, future research can further validate and enhance the proposed framework, ensuring its practical applicability in industry and its contribution to academic advancements in Lean-driven modular construction methodologies.

2.2.6 Research communication

In the final phase of the Design Science Research (DSR) methodology, effectively communicating research findings is essential for ensuring their impact and applicability. As noted by De Sordi (2021), the primary audience for this research includes both industry professionals and academic researchers. To facilitate clear dissemination, this thesis is structured into two scholarly articles, each addressing a distinct aspect of Lean Management (LM) and Sustainable Development (SD) in Modular Off-Site Construction (MOC). The following sections provide a brief summary of these articles.

2.2.6.1 Article 1: Systematic Literature Review on the Integration of Lean Management and Sustainable Development in Modular Off-Site Construction (Conference Publication)

This article represents the initial phase of the research, aligning with the first step of the DSR methodology. It presents a systematic literature review (SLR), detailed in Chapter 3, which examines scholarly publications from 2004 to 2024 to assess the integration of Lean principles and sustainability metrics in MOC. The study categorizes research themes, identifies existing gaps such as the lack of studies addressing the dual impact of Lean on different sustainability dimensions and highlights underexplored areas like on-site assembly in modular construction. These findings provide valuable insights for both researchers and industry practitioners, offering a foundational understanding of how Lean and SD intersect in MOC.

2.2.6.2 Article 2: Enhancing Modular Off-Site Construction through a Lean Sustainability Framework: Focus on Manufacturing and On-Site Assembly Phases

Building on the insights gained from the SLR, this article advances the research by focusing on the development of a conceptual framework for integrating Lean principles into MOC while considering sustainability objectives. Discussed in Chapter 4, this article refines the framework through expert interviews, allowing for its evaluation and validation in the context of Lean Production and Lean Assembly on-site. It particularly examines how Lean methodologies can optimize efficiency, reduce waste, and enhance sustainability in the critical stages of manufacturing and on-site assembly two phases often overlooked in prior research. By structuring the research into these two articles, this thesis enhances the accessibility and applicability of its findings, facilitating further exploration and practical implementation of Lean-driven sustainable practices in MOC. It is important to note that Article 2 has been submitted to ASCE construction engineering and management journal.

CHAPTER 3

SYSTEMATIC LITERATURE REVIEW ON THE INTEGRATION OF LEAN MANAGEMENT AND SUSTAINABLE DEVELOPMENT IN MODULAR OFF-SITE CONSTRUCTION

Rasouli, H.[1], Melhado, S.[1], Iordanova, I.[1]

[1] Department of Construction Engineering, École de Technologie Supérieure, 1100 Notre-Dame West, Montreal, Quebec, Canada H3C 1K3

Paper submitted at the *Canadian Society of Civil Engineering (CSCE) Annual Conference*, July 2025

3.1 Abstract

Modular Off-site Construction (MOC) offers greater efficiency and cost-effectiveness compared to traditional construction methods. However, there is significant potential to further enhance sustainability outcomes by adopting Lean principles on a wider scale. With growing expectations for sustainable practices, it is essential to explore how Lean management principles recognized for reducing waste and improving efficiency can be effectively integrated into MOC to address the economic, environmental, and social dimensions of Sustainable Development (SD).There is an opportunity to optimize SD outcomes, including cost reduction, waste minimization, quality improvement, and social well-being, through the application of specific Lean tools and practices in MOC. However, adapting Lean tools within MOC to align with SD goals remains complex. This study aims to assess the current state of Lean practices in modular construction and their implications for the triple bottom line of sustainability. A bibliometric analysis is conducted to explore relationships between these concepts, identifying research gaps, such as limited attention to social aspects and the nuanced dual impacts both positive and negative of Lean applications. This literature review contributes to the body of knowledge by providing an in-depth analysis of key trends in Lean practices and off-site construction, their outcomes in sustainable dimensions.

Keywords: Modular off-site Construction (MOC), Sustainable Development, Lean Management

3.2 Introduction

Modular Off-site Construction (MOC) is increasingly recognized as a modern construction method with the potential to address major industry challenges such as inefficiency, high waste, and environmental impact. It offers advantages including faster project delivery, improved quality, and reduced material usage. These benefits align well with the principles of Sustainable Development (SD), particularly in reducing the construction sector's environmental footprint and improving cost and time efficiency (Kamali et al., 2018). However, despite its promise, MOC still faces implementation challenges such as transportation constraints, design complexity, limited public acceptance, and fragmented supply chains (Hussein & Zayed, 2021). This underscores the need for strategic frameworks to optimize its processes and sustainability outcomes.

Lean Management (LM), a philosophy focused on waste elimination, continuous improvement, and value creation, has been applied in the construction industry to improve process efficiency. While it originated in manufacturing, Lean's principles are highly compatible with the off-site modular context. Nevertheless, the integration of Lean with MOC to support sustainable outcomes remains underdeveloped (Du et al., 2023). Most studies focus on either Lean and construction, Lean and sustainability, or MOC and sustainability in isolation. Few studies examine how Lean principles influence all three dimensions of the Triple Bottom Line (TBL) in Modular Off-site Construction (Carvajal-Arango et al., 2019; Goh & Goh, 2019).

Moreover, previous reviews highlight gaps in understanding how Lean tools (e.g., Just-in-Time, Kaizen, Value Stream Mapping) contribute to sustainability across the construction lifecycle. For instance, (Jin et al., 2018) and (Peiris et al., 2023) observed that while methods like Lean, BIM, and IPD are individually discussed in off-site construction, their integration particularly with sustainability is rarely explored. Studies also show a significant imbalance in the treatment of sustainability dimensions: economic aspects dominate the literature, while environmental and especially social dimensions receive limited attention (Carvajal-Arango et al., 2019; Hussein & Zayed, 2021). This lack of holistic analysis and integration points to the need for a structured and targeted review.

This work seeks to answer two key research questions: (a) What are the current research topics and trends regarding the integration of Lean management and sustainability in MOC? (b) What are the research gaps, needs, current activities, and opportunities for future research (research roadmap)? The findings of this review provide an in-depth discussion of emerging trends, critical research gaps, and recommendations for future studies. Ultimately, this review serves as a foundation for optimizing Lean applications in MOC, aiming to achieve a balanced and holistic approach to sustainable development in the construction industry.

3.3 Methodology

The study employs systematic literature review (SLR), combining quantitative and qualitative analyses to offer a comprehensive and nuanced perspective on existing literature. Bibliometric mapping is a well adopted method for visualizing trends and connections in scientific research (Xiao & Watson, 2019). VOSviewer, a bibliometric mapping tool designed to construct and display bibliometric networks. This tool enhanced the clarity and usability of the findings, aiding in the identification of future research areas (Van Eck & Waltman, 2010). Initial Key search terms, such as "Lean Construction," "Modular Off-Site Construction," and "Sustainable Development," were selected based on prominent terms identified in pioneering studies on Lean and modular construction.

Scopus was selected as the primary database due to its wide coverage of peer-reviewed journals in construction, engineering, and sustainability, and its integration with VOSviewer for bibliometric mapping (Hu et al., 2019).

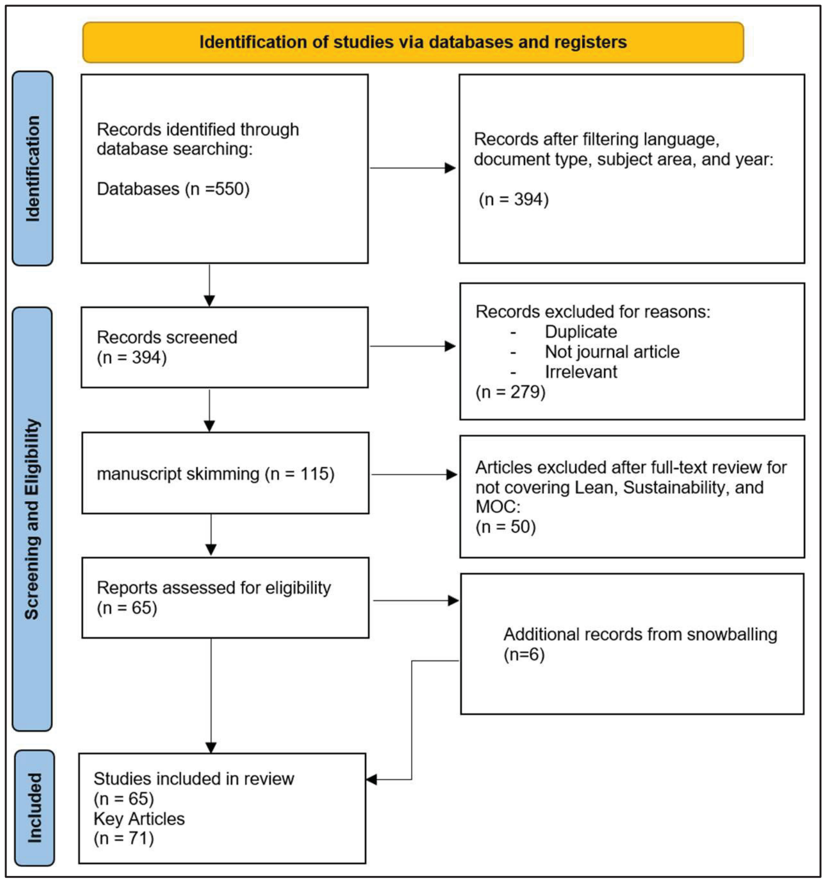

Figure 3.1 Literature search and evaluation for inclusion

Figure 3.1 illustrates the PRISMA diagram for the systematic literature search and evaluation process conducted in this study. A structured search was conducted for English-language publications from 2004 to 2024 using the query: (Lean OR "Lean Management") AND (Sustainability OR Sustainable Development OR Green) AND (Construction OR "Modular Construction" OR "Off-Site Construction" OR MOC), returned 550 records. Filters were then applied to refine results by language (English), document type (journal articles only), subject area (Engineering, Energy, and Environmental Science), and publication year (2004–2024), reducing the dataset to 394 records. After title and abstract screening, 279 records were excluded due to duplication, irrelevance, or being non-journal publications. This left 115 full-text articles for detailed eligibility assessment. A further 50 articles were excluded during skimming review for not sufficiently addressing all three key domains: Lean, Sustainability, and MOC.

Ultimately, 65 studies were selected. To improve coverage, 6 additional studies were identified through backward snowballing (Jayawardana et al., 2023), resulting in a total of 71 key articles. These were analyzed using thematic and bibliometric techniques and categorized under three core themes: Lean Practices, Sustainability, and MOC. Table 3.1 presents a summary of key contributions across these themes, emphasizing their integration potential.

Table 3.1 Comprehensive table of key articles – Sorted by year

No.	Author	Year	Method	Research Theme		
				Lean	SD	MOC
1	(A. Singh et al., 2024)	2024	Literature Review, AHP Model	•		•
2	(Negi et al., 2024)	2024	Survey, Exploratory Analysis		•	•
3	(Moradi & Sormunen, 2023)	2023	Systematic Review	•	•	
4	(Batwara et al., 2023)	2023	Systematic Review (PRISMA)	•	•	
5	(Jayawardana et al., 2023)	2023	Systematic Review, Bibliometric Analysis		•	•
6	(McDermott et al., 2023)	2023	Case Study	•		•
7	(S. Lee et al., 2023)	2023	IPA, Literature Review, Survey	•		•
8	(Du et al., 2023)	2023	Scient metric, Systematic Review	•		•
9	(Pan & Pan, 2023)	2023	Mixed-method Study	•	•	•
10	(Zaalouk & Han, 2022)	2022	Case Study, Optimization			•
11	(Ikram et al., 2022)	2022	Literature Review, Conceptual Framework	•	•	
12	(Naeemah & Wong, 2022)	2022	Systematic Review (SLR)	•		
13	(Rahima Shabeen & Aravind Krishnan, 2022)	2022	Case Study			•
14	(Assaad et al., 2022)	2022	Survey, Interviews, Literature Review		•	•
15	(Demirkesen & Bayhan, 2022)	2022	Literature Review, Factor Analysis	•		

Table 3.1 Comprehensive table of key articles – Sorted by year (cont'd)

No.	Author	Year	Method	Research Theme		
				Lean	SD	MOC
16	(Moradi et al., 2022a-03-07)	2022	Literature Review, Qualitative Analysis		•	
17	(Caldarelli et al., 2022)	2022	Case Study	•	•	•
18	(Han et al., 2022)	2022	Literature Review, Bibliometric Analysis			•
19	(Mossman & Sarhan, 2021)	2021	Case Studies, Literature Review		•	•
20	(D. Lee & Lee, 2021)	2021	Case Study, Framework Development			•
21	(Jang et al., 2021)	2021	Literature Review		•	•
22	(Hussein et al., 2021)	2021	Review (Scientometric & Systematic)			•
23	(Hussein & Zayed, 2021)	2021	Systematic Review, Meta-analysis		•	•
24	(Mellado & Lou, 2020)	2020	Literature Review, Framework Development	•	•	•
25	(J. Singh et al., 2020)	2020	Questionnaire, Interviews, SEM	•		
26	(Dieste et al., 2020)	2020	Case Study, Interviews	•	•	
27	(Demirkesen & Bayhan, 2020)	2020	Literature Review, ANP Model	•		
28	(Zhang et al., 2020)	2020	Case Study, Framework Development			•
29	(Gao et al., 2020)	2020	Literature Review, Systematic Review		•	•

Table 3.1 Comprehensive table of key articles – Sorted by year (cont'd)

No.	Author	Year	Method	Research Theme		
				Lean	SD	MOC
30	(Gbadamosi et al., 2019)	2019	BIM Optimization, DFMA, Lean Construction			•
31	(Francis & Thomas, 2019)	2019	System Dynamics, Conceptual Modeling	•	•	
32	(Carvajal-Arango et al., 2019)	2019	Literature Review	•	•	
33	(Innella et al., 2019)	2019	Systematic Review	•	•	•
34	(Minh et al., 2019)	2019	Survey, Partial Least Squares (PLS)	•		
35	(Bridi et al., 2019)	2019	Systematic Mapping	•		•
36	(Goh & Goh, 2019)	2019	Case Study, Discrete Event Simulation (DES)	•		•
37	(Solaimani et al., 2019)	2019	Systematic Review	•	•	
38	(Terreno et al., 2019)	2019	Review Study	•		
39	(Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019)	2019	Literature Review, Survey	•		
40	(Meng, 2019)	2019	Literature Review, Questionnaire, Interviews	•		
41	(Maqbool et al., 2019)	2019	Case Study	•	•	
42	(Jiang et al., 2019)	2019	Comparative Study, Questionnaire		•	•
43	(Peltokorpi et al., 2018)	2018	Case Studies, Framework Development			•

Table 3.1 Comprehensive table of key articles – Sorted by year (cont'd)

No.	Author	Year	Method	Research Theme		
				Lean	SD	MOC
44	(Souza & Alves, 2018)	2018	Theoretical Framework, Action Research	•	•	
45	(Khodeir & Othman, 2018)	2018	Literature Review, Correlation Matrix	•	•	
46	(Kong et al., 2018)	2018	Case Study		•	•
47	(Caiado et al., 2018)	2018	Systematic Review	•	•	
48	(Jin et al., 2018)	2018	Review		•	•
49	(Arashpour et al., 2017)	2017	Theoretical Modeling, Precast Production		•	•
50	(Heravi & Firoozi, 2017)	2017	Case Study	•		•
51	(Cherrafi et al., 2016)	2016	Literature Review	•	•	
52	(Kamali & Hewage, 2016)	2016	Review		•	•
53	(Mostafa et al., 2016)	2016	Systematic Review (SLR)			•
54	(Ng et al., 2015)	2015	Case Study	•	•	
55	(Ko & Kuo, 2015)	2015	Case Study, Lean Model	•		•
56	(Belekoukias et al., 2014)	2014	Quantitative Study, Regression, Structural Modeling	•		
57	(Martínez-Jurado & Moyano-Fuentes, 2014)	2014	Literature Review	•	•	
58	(Rosenbaum et al., 2014)	2014	Case Study		•	
59	(Ogunbiyi et al., 2014)	2014	Questionnaire Survey	•	•	
60	(Yu et al., 2013)	2013	Case Study			•

Table 3.1 Comprehensive table of key articles – Sorted by year (cont'd)

No.	Author	Year	Method	Research Theme		
				Lean	SD	MOC
61	(Firoozi & Heravi, 2013)	2013	Survey, Lean Methods, Data Collection			•
62	(Boyd et al., 2013)	2013	Case Study, Theoretical Analysis		•	•
63	(Aziz & Hafez, 2013)	2013	Review, Case Study	•		
64	(Stump & Badurdeen, 2012)	2012	Case Study	•		
65	(Nahmens & Ikuma, 2012)	2012	Case Studies		•	•
66	(Vieira & Cachadinha, 2011)	2011	Case Study	•	•	
67	(Song & Liang, 2011)	2011	Case Study	•	•	
68	(Yang et al., 2011)	2011	Empirical Study	•	•	
69	(Yu et al., 2009)	2009	Case Study, Simulation	•		
70	(Abdulmalek & Rajgopal, 2007)	2007	Case Study, Simulation (Steel Industry)	•	•	
71	(Bertelsen & Koskela, 2004)	2004	Theoretical Analysis, Literature Review	•	•	•

3.4 Quantitative Analysis

To identify publications related to the integration and impact of Lean Management on Sustainable Development (SD) in Modular Off-Site Construction (MOC), a systematic search was conducted using Scopus for English-language articles published between 2004 and 2024.

Figure 3.2 illustrates the temporal distribution and thematic coverage of the selected studies. The graph on the right side shows the number of publications per year for each domain. A notable rise in Lean-focused publications is observed after 2019, indicating increased academic interest in Lean practices. The graph also demonstrates a general upward trend across all three themes, underscoring their growing significance in shaping sustainable construction practices.

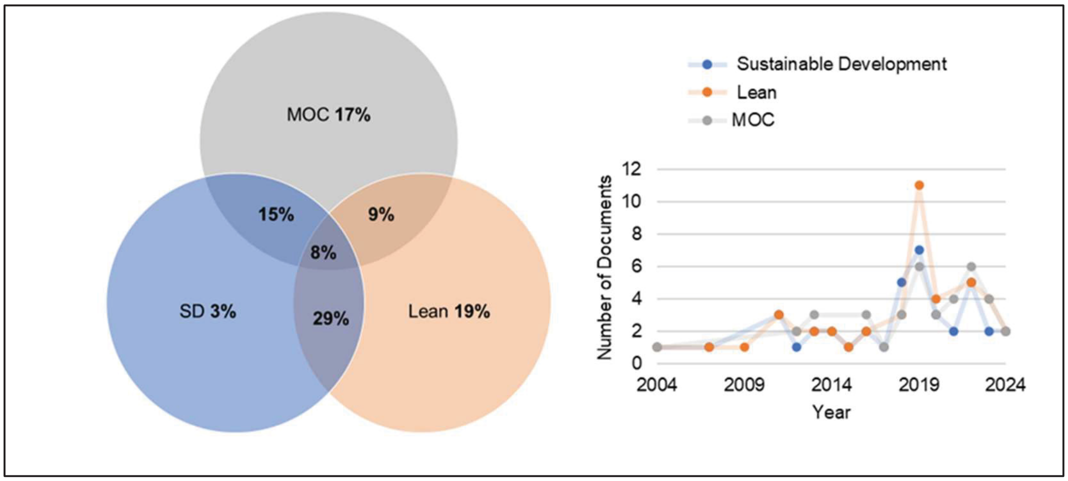

Figure 3.2 Left: Venn diagram of topic distribution across SD, Lean, and MOC. Right: Yearly publication trends (2004–2024) showing rising interest and thematic overlap

The Venn diagram (
Figure 3.2 – Left) represents the distribution of 71 reviewed studies across the three themes: 8% of studies addressed all three domains (Lean, SD, and MOC); 17% focused only on MOC; 19% on Lean; and 3% solely on SD. Furthermore, 15% examined both MOC and SD, 29% focused on Lean and SD, and 9% addressed Lean and MOC. These percentages reflect both individual and overlapping coverage, offering a more nuanced understanding of research patterns. The relatively low number of studies covering all three areas highlights a gap in integrated approaches.

To investigate sustainability priorities within MOC-related studies, a qualitative coding process was conducted using NVivo 14, following the methodological framework of (Skjott

Linneberg & Korsgaard, 2019). The analysis was carried out in two stages. First, a deductive coding strategy was applied based on the three pillars of sustainability economic, environmental, and social as parent nodes. Codes were generated by reviewing key articles from the dataset, aligning with prior practices for qualitative systematic reviews (Lewins & Silver, 2009). In the second stage, word frequency analysis was used to refine sub-categories and detect recurring patterns, ensuring a systematic and replicable interpretation of the literature. This method allowed for a data-driven understanding of the emphasis placed on each sustainability dimension (Wong, 2008).

Figure 3.3 presents the distribution of sustainability aspects discussed in the reviewed studies. Economic sustainability appeared in 44% of the publications, followed by environmental sustainability at 32%. Social sustainability, however, was addressed in only 24% of the studies, making it the most underrepresented dimension. These findings underline the need for a more balanced integration of social concerns into Lean-MOC frameworks, especially considering the broader goals of sustainable development.

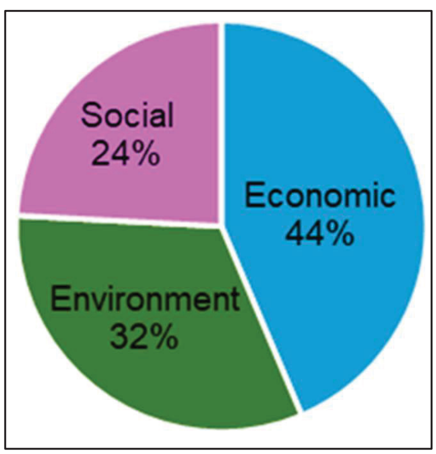

Figure 3.3 Aspects of Sustainable Development (SD) in Modular Off-site Construction (MOC)

In addition to thematic analysis, bibliometric data from Scopus was analyzed using VOS viewer to examine patterns of international collaboration and keyword co-occurrence.

Table 3.2 highlights countries with more than five publications in the selected domains. The USA, China, and England emerged as leading contributors, both in publication volume and citation impact, indicating their central role in advancing research in Lean, MOC, and sustainability. Countries like Canada, Australia, and the Netherlands also demonstrated notable collaboration networks, as reflected in their total link strength values. Co-authorship analysis of countries can contribute to redefining strategies and establishing policies to improve productivity (Karimi & Iordanova, 2021).

Table 3.2 Countries with more than 5 publications in MOC, Lean, SD

Country	**Documents**	**Citations**	**Total Link Strength**
China	10	701	6
England	7	919	5
USA	13	2167	5
Netherlands	5	232	4
Australia	10	691	3
Canada	7	708	2
South Korea	3	57	1
Chile	3	122	1
India	4	55	1
Italy	5	361	1
Brazil	3	181	0
Malaysia	3	142	0

As noted by Karimi & Iordanova (2021), bibliometric analyses such as co-authorship and keyword mapping are essential tools for identifying research trends and guiding future collaboration strategies in off-site construction and sustainability contexts. Keyword co-occurrence analysis further reveals major research clusters and thematic interconnections. Figure 3.4 generated via VOS viewer, displays a network of frequently occurring terms (minimum three occurrences), with prominent keywords including "performance," "sustainability," "lean construction," and "prefabrication."

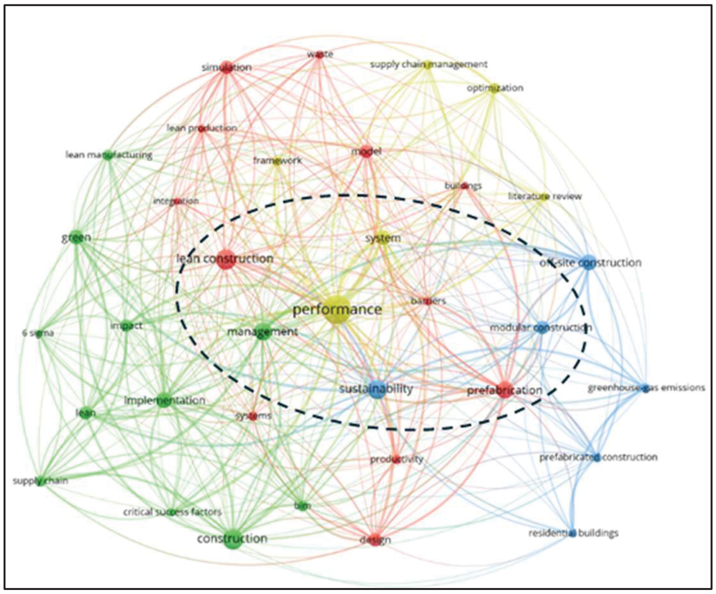

Figure 3.4 Keyword co-occurrence map
(generated with VOS Viewer)

Table 3.3 lists the top 15 most frequent terms alongside their total link strength. The findings show strong associations between Lean principles and performance/sustainability outcomes. However, the relatively weaker linkage between Lean and modular/prefabrication terms suggests a gap in integrating Lean with MOC practices.

Collectively, these results provide a comprehensive view of the current research landscape. While lean and sustainability have been extensively studied, their joint application in modular construction remains limited. Addressing this gap can unlock new insights into optimizing sustainable outcomes in MOC through Lean principles. Future studies should prioritize exploring how Lean principles can enhance the efficiency, resilience, and sustainability of MOC.

Table 3.3 Top 15 high occurrence keywords in MOC, Lean, SD

Ranking	**Keyword**	**Occurrences**	**Total Link Strength**
1	Performance	24	112
2	Management	14	69
3	Prefabrication	13	64
4	Implementation	12	61
5	System	11	61
6	Construction	16	56
7	Lean Construction	13	55
8	Sustainability	15	55
9	Off-site Construction	12	53
10	Green	11	50
11	Design	10	46
12	Simulation	10	46
13	Impact	9	45
14	BIM	10	44
15	Model	10	43

3.5 Qualitative Analysis

The qualitative analysis presented in this study is part of an ongoing comprehensive research initiative aimed at identifying the critical success factors for integrating Lean principles into MOC to optimize Sustainable Development (SD), with a particular focus on its social dimension. To achieve this, key articles included in the SLR were analyzed to uncover potential factors contributing to the successful implementation of Lean practices in MOC projects. The classification of research themes, as outlined in Table 3.1, indicates the specific focus areas and methodological approaches of each study, based on keyword co-occurrence analysis and a rigorous abstract screening process.

3.5.1 Combination of Lean management, Sustainable Development and MOC

Prefabricated construction involves demanding management requirements across its design, prefabrication, and construction stages, making traditional construction management methods insufficient to meet these demands. In contrast, Lean principles align well with prefabricated construction management, as both focus on reducing waste and shortening project timelines. Koskela formally incorporated Lean principles into construction, introducing the Transformation, Flow, and Value Generation (TFV) theory as a structured framework (Du et al., 2023). Lean management in modular construction offers a wide range of benefits, particularly in economic, environmental, and social sustainability. Numerous case studies highlight economic advantages, such as productivity increases of up to 40%–50%, lead time reduction, waste minimization, cost reduction, and higher throughput (Innella et al., 2019; Nahmens & Ikuma, 2012). Beyond economic gains, Lean principles enhance sustainability by improving safety and job satisfaction and reduced pollution (Innella et al., 2019).

Several studies have explored the intersection of these three domains, demonstrating the potential benefits and challenges of their combined implementation. Their findings suggest that while economic and environmental benefits are well documented, achieving an optimal balance across all three sustainability dimensions remains complex due to trade-offs, such as the higher upfront costs of energy-efficient modular buildings (Kamali et al., 2018).Similarly, Peiris et al. (2023) identified a gap in the application of Lean construction principles for the development of Manufacturing Execution & Control (MEC) systems within MOC, underscoring the need for more structured Lean-MOC integration. While Lean principles and sustainability objectives share common goals such as waste minimization and resource efficiency, their practical integration in MOC remains inconsistent. Furthermore, Khodeir & Othman (2018) emphasized that Lean tools, particularly Just-in-Time (JIT) and Value Stream Mapping (VSM), can improve sustainability metrics in MOC projects. However, Martínez-Jurado & Moyano-Fuentes (2014) cautioned that JIT strategies, while improving production flow, could inadvertently increase supply chain environmental impacts if not carefully managed.

Kamali et al. (2018) mentioned that existing research primarily focuses on economic and environmental aspects, while the social dimension of sustainability remains underexplored. For example, Batwara et al. (2023) highlighted the need to integrate social sustainability considerations such as worker well-being, job stability, and community impact into Lean tools like VSM. Additionally, Demirkesen & Bayhan (2022) noted that MOC differs from traditional manufacturing due to its variability in project designs, stakeholder dynamics, and site conditions, which complicate Lean adoption. As Moradi & Sormunen (2023) mentioned the success, challenges, and impact of integrating Lean Construction and sustainability are deeply connected to people their mindset, collaboration, and adaptability. For example, these challenges are further amplified by fragmented implementation practices across regions, such as in Hong Kong, where standardization remains a key issue. Similarly, Sarhan & Fox (2013) identified cultural resistance within the UK construction industry as a major barrier to Lean adoption, highlighting the need for a systematic framework that aligns Lean principles with MOC workflows. Hence, future research should adopt qualitative methodologies, including semi-structured interviews with industry professionals, worker satisfaction surveys, and case studies on successful Lean-MOC implementations (Demirkesen & Bayhan, 2022). Additionally, integrating Lean principles with Human-Centered Design (HCD) could enhance ergonomics, safety, and labor welfare considerations, thus strengthening the social sustainability of MOC projects (Gbadamosi et al., 2019).

3.6 Conclusion

This study examines the integration of Lean Management, Modular Off-Site Construction (MOC), and sustainability to improve economic, environmental, and social outcomes in the construction industry. The findings highlight significant progress in these areas but also reveal clear gaps particularly in integrating Lean tools within MOC to comprehensively address sustainability across its three dimensions. The study confirms that Lean practices enhance sustainability through reduced waste, improved efficiency, and streamlined processes. However, several limitations should be noted, including the focus on English-language publications, the exclusion of empirical validation, and limited attention to emerging technologies such as AI and IoT in Lean-MOC applications. Future research should concentrate on developing structured frameworks that link Lean tools to MOC workflows specifically in design, production, and on-site assembly. Further studies should also investigate how Lean can overcome challenges unique to MOC, such as logistical complexity and fragmentation, while expanding the examination of social sustainability within these systems. Additionally, simulation-based and life-cycle analyses could help quantify Lean-MOC impacts, offering deeper insights into their long-term economic and environmental performance.

3.7 Acknowledgement

The authors would like to thank École de technologie supérieure for their support in this research. We also appreciate the contributions of industry professionals who participated in the study.

CHAPTER 4

ENHANCING MODULAR OFF-SITE CONSTRUCTION THROUGH A LEAN-SUSTAINABILITY FRAMEWORK: FOCUS ON MANUFACTURING AND ON-SITE ASSEMBLY PHASES

Rasouli, H.[1], Mehdipoor, A.[2] Melhado, S.[1], Iordanova, I. [1]

[1] Department of Construction Engineering, École de Technologie Supérieure,
1100 Notre-Dame West, Montreal, Quebec, Canada H3C 1K3
[2]Construction Research Centre, National Research Council of Canada, Ottawa, Canada

Paper submitted for publication, June 2025

4.1 Abstract

While Lean principles and sustainability have attracted growing attention in modular off-site construction, their integration during manufacturing and on-site assembly phases remains underexplored. Unlike earlier studies focused mainly on manufacturing, few have assessed Lean's impacts across all three sustainability pillars: economic, environmental, and social. This study fills that gap by proposing and validating a conceptual framework linking Lean tools to sustainability metrics using a mixed-method approach including literature review, NVivo-assisted analysis, and 13 expert interviews. Results show that Lean practices most strongly support social sustainability enhancing safety, communication, and inclusivity. Economic and environmental benefits were also evident, especially in reducing waste, boosting productivity, and shortening delivery times. The framework was endorsed by 84% of experts as practically relevant. This research offers a validated model for integrating Lean with sustainability in modular off-site construction, focusing on the often-overlooked manufacturing and on-site assembly stages.

Keywords: Modular Off-site Construction (MOC), Lean Management, Sustainable Development (SD), On-site Assembly, Manufacturing in Construction

4.2 Introduction

Despite the construction industry's projected growth from $7.4 to $10.3 trillion between 2010 and 2020, it remains fragmented and inefficient, plagued by delays, cost overruns, and waste (Demirkesen & Bayhan, 2020; Global Construction Outlook, 2015). Modular and Off-site construction (MOC), a form of industrialized construction, relocates activities to factory settings using automation and digital tools to reduce variability and enhance productivity (Andersson & Lessing, 2017; Moghadam & Al-Hussein, 2013).Lean thinking offers a valuable set of principles and tools to enhance MOC effectiveness. Although originally developed for manufacturing, Lean has shown strong potential in construction by improving transparency, reducing cycle times, and increasing value delivery (Mostafa et al., 2016). Its benefits are most fully realized when integrated throughout the entire lifecycle, including on-site assembly (Innella et al., 2019). Koskela (1993) outlined Lean principles such as eliminating non-value activities, minimizing variability, enhancing flow, and fostering continuous improvement. These principles rest on two core pillars: Respect for People and Continuous Improvement (Cherrafi et al., 2016; Jørgensen & Emmitt, 2008)

Despite this foundation, Lean implementation in MOC remains fragmented. Limited research has assessed which Lean tools are most effective across modular production phases or how they impact sustainability outcomes. The negative effects of poorly managed Lean practices such as increased emissions are rarely addressed. Although sustainability discussions often center on the design phase, studies highlight that manufacturing and assembly phases have major environmental and social impacts (Marjaba & Chidiac, 2016; Quale et al., 2012). Furthermore, while Lean can support sustainability outcomes, its integration is often hindered by broader organizational challenges faced by stakeholders, especially within design firms.
As De Paula & Melhado (2018) note, achieving sustainable outcomes requires not only financial investment and expanded technical expertise but also the restructuring of daily

management processes. These include additional training, collaboration with consultants, longer work hours, and the adoption of new tools and certification procedures, all of which can strain existing resources and impede progress.

A critical gap exists in examining how Lean supports all three dimensions of Sustainable Development (SD): economic, environmental, and social. While cost and environmental gains are better documented, the social dimension including workforce well-being, equity, and communication remains understudied (Cherrafi et al., 2016; Martínez-Jurado & Moyano-Fuentes, 2014). According to Gladwin et al. (1995), sustainability requires balance across all three. Yet, social considerations are often marginalized. As Goh & Goh (2019) and Carvajal-Arango et al. (2019) argue, the assembly phase holds untapped potential for advancing social sustainability through Lean strategies.

This study addresses these gaps by developing a conceptual framework that integrates Lean management and SD within MOC. The objectives are: (1) to evaluate the impact of Lean tools across the three SD dimensions, and (2) to identify the most effective tools for manufacturing and assembly phases. This research offers actionable, stage-specific guidance for Lean–SD integration in modular construction.

4.3 Research Background

Modular and Off-Site Construction (MOC) represents a shift from traditional construction by relocating core activities to controlled manufacturing environments, improving productivity, reducing delays, and minimizing waste (Bhatia et al., 2023; Wang et al., 2020). MOC encompasses various construction methods, including modular, panelized, and hybrid techniques, offering flexibility across residential, commercial, and infrastructure projects (Yu et al., 2013). Researchers highlight MOC's potential in enhancing sustainability, standardization, and overall building quality compared to conventional construction methods (Boyd et al., 2013; Moghadam et al., 2012).

Originating from the Toyota Production System, Lean Management focuses on eliminating waste and maximizing value (Ohno & Ohno, 2008; Womack & Jones, 1997). Although widely adopted in manufacturing, Lean's structured application in MOC has faced coordination and standardization challenges, leading to inconsistent implementation across projects (Pan & Pan, 2023). For example, studies in Hong Kong show that Lean adoption in modular settings has encountered organizational resistance and supply chain misalignment, pointing to the need for project-specific customization and better integration between Lean strategies and modular workflows (H. Lu et al., 2018).

The transition of Lean principles into the construction sector was further developed through Koskela's work in the 1990s, introducing a new production model that emphasized three key aspects: transformation of inputs into outputs, the continuous flow of materials and information, and value creation for end users (Koskela, 1993). His framework laid the foundation for Lean Construction, a discipline that has evolved significantly in recent decades, proving its potential in improving operational efficiency across various construction processes (Moghadam et al., 2012). However, despite its theoretical advancements, Lean Construction lacks a universally accepted framework, which continues to fuel debates within the academic and professional communities (Da C. et al., 2012). The link between Lean principles and sustainable development (SD) has been explored extensively in the literature. Khodeir & Othman (2018) suggest that Lean Construction contributes to sustainability goals by reducing waste, optimizing resource use, and enhancing operational efficiency. However, Lean techniques such as Just-in-Time (JIT) and Kanban improve material flow and reduce excess inventory but may inadvertently increase transportation-related emissions due to more frequent deliveries (Caldarelli et al., 2022). Despite these challenges, Lean methodologies in MOC have demonstrated significant sustainability benefits, including lower material waste and improved energy efficiency (Nahmens & Ikuma, 2012).

Although research highlights the advantages of Lean-MOC integration, critical domains remain underexplored. A significant gap exists in understanding how lean principles can enhance Manufacturing Execution and Control (MEC) systems within MOC settings, an area requiring further investigation (Peiris et al., 2023). A few recent studies have started addressing the digital transformation of off-site processes through semiautomated and BIM-driven workflows. For instance, Mehdipoor et al. (2025) introduced a digitalized semiautomation workflow tailored to Light Gauge Steel (LGS) modular construction, enhancing design-to-manufacturing integration using BIM and CNC code generation. This approach not only streamlined coordination between design and production but also demonstrated measurable gains in efficiency and accuracy, illustrating the potential of customized digital solutions in overcoming modular construction uncertainties. Additionally, while Lean is well-developed in traditional manufacturing, its application within MOC lacks a coherent, standardized framework, leading to varied adoption across projects (H. Lu et al., 2018). The complexity of off-site supply chains poses additional challenges, introducing uncertainties in logistics, material flow, and inventory management (Blismas & Wakefield, 2009). Furthermore, while economic and environmental sustainability aspects of Lean-MOC integration have been studied, the social dimension remains largely unexplored. Issues such as workforce well-being, safety, and ergonomics are often overlooked, despite their significance in creating a more holistic sustainability model (Batwara et al., 2023).

Moreover, a few studies have provided a detailed review of the impact of different Lean Management (LM) tools on the three dimensions of sustainability. While Lean techniques offer potential synergies with sustainability goals, research remains limited in understanding how these tools support or unintentionally conflict with sustainable development strategies (Naeemah & Wong, 2022). Most notably, there is a lack of stage-specific analysis, particularly during the manufacturing and on-site assembly phases, regarding which Lean tools are most effective in driving sustainability metrics across economic, environmental, and social domains. To address the identified gaps, this study proposes a stage-specific conceptual framework that integrates Lean principles with sustainable development goals in modular construction. The research focuses on evaluating Lean tools across the three pillars of sustainability and identifying those most effective during manufacturing and on-site assembly phases.

4.4 Research methods

This study adopts a multistage mixed-methods design, integrating qualitative and quantitative approaches to examine the influence of Lean Management (LM) tools on Sustainable Development (SD) within Modular Off-Site Construction (MOC). The research is structured into four sequential phases: (1) Research Definition, (2) Data Collection, (3) Qualitative Analysis, and (4) Quantitative Analysis. The process is illustrated in Figure 4.1.

Each phase builds systematically toward developing and validating a conceptual framework that maps Lean practices to sustainability performance across the economic, environmental, and social dimensions. This iterative approach ensures saturation in the qualitative stage and robustness in the quantitative stage.

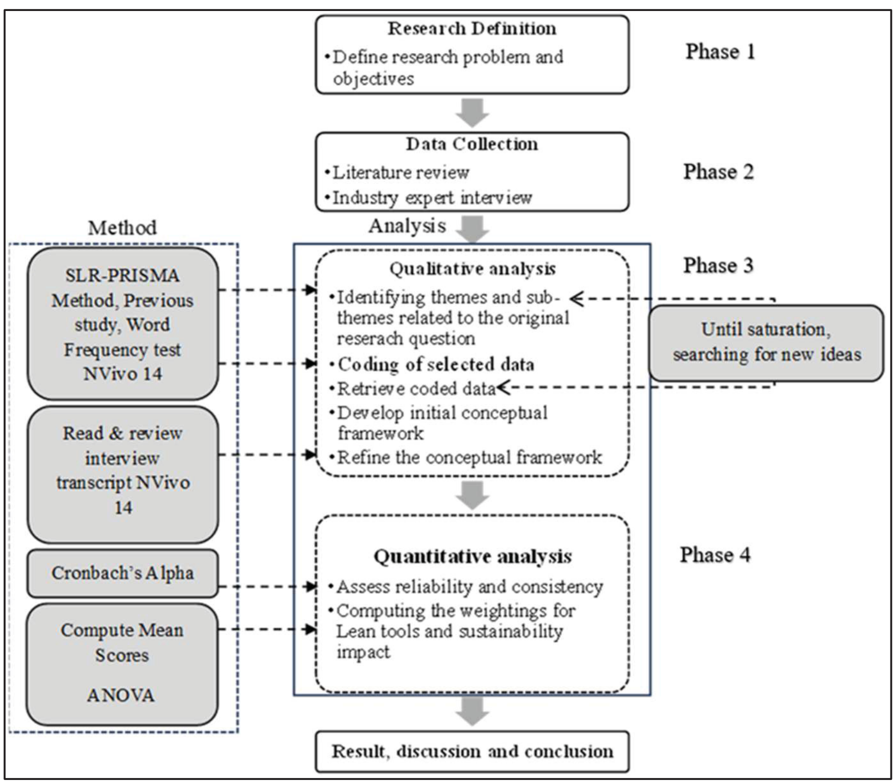

Figure 4.1 Multistage methodological approach flowchart

4.4.1 Phase 1: Research definition

The research begins by identifying a gap in the literature regarding the application of Lean tools during the manufacturing and on-site assembly phases of MOC, critical stages often overlooked in sustainability-focused construction research. The core objective is to establish a framework that aligns Lean tools with triple bottom line sustainability metrics, enabling their practical integration into MOC processes.

4.4.2 Phase 2: Data collection

Systematic Literature Review: A Systematic Literature Review (SLR) was conducted using the PRISMA method, targeting articles from databases such as Scopus and Web of Science.

Boolean logic was used with the following search query:

("Lean Tools" OR "Lean Construction") AND ("Sustainability" OR "Triple Bottom Line") AND ("Modular Construction" OR "Offsite Manufacturing")

Articles were filtered by relevance, date, and language. The extracted literature was coded and analyzed using NVivo 14, with word frequency analysis employed to identify key Lean practices and sustainability themes. Semi-Structured Expert Interviews: To validate and refine the SLR findings, 13 semi-structured interviews were conducted with industry and academic experts, focusing on the application of Lean tools across sustainability dimensions during the manufacturing and assembly stages of Modular Off-Site Construction (MOC). Interviews were conducted online, recorded, transcribed, and analyzed in NVivo 14. Participant profiles are provided in Table 4.1. A structured questionnaire was then developed, incorporating insights from literature and expert input. It covered expert background, framework comprehension, evaluation of Lean tools across economic, environmental, and social dimensions, and suggestions for improvement. Economic factors focused on budget, quality, and productivity; environmental waste, emissions, and resource efficiency; and social on safety, health, and working conditions. Experts also recommended refinement, notably the integration of IDEA (Inclusivity, Diversity, Equity, and Accessibility) into the social dimension. Ethical protocols were upheld throughout, and transcripts were analyzed in NVivo 14 to support systematic coding and thematic mapping (Wong, 2008).

Table 4.1 Interviewees' profile

Interviewee	**professional role**	**Type of company**	**Industry experience (years)**	**Interview duration**
Int-1	Research Officer	General contractor	12	55 min
Int-2	Director	Architecture	20	40 min
Int-3	Architect	Manufacturer	9	30 min
Int-4	Professor	Academia	15	60 min
Int-5	Professor	Academia	22	53 min
Int-6	Lean Advisor	Academia	45	60 min
Int-7	Innovation manager	Manufacturer	8	60 min
Int-8	Director	General contractor	14	42 min
Int-9	Quality Leader	Manufacturer	20	55 min
Int-10	CEO	Manufacturer	40	37 min
Int-11	Research Officer	General contractor	14	55 min
Int-12	Digital research officer	General contractor	10	44 min
Int-13	Consultant	General contractor	15	57 in

4.4.3 Phase 3: Qualitative analysis

Thematic Coding and Framework Development: This phase involved thematic analysis using NVivo 14, focusing on identifying and coding themes and sub-themes related to sustainability performance in MOC projects.

Key steps included:

- Identification of primary themes and sub-themes grounded in the research question.
- Coding of selected qualitative data, both from literature and expert transcripts.
- Retrieval of coded data to inform and shape an initial conceptual framework.
- Refinement of the conceptual framework based on emerging data and expert validation.

The process continued until saturation was reached, meaning no new themes emerged despite further data review.

In this study, the coding process was structured based on the approach outlined by Dransfield et al. (2004) and was carried out in two key steps: NVivo codes were established through a comprehensive review of existing literature, focusing on studies that formed the theoretical foundation of this research. Given that Lean, and Sustainable Development (SD) are the main themes of this study, the first step was to identify key metrics for each one before categorizing them into main categories and subcategories. First, for Sustainable Development (SD), it was essential to define relevant metrics across three dimensions: economic, environmental, and social. Through an in-depth analysis, these metrics were categorized into six economic, five environmental, and five social categories similarly outlined by Naeemah & Wong (2022). The economic dimension included budget, construction and delivery time, productivity, quality, uncertainties and risks, and value creation. The environmental aspect was classified into atmospheric impact, energy consumption, material consumption, waste, and water consumption. Meanwhile, the social dimension encompassed employee skills (training and learning), organizational influence, relationships and communication, as well as safety, health, and working conditions. These categories, considered as parent codes, provide a structured approach to evaluating how Lean principles influence sustainability outcomes within MOC. Next, for Lean Management, the focus was on identifying Lean tools and practices that impact sustainability specially in each stage of MOC both positively and negatively. Following an iterative analysis, the most frequently mentioned Lean tools were identified and categorized into fourteen key practices similarly to the approach taken by Carvajal-Arango et al. (2019) : 5S, Integrated Project Delivery (IPD), Just-in-Time (JIT), Kaizen, Kanban, Last Planner, Lean Project Delivery System, Poka Yoke (Error Proofing), Pull Strategy, Six Sigma, Single-Minute Exchange of Dies (SMED), Target Value Design, Visual Management (Andon Line), and Value Stream Mapping (VSM). These tools were selected based on their recurring presence in the literature and their potential to influence sustainability metrics across economic, environmental, and social aspects as evidenced by studies such as (Carvajal-Arango et al., 2019; Li et al., 2022; Moradi & Kähkönen, 2022; Naeemah & Wong, 2022). In line with the Modular and Off-Site Construction (MOC) process structure outlined by (Innella et al., 2019), this study acknowledges five key stages: design, supply chain, manufacturing, transportation, and on-site assembly. Among these, particular emphasis is placed on the manufacturing and on-site assembly phases, as they represent the most critical operational stages where Lean Management principles can be practically implemented and directly observed (Goh & Goh, 2019). By concentrating on production and assembly, the research aims to explore where Lean practices have the greatest potential to enhance sustainability performance across economic, environmental, and social dimensions within modular construction. After importing interview transcripts and systematic review of literature into NVivo 14, word frequency tests were conducted to identify recurring themes and concepts. As highlighted by Ryan & Bernard (2003), analyzing word frequency is an effective method for discovering underlying patterns in qualitative data. Similarly, Jackson (2019) emphasizes that identifying frequently repeated ideas helps reveal the contextual importance of certain concepts. To refine sub-themes, separate word frequency queries were performed for each main category, analyzing key terms based on their frequency, weighted percentage, and synonymous terms.

Table 4.2 shows the Sustainable Development (SD) metrics used in framework and Table 4.3 shows key Lean tools and practices identified.

Table 4.2 Sustainable Development (SD) metrics used in framework

Dimension	**Sub-Categories**
Economic	Budget, Delivery Time, Productivity, Quality, Risks, Value Creation
Environmental	Atmospheric Impact, Energy, Materials, Waste, Water
Social	Training, Organizational Influence, Communication, Safety, Working Conditions

Table 4.3 Key Lean Tools and Practices identified

Lean Tool	**Description**
5S	Workplace organization
JIT (Just-in-Time)	Inventory and delivery control
VSM (Value Stream Mapping)	Workflow analysis
Last Planner System	Collaborative planning
Kaizen	Continuous improvement
Kanban	Visual scheduling system
IPD (Integrated Project Delivery)	Multi-party collaboration
SMED	Setup time reduction
Poka-Yoke	Error-proofing
Six Sigma	Process quality control
TVD (Target Value Design)	Cost-focused design planning
Pull Strategy	Demand-driven scheduling
Visual Management	Visual control systems
Lean Project Delivery System	Lean-based project execution model

4.4.4 Phase 4: Quantitative analysis

Survey Design and Reliability Testing: Following the framework development, a structured survey was deployed to experts to validate the impact of identified Lean tools on the 16 sustainability sub-metrics. Data from the survey were analyzed using:

- Cronbach's Alpha to assess internal consistency and reliability of the responses (value = 0.944).
- Mean Score (MS) computations to rank the relative importance and perceived impact of each metric.
- ANOVA (Analysis of Variance) to test for significant differences in opinions among different expert groups (e.g., academia vs. industry).

This phase enabled quantification of the qualitative findings and provided statistical rigor to the framework validation.

A semi-structured survey was administered to 13 industry experts with extensive experience in construction, Lean implementation, and MOC. The survey was structured into five sections, focusing on assessing the clarity, comprehensiveness, relevance, and practical applicability of the framework. Each item was rated on a Likert scale from 1 (Strongly Disagree) to 5 (Strongly Agree), with space provided for open-ended comments and suggestions. Experts were asked to assess the significance and applicability of specific Lean tools in relation to 16 sustainability metrics grouped under the three dimensions of SD: economic, environmental, and social. For instance, participants evaluated whether the framework helped address critical issues such as budget control, energy consumption, quality assurance, and workplace safety. Their responses provided nuanced insights into which tools such as Value Stream Mapping (VSM), Just-in-Time (JIT), or Visual Management were perceived as most impactful in enhancing sustainability performance in the manufacturing and on-site assembly phases of MOC. The goal was to assess whether the framework effectively incorporates the most impactful Lean tools and practices across sustainability metrics, ensuring optimized economic, environmental, and social outcomes in MOC.

Open-ended survey questions and in-depth interviews provided further context. These qualitative components allow experts to discuss the strengths and weaknesses of the framework, share practical challenges, and offer suggestions for improvement. Notably, these discussions also identified additional Lean tools and sustainability metrics that were not initially included in the framework, offering valuable insights for further refinement. Table 4.4 used to assign the degree of importance based on transcription:

Table 4.4 Likert scale and coding interpretation

Scale	Interpretation	Frequency Meaning
1	Strongly Disagree	Lean tools and practices not mentioned properly at all.
2	Disagree	Lean tools were addressed but without any relation to Sustainable Development (SD) metrics.
3	Neutral	Lean tools were mentioned with minimal elaboration on their connection to SD metrics.
4	Agree	Lean tools were discussed multiple times, demonstrating a clear relationship with SD metrics and their impact.
5	Strongly Agree	Lean tools and practices not mentioned properly at all.

The scale was interpreted as follows: 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly Agree. To ensure the reliability of the dataset and the survey instrument, the data was analyzed using the Statistical Package for the Social Sciences (IBM SPSS v.25). Cronbach's Alpha was applied to assess internal consistency, following the approach outlined by (Tavakol & Dennick, 2011).

$$\propto = \frac{K}{K-1}\left[1 - \frac{\sum S^2 y}{S^2 x}\right] \tag{4.1}$$

Cronbach's Alpha, which ranges from 0 to 1, was used to determine the reliability of responses, where 0 indicates no reliability and 1 signifies absolute reliability. A threshold value of 0.7 is generally considered acceptable for reliability assessment. The analysis yielded a Cronbach's Alpha score of 0.944, exceeding the acceptable threshold and confirming a high level of reliability in the dataset. Table 4.5 presents the variables along with their respective internal consistency values based on Cronbach's Alpha.

Table 4.5 Internal consistency

Variable	**Description**	**Value**	**Internal consistency** (α)
K	Number of SD metrics	16	0.944
$\sum s^2 y$	Sum of each SD metric's variance	13.79	
$s^2 x$	The variance of a sum of SD metric's value	120.00	

Mean scoring and ranking of Sustainable Development (SD) Dimensions and Metrics: The mean scores (MS) for sustainability metrics and Lean tools in Modular Off-Site Construction (MOC) were determined using a structured 5-point Likert scale, incorporating expert evaluations collected through semi-structured surveys and supported by qualitative insights from interviews. This integrated scoring process allowed for both numerical assessment and contextual validation. The approach is informed by the methodology of Wuni & Shen (2020) and Attouri et al. (2022), who employed mean scoring to systematically evaluate and prioritize critical factors in construction-related frameworks. In this study, the mean score analysis serves to reflect the perceived importance, practical relevance, and strategic alignment of each sustainability metric and Lean practice within the context of Lean–Sustainable Development (SD) integration in MOC.

$$MS = \frac{\sum(E \times F)}{N}, (1 \leq MS \leq 5) \tag{4.2}$$

In this study, E represents the score given to each sustainability metric and the Lean tools and practices that can influence it. This score reflects how well each tool or practice helps improve the metric and reduces defects related to it. The scoring was based on semi-structured survey responses and expert evaluations, using a 1 to 5 rating scale. F denotes the frequency of each rating (1–5) provided by industry experts, while N represents the total number of respondents. This approach ensures that the most impactful Lean tools and practices are identified based on their relevance and ability to optimize sustainability metrics across the economic, environmental, and social dimensions of Modular Off-Site Construction (MOC).

Table 4.8 presents the mean score (MS) analysis results based on expert evaluations, identifying the most significant sustainability metrics influenced by Lean practices across the manufacturing and assembly stages of Modular Off-Site Construction (MOC).

Sample grouping and one-way analysis of variance (ANOVA): The dataset was categorized to examine whether statistically significant differences exist among the evaluations of more than three groups of experts (Ostertagová & Ostertag, 2013). To examine whether expert groups perceive the impact of Lean tools on sustainability metrics differently, the following hypotheses were proposed:

Null Hypothesis (H_0): There is no statistically significant difference in the mean evaluation of sustainability metrics among the three expert groups (Group A – Management, Group B – Academia, Group C – Industry Practitioners).

Alternative Hypothesis (H_1): There is a statistically significant difference in the mean evaluation of sustainability metrics among the three expert groups.

To assess whether experts from different professional backgrounds perceive the impact of Lean tools on sustainability metrics differently, the participants were divided into three distinct groups: Group A (Management professionals, including project and construction managers), Group B (Academia), and Group C (Industry practitioners such as manufacturers, suppliers, and general contractors). A one-way ANOVA test was employed to determine whether statistically significant differences existed in the evaluations provided by these groups. The analysis was performed using IBM SPSS Statistics v25, with the significance level (α) set at 0.05. The null hypothesis (H_0) posits that there is no statistically significant difference between the groups' perceptions regarding the effectiveness of Lean tools across sustainability dimensions. A p-value below 0.05 leads to the rejection of the null hypothesis, indicating significant variation among expert opinions, while a p-value above 0.05 implies relative consensus across the groups (Hussain et al., 2017; Kim, 2017). The ANOVA results, summarized in Table 4.9, reveal dimension-wise and overall p-values, highlighting where expert evaluations diverged or aligned. These results offer insight into how different stakeholder perspectives influence the prioritization of sustainability metrics in Modular Off-Site Construction (MOC). Specifically, metrics such as construction and delivery time, productivity, and material consumption showed notable variation in mean scores. For instance, Group A emphasized productivity and risk mitigation more strongly, while Group B showed higher concern for long-term environmental impacts. On the other hand, metrics such as employee training and water consumption exhibited less variation across the three groups, suggesting broader consensus on their importance regardless of role or experience.

4.5 Result

4.5.1 SLR findings

The SLR highlighted a lack of comprehensive studies examining the impact of specific LM tools on the three dimensions of sustainability. Currently, there is limited understanding of how Lean techniques contribute to sustainability efforts, including their benefits, challenges, and potential conflicts. More research is needed to explore how Lean and sustainability can work together effectively (Naeemah & Wong, 2022). Additionally, although the economic and environmental aspects of Lean-MOC integration have been examined, the social dimension has received little attention and remains understudied (Batwara et al., 2023).

Sustainability involves maintaining a balance across three core dimensions economic, social, and environmental, which are collectively referred to as the "triple bottom line". In the construction phase, the economic aspect focuses on optimizing the project budget by reducing operational and maintenance costs (Ogunbiyi et al., 2014). The social aspect aims to enhance the health, safety, and overall well-being of workers (Khodeir & Othman, 2018), while the environmental aspect seeks to minimize resource consumption and reduce material and energy waste generated during construction (Koranda et al., 2012). This study considers specific elements from construction activities that contribute to these three dimensions, using them to assess and manage the sustainability performance of construction projects such as atmospheric emissions, water consumption, value creation, quality, working condition (Carvajal-Arango et al., 2019; Li et al., 2022; Moradi & Kähkönen, 2022; Naeemah & Wong, 2022).

To identify the most effective tools in MOC and their connection to the three dimensions of sustainable development, insights were gathered from both the literature review and industry experts, drawing on their experience and perspectives. Interviews are a widely recognized method for data collection in research (Taylor, 2005), with semi-structured interviews being the most commonly used approach in qualitative studies (DiCicco-Bloom & Crabtree, 2006). In this study, a semi-structured interview approach was employed, where open-ended questions were designed around a predefined theme and framework, as described by (Denzin & Lincoln, 2018). This method, as noted by Kallio et al. (2016), ensured the collection of reliable and comparable data, while also allowing for flexibility, enabling additional questions to be asked as needed and key discussion points to be planned in advance.

4.5.2 Synthesis and Interpretation

Findings from both qualitative and quantitative analyses were synthesized to develop a validated framework linking Lean tools to sustainable practices in Modular Off-Site Construction (MOC). NVivo 14 was used to systematically code interview transcripts and literature sources, ensuring alignment between research objectives and empirical evidence. Word frequency and matrix coding queries Figure 4.2 facilitated theme identification across Sustainable Development (SD) metrics and Lean tools.

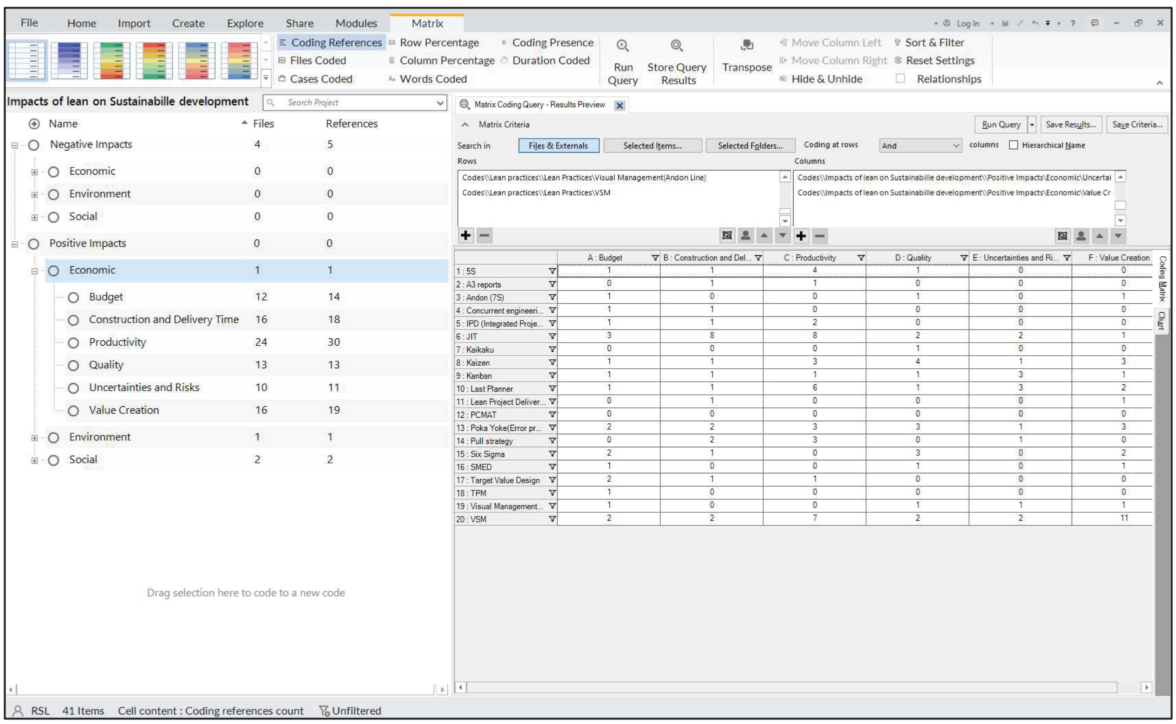

Figure 4.2 Matrix coding query for one of the main metrics of SD vs
The most effective lean tools by NVivo 14

Table 4.6 and Table 4.7 summarizes the categorized findings, showcasing key sustainable development indicators and metrics alongside the most impactful Lean tools and practices, as identified through the literature review and thematic analysis.

Table 4.6 Sustainable development indicators and aspects through MOC

Theme 1	**Categories**	**Sub categories**	**Number of coding**
Sustainable Development	Economic	Productivity	24
		Construction and Delivery Time	16
		Value Creation	15
		Quality	14
		Budget	13
		Uncertainties and Risks	10
	Environment	Waste	27
		Atmospheric	15
		Material Consumption	12
		Energy Consumption	9
		Water Consumption	5
	Social	Safety and Health	17
		Influence on the Organization	14
		Relationships and communication	10
		Working conditions	7
		Employee skills (Training and Learning)	3

Table 4.7 Most impactful Lean tools and practices through MOC

Theme 2	**Categories**	**Number of coding**
Lean Management (Tools and Practices)	VSM	37
	JIT	27
	Last Planner	21
	Kaizen	19
	5S	19
	Poka Yoke (Error proofing)	12
	Kanban	11
	Six Sigma	8
	Visual Management (Andon Line)	7
	Lean Project Delivery System	5
	Pull Strategy	5
	IPD (Integrated Project Delivery)	4
	Target Value Design	3
	SMED	3

To establish the initial interview framework, coding analysis was conducted to classify sustainability into three core dimensions: economic, environmental, and social. As illustrated in Figure 4.3 ,the economic dimension emphasized productivity, cost, and risk management; the environmental dimension focused on resource use and waste; and the social dimension addressed safety, working conditions, and organizational influence. This structure provided a clear foundation for assessing Lean's impact on sustainability in Modular Off-Site Construction (MOC).

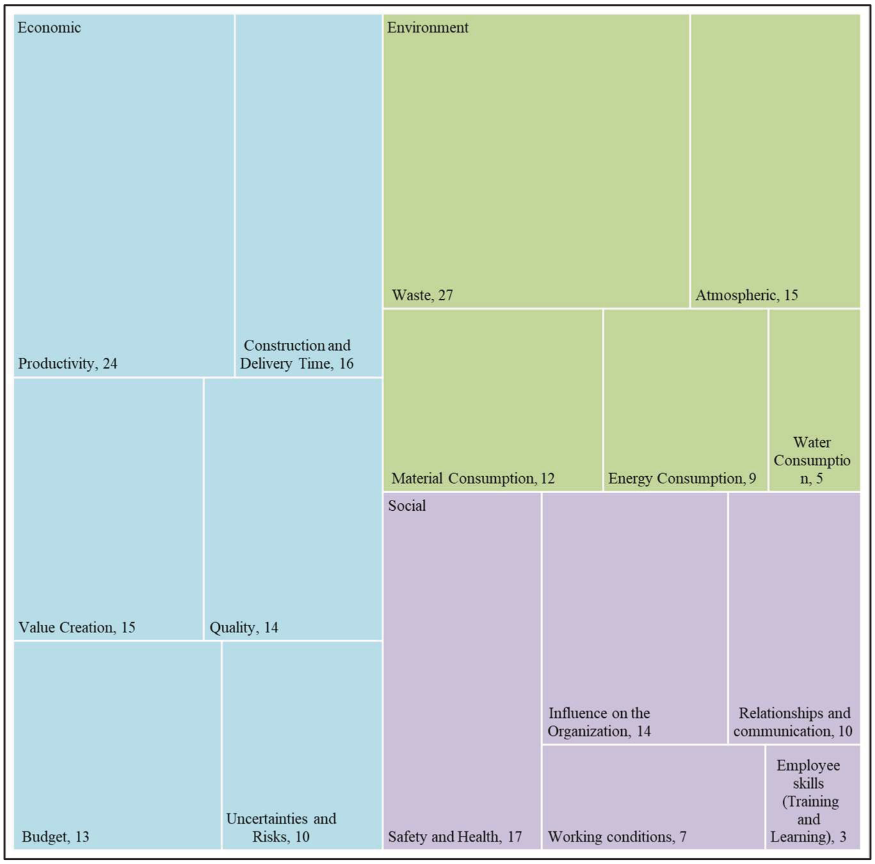

Figure 4.3 The three dimensions of sustainability along with key metrics in Modular Off-Site Construction (MOC)

In the following, Figure 4.4 presents the frequency of Lean management tools and practices identified through coding analysis. Value Stream Mapping (VSM), Just-in-Time (JIT), and Last Planner emerged as the most frequently coded tools, indicating their strong relevance in Lean applications for Modular Off-Site Construction (MOC).

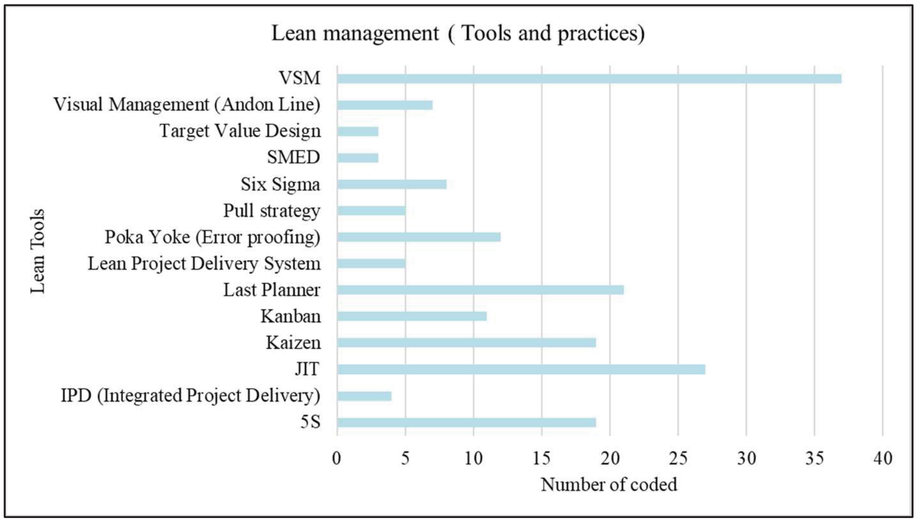

Figure 4.4 The frequency of Lean management tools and practices identified through coding analysis

To support the development of the conceptual framework, a structured matrix-based analysis was conducted. As shown in Figure 4.5 the matrix maps Lean practices against the three pillars of sustainability economic, environmental, and social highlighting both positive and negative impacts. Building on Carvajal-Arango et al. (2019), this study expands the methodology with a dual-impact perspective, capturing not only benefits but also unintended consequences of Lean in Modular Off-Site Construction (MOC). Blue cells indicate positive impacts, such as Value Stream Mapping's (VSM) association with waste reduction and improved energy efficiency. Orange cells highlight drawbacks, particularly in the atmospheric category, where JIT, Pull Strategy, and Visual Management may increase emissions if poorly adapted. For instance, the atmospheric category exhibits a concentration of negative scores particularly for JIT, Pull Strategy, and Visual Management. These negative values reflect concerns raised in the literature about the environmental downsides of certain Lean tools when not contextually adapted. Just-in-Time (JIT) was frequently associated with increased transportation emissions due to frequent small-lot deliveries, especially in regions where supplier reliability or proximity is low (Francis & Thomas, 2019). Similarly, Pull Strategies and Visual Management systems, which require synchronized logistics, may inadvertently contribute to higher fuel usage and emissions when delivery infrastructure is inefficient (Dieste et al., 2020; Sartal et al., 2017). Some studies also highlight that Kaizen events, although useful for process improvement, can lead to short-term spikes in energy usage or hazardous waste generation (Cherrafi et al., 2016).

These findings emphasize that Lean tools like JIT can improve productivity but may also increase environmental impacts if not tailored to local logistics. Rather than discrediting such tools, the results underscore the need for context-sensitive implementation in MOC. This matrix serves as a foundation for understanding Lean's influence on sustainability across project stages and directly supports the next phase expert interviews to validate and refine the framework for strategic, goal-aligned decision-making in modular construction.

MATRIX SUSTAINABLE IMPACTS VS LEAN PRACTICES	Budget	Construction and Delivery Time	Productivity	Quality	Uncertainties and Risks	Value Creation	Atmospheric	Energy Consumption	Material Consumption	Waste	Water Consumption	Employee skills (Training and Learning)	Influence on the Organization	Relationships and communication	Safety and Health	Working conditions
5S	1	1	4	1	0	0	1	1	1	8	1	0	2	2	4	2
IPD (Integrated Project Delivery)	1	1	2	0	0	0	0	0	0	1	0	0	0	2	0	0
JIT	3	8	8	-1 2	2	1	-9 1	-3 2	-1 4	4	0	0	1	1	3	1
Kaizen	1	1	3	4	1	3	-1 1	2	3	-1 8	-1	0	1	2	7	2
Kanban	1	1	1	1	3	1	-2 1	3	4	4	0	0	1	1	1	1
Last Planner	1	1	6	1	3	2	1		0	4	0	0	4	1	5	3
Lean Project Delivery System	0	1	0	0	0	1	-2	-1	0	0	0	0	0	1	0	0
Poka Yoke(Error proofing)	2	2	3	3	1	3	1	2	1	5	0	0	1	1	4	1
Pull strategy	0	2	3	-1	1	0	0	0	0	1	0	0	0	2	0	0
Six Sigma	2	1	0	3	0	2	1	1	1	4	0	1	2	1	2	1
SMED	1	0	0	1	0	1	1	1	1	3	0	0	0	1	1	1
Target Value Design	2	1	1	0	0	0	0	0	0	2	0	0	0	1	0	0
Visual Management(Andon Line)	1	0	0	1	1	1	1	1	2	1	0	0	1	2	3	3
VSM	2	2	7	-1 2	2	11	1	1	5	17	1	0	-1 1	3	3	2
	ECONOMIC						ENVIRONMENT					SOCIAL				

Figure 4.5 Matrix of Lean Tools and their positive and negative impacts on Sustainable Development metrics in MOC

Findings from the NVivo analysis laid the foundation for expert validation. A comprehensive coding framework comprising 16 SD subcategories and key Lean practices was developed and evaluated through interviews with 13 industry experts. The analysis, focused on the manufacturing and on-site assembly phases of MOC, confirmed Lean's strong influence on integration and efficiency. Built on SLR insights, the framework aligns Lean practices with emerging technologies (Pan & Pan, 2023) and sustainability principles outlined by Koskela (1993) and emphasized by Sui Pheng & Hui Fang (2005). To validate this integration, a mixed-method approach combining interviews and structured surveys was used. Table 4.8 presents the ranking of SD metrics in MOC based on mean scores (MS).

Table 4.8 Ranking of SD metrics in MOC based on mean scores (MS)

Metrics	**Factor**	**Dimension**	**MS**	**Rank**
Construction and Delivery time	F2	Economic (D1)	4.31	1
Material Consumption	F9	Environmental (D2)	4.31	2
Productivity	F3	Economic (D1)	4.23	3
Waste	F10	Environmental (D2)	4.23	4
Relationship and communication	F14	Social (D3)	4.23	5
Safety and health	F15	Social (D3)	4.15	6
Working Condition	F16	Social (D3)	4.15	7
Budget	F1	Economic (D1)	4.08	8
Energy Consumption	F8	Environmental (D2)	4.08	9
Influence in the organization	F13	Social (D3)	4.08	10
Quality	F4	Economic (D1)	4.00	11
Value Creation	F6	Economic (D1)	3.92	12
Employee Skill	F12	Social (D3)	3.92	13
Uncertainties and Risk	F5	Economic (D1)	3.85	14
Water Consumption	F11	Environmental (D2)	3.77	15
Atmospheric	F7	Environmental (D2)	3.69	16

Table 4.9 ANOVA results of expert group evaluations across sustainability dimensions in Lean-MOC integration

Dimension	**Factors**	**MS**			**Total MS**	**Total SD**	**Single Dimension P -Value**	**Dimension MS**	**Dimension Rank**
		Group A	**Group B**	**Group C**					
D1	F1	4.4	2.7	4.6	4.08	1.19	7.19E-06	4.06	2
	F2	4.4	3.3	4.8	4.31	0.75			
	F3	4.2	3.7	4.6	4.23	0.60			
	F4	4.4	3.3	4	4.00	0.91			
	F5	4.0	3.0	4.2	3.85	0.90			
	F6	4.0	3.3	4.2	3.92	0.95			
D2	F7	4.2	3.3	3.4	3.69	0.95	0.000469	4.02	3
	F8	4.4	3.0	4.4	4.08	1.26			
	F9	4.4	3.3	4.8	4.31	0.85			
	F10	4.6	3.3	4.4	4.23	0.83			
	F11	4.0	3.0	4	3.77	1.09			
D3	F12	4.6	2.7	4	3.92	1.26	0.00232	4.11	1
	F13	4.2	3.7	4.2	4.08	1.12			
	F14	4.4	3.7	4.4	4.23	0.73			
	F15	4.6	3.7	4	4.15	0.99			
	F16	4.0	3.7	4.6	4.15	0.80			
Overall P - Value							1.1166E-12		

Furthermore, dimension-level evaluations ranked the social dimension (D3) as the highest in terms of mean impact (MS = 4.11), followed by economic (D1) and environmental (D2) dimensions. These findings suggest that social factors are considered the most influential in integrating Lean practices into Modular Off-Site Construction (MOC). These findings highlight the importance of considering contextual differences in expert perspectives when designing or applying Lean frameworks in modular construction. In line with Wuni & Shen (2020), and Attouri et al. (2022), this result also supports the use of mean scoring and ANOVA as complementary tools to capture both consensus and divergence among stakeholders in Lean-SD integration efforts. The ANOVA results, summarized in Table 4.9. This variation in expert opinions highlights the need for a more tailored approach when integrating Lean tools, particularly in addressing workplace conditions, communication, and organizational influence. These results set the stage for the next section, which interprets how Lean practices, supported by empirical insights, influence the economic, environmental, and social dimensions of sustainability in MOC projects.

4.6 Discussion

The framework is structured around three main SD categories economic, environmental, and social divided into 16 sustainability sub-metrics capturing key performance indicators in MOC projects. These are linked with 14 Lean tools and practices, acting as strategic enablers to enhance sustainability across production and on-site assembly phases.

Based on expert evaluations Table 4.8, construction and delivery time (F2 – Economic) and material consumption (F9 – Environmental) were the most influential metrics, highlighting Lean's strong role in schedule efficiency and resource optimization. Productivity (F3 – Economic) closely followed, reflecting Lean's impact on workflow and performance. In contrast, uncertainties and risks (F5), water consumption (F11), and atmospheric impact (F7) showed the lowest perceived impact, indicating limited or underexplored Lean integration.

Overall, as shown in Table 4.9, social sustainability was ranked highest, followed by economic sustainability, where Lean tools proved effective for cost control, productivity, and time management. Environmental sustainability, though slightly less emphasized, remained relevant through Lean strategies targeting waste, energy, and emissions. The final conceptual framework, derived from expert assessments and shown in Figure 4.6 , Figure 4.7 and Figure 4.8. captures the perceived influence of Lean practices on sustainability in MOC. Blue labels represent Lean tools used in on-site assembly; red-dashed items denote tools in production. Green text reflects refinements suggested through interview feedback. The next sections detail each SD dimension, starting with social sustainability, which is ranked highest.

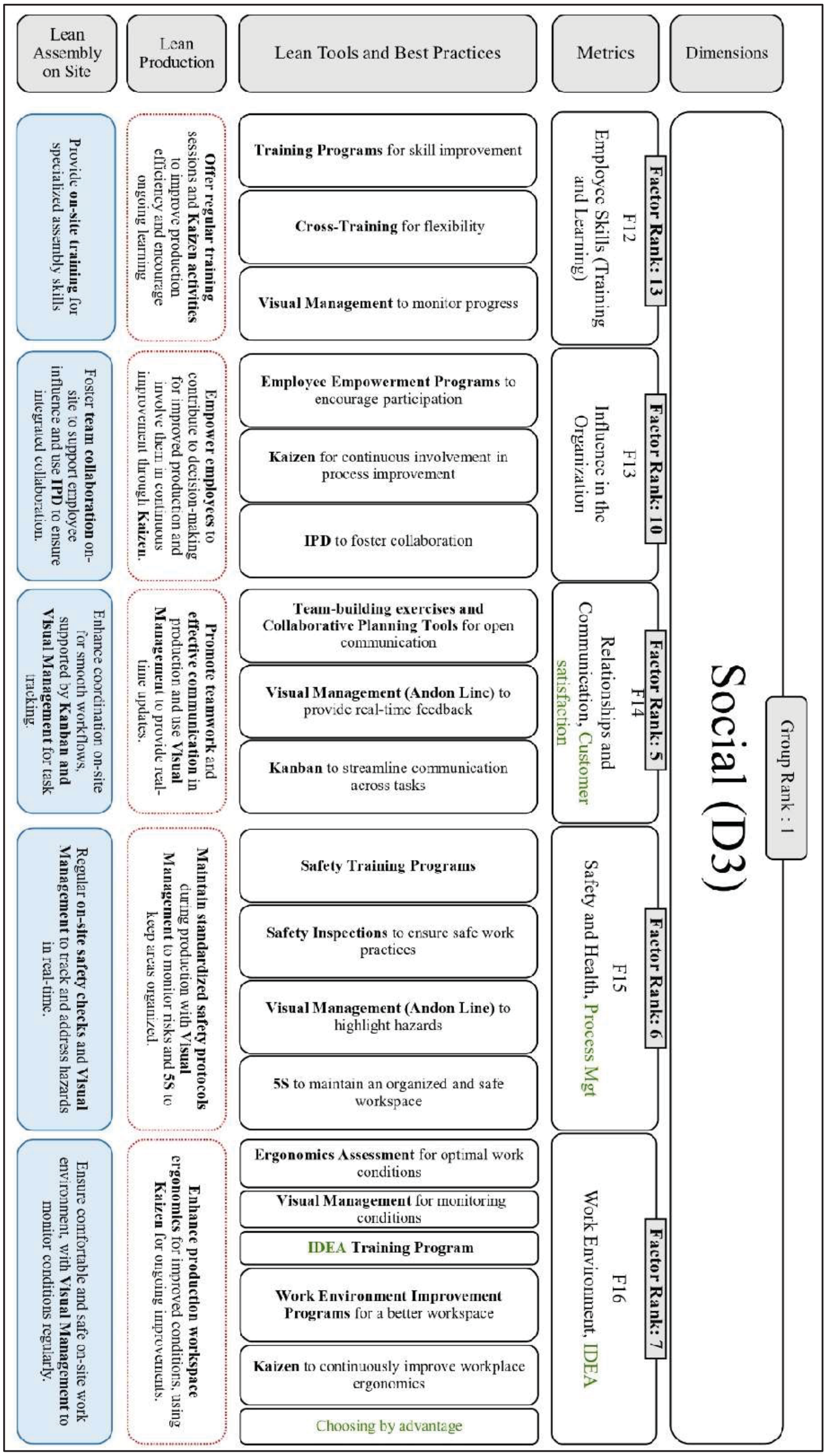

Figure 4.6 Lean–SD framework for Social (D3) metrics in MOC
(Blue: Lean practices for assembly; Red dashed: Production)

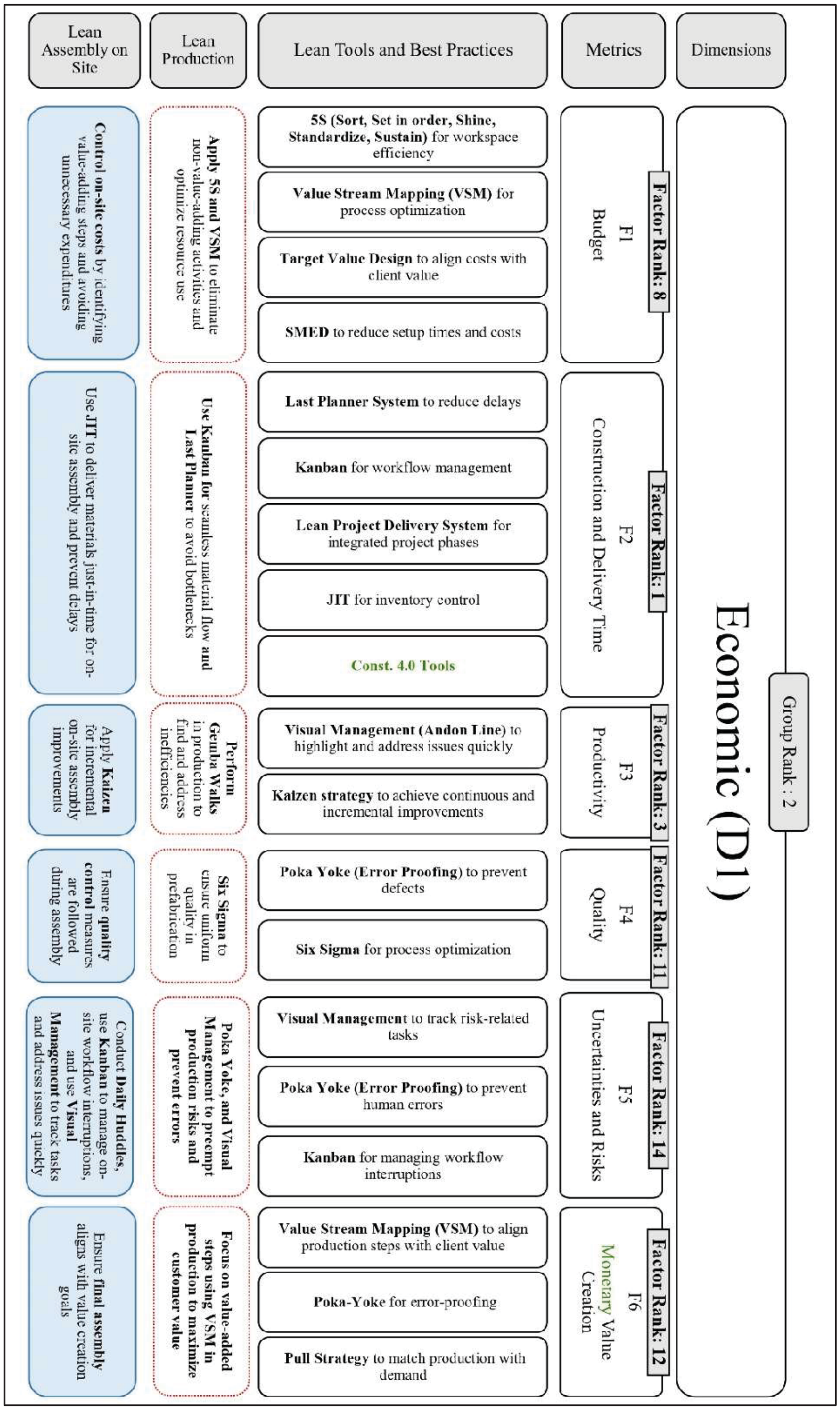

Figure 4.7 Lean–SD framework for Economic (D1) metrics in MOC (Blue: Lean practices for assembly; Red dashed: Production)

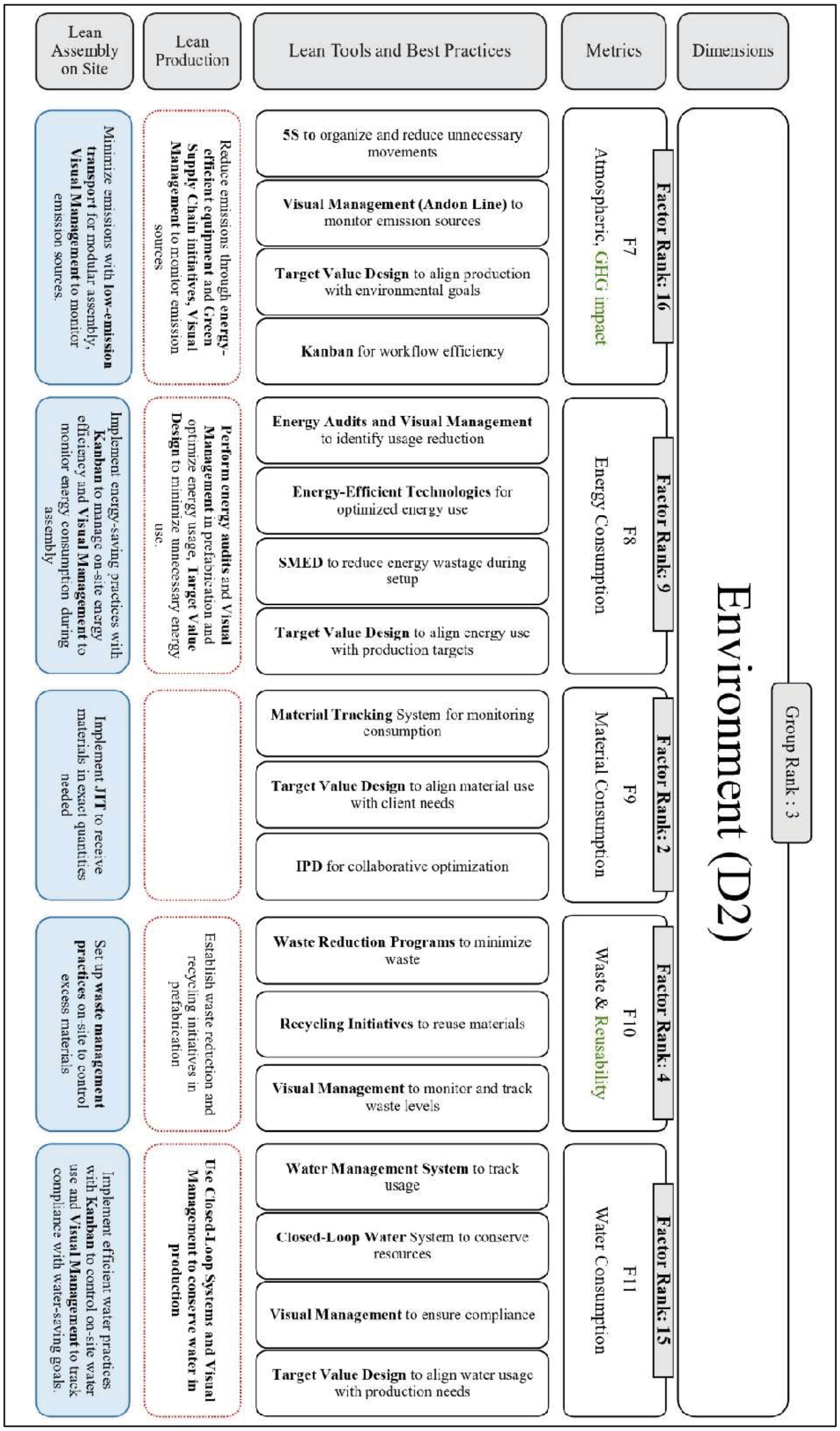

Figure 4.8 Lean–SD framework for Environment (D2) metrics in MOC
(Blue: Lean practices for assembly; Red dashed: Production)

4.6.1 Social dimension

Among the three sustainability dimensions explored, the social dimension emerged as the most significantly impacted by Lean practices in Modular Off-Site Construction (MOC), achieving the highest overall mean score of 4.11 Table 4.9 This dimension includes five key metrics Figure 4.6: employee skills development (F12), influence in the organization (F13), relationships and communication (F14), safety and health (F15), and working conditions (F16). As one expert reflected, *"When we talk about sustainability, the first thing that comes to my mind is people. Social sustainability is not just an add-on, it's foundational. If the people on site are not safe, healthy, or motivated, no system will function well" (Int-13).* Among the D3 factors, Relationships and Communication (F14) achieved the highest individual mean score of 4.23, followed by Safety and Health (F15) and Working Conditions (F16), both with a score of 4.15, making them the most influential metrics within the social dimension. These outcomes reflect the experts' strong emphasis on fostering effective communication, ensuring safety, and maintaining favorable working conditions as essential prerequisites for achieving socially sustainable project delivery.

Qualitative analysis of expert interviews revealed that the human-centered nature of lean particularly its core principle of "Respect for People" is what makes it so impactful across social sustainability metrics Figure 4.9. This observation aligns with prior research findings, which identify respect for people and continuous process improvement as Lean's foundational pillars. These principles not only support process efficiency and defect prevention but also reinforce employee empowerment, communication, and workforce satisfaction essential factors for meeting client expectations in construction projects (Carvajal-Arango et al., 2019; Cherrafi et al., 2016; Fuenzalida et al., 2016; Korb, 2016).

Experts emphasized that practices such as Visual Management and Kaizen empower workers and foster collaboration, aligning with the "Respect for People" principle. As one expert explained, *"Lean isn't just about eliminating waste, it's about valuing your people, making their jobs easier, and giving them the tools to grow and succeed" (Int-7)*. These insights are echoed in the literature, which recognizes visual controls as a means of maintaining production consistency, preventing hazardous incidents, and fostering teamwork. Kaizen, meanwhile, supports productivity, quality improvement, and environmental problem-solving through a continuous learning culture. Regular use of lean practices like employee training and quality control processes further promotes resilient, people-focused work environments (Carvajal-Arango et al., 2019; Leksic et al., 2020; Naeemah & Wong, 2022).

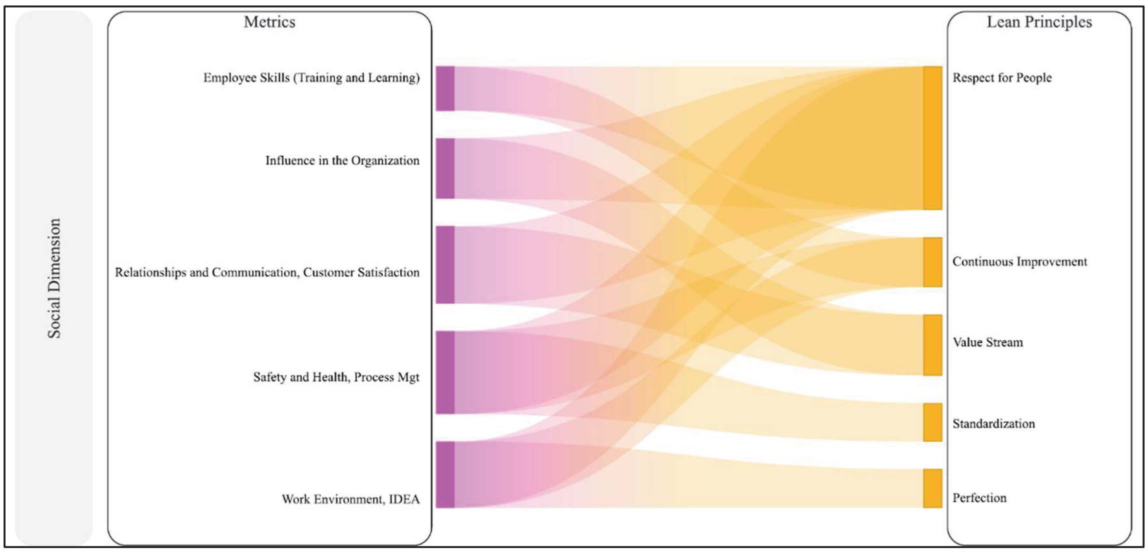

Figure 4.9 Mapping of lean principles to social dimension of SD metrics in MOC projects

Several experts emphasized the growing importance of IDEA (Inclusivity, Diversity, Equity, and Accessibility) in building socially sustainable workplaces. Based on their insights, the framework was further refined to incorporate IDEA considerations within the Work Environment metric (F16). As one expert noted, *"IDEA must be a mindset… when workers feel represented and respected, everything from productivity to morale improves" (Int-11).* This addition aligns with Lean's Respect for People philosophy, emphasizing inclusive design and fair practices as enablers of long-term workforce engagement.

Additionally, most experts highlighted the value of the "Choosing by Advantages" (CBA) method for inclusive decision-making in modular teams. As one expert put it, *"CBA improves* *transparency in team decisions it gives structure to inclusivity" (Int-12)*. Integrating this tool supports the broader IDEA philosophy by ensuring diverse perspectives are systematically considered during collaborative planning and problem-solving processes.

Expert interviews highlighted the essential roles of customer satisfaction and process governance in enabling sustainable outcomes. As one expert stated, *"You have to involve the customer to know what the customer needs it's called value alignment. For you to do value creation, you have to know what value means for them" (Int-5).* This reinforces Lean's value-driven philosophy and is now explicitly embedded under F14 – Relationships and Communication. Similarly, Nóbrega Júnior & Melhado (2008) recommend the evaluation of both direct and indirect client satisfaction regarding productivity, waste reduction, and long-term performance key elements of Lean design management that contribute to better project outcomes and stakeholder alignment.

The importance of process control was also noted as a key enabler of health and safety outcomes. *"Without proper process control, even the best safety protocols fall apart. Lean brings structure that protects both time and people" (Int-1).* As a result, Process Management was formally integrated into F15 – Safety and Health to reflect its direct influence on safe and effective site environments.

In conclusion, the social dimension stands out not only for its top ranking in expert evaluations but also for the depth of qualitative insights linking Lean practices to workforce well-being. Experts consistently described lean as a people-centric approach that improves communication, inclusivity, and job satisfaction. The integration of IDEA, Process Management, and Customer Satisfaction into the framework reflects a clear industry demand for socially responsible practices that go beyond efficiency. These findings reinforce existing literature while highlighting new opportunities to expand the role of Lean in shaping sustainable, human-centered construction environments.

4.6.2 Economic dimension

Among the three core sustainability dimensions, the economic aspect ranked second overall in terms of Lean's perceived influence, with an expert-averaged mean score of 4.06 Table 4.9. As shown in Figure 4.7, this dimension encompasses six key metrics: Budget (F1), Construction and Delivery Time (F2), Productivity (F3), Quality (F4), Uncertainties and Risks (F5), and Value Creation (F6).

Experts consistently highlighted time efficiency and productivity as critical economic drivers in MOC. Among these, Construction and Delivery Time (F2) received the highest mean score of 4.31, followed by Productivity (F3) at 4.23. One expert emphasized, *"In MOC, time is everything. The ability to stick to delivery schedules while maintaining quality is what makes or breaks a project financially" (Int-2).* This aligns closely with Lean principles such as Flow, Just-in-Time (JIT), and Elimination of Waste, all promoting streamlined and delay-free production cycles Figure 4.10.

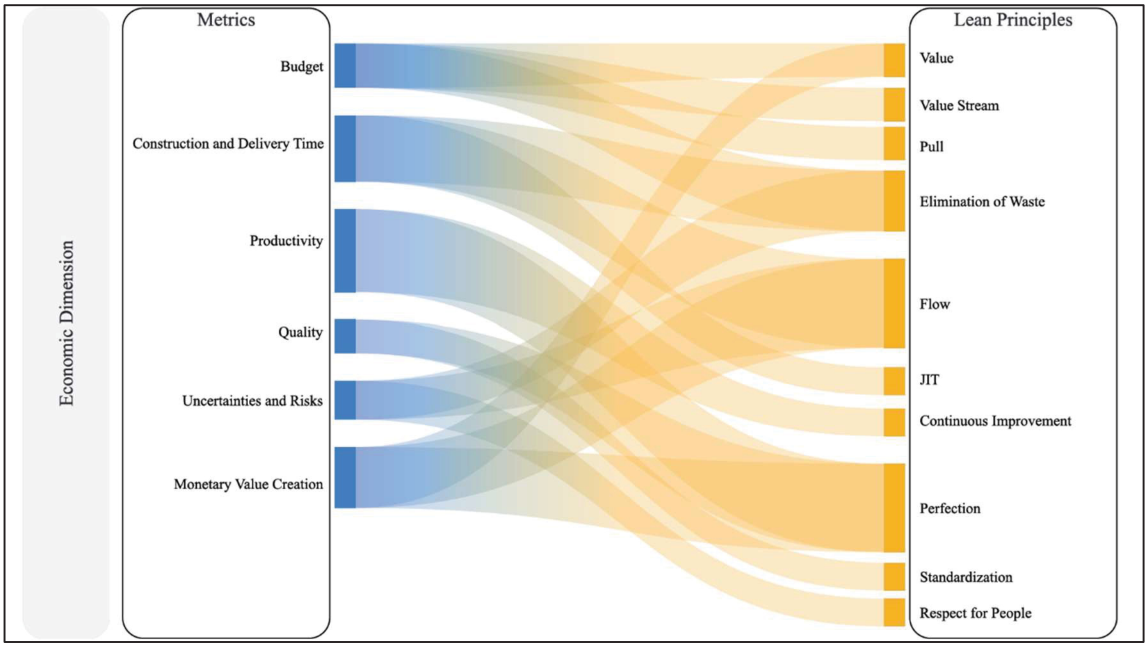

Figure 4.10 Mapping of lean principles to economic dimension of SD metrics in MOC projects

The Last Planner System (LPS), Kanban, and JIT were frequently mentioned as effective tools for improving schedule reliability and reducing idle time, supporting findings from (Aziz & Hafez, 2013) and (McDermott et al., 2023). As noted by one expert, *"We use LPS and Kanban to avoid last-minute surprises. These tools give structure and foresight to our process" (Int-5)*. These lean methods directly contribute to cost control and workflow optimization during production and assembly phases. Their effectiveness is further enhanced when integrated with Artificial Intelligence (AI). Specifically, AI augments systems like LPS by automating data collection, enabling real-time monitoring, and enhancing forecasting and visual management. This integration addresses key implementation gaps in Lean Construction such as informal planning structures and limited predictive capabilities and supports more agile and informed decision-making. The synergy between AI and Lean reinforces planning efficiency and adaptability, ultimately aligning with core Lean objectives of waste reduction, flow continuity, and value generation (Nunes & Melhado, 2025).

In addition, tools such as Value Stream Mapping (VSM), 5S, SMED, and Kaizen were identified as impactful for eliminating non-value-adding activities and improving productivity. Experts emphasized that VSM and TVD help align project costs with client expectations early in the lifecycle, ensuring better financial control and reducing the risk of scope creep. These insights mirror prior literature (Carvajal-Arango et al., 2019; Lombardo et al., 2023). The concept of Value Creation (F6) was refined to Monetary Value Creation based on expert feedback. As one respondent stressed, *"If you want stakeholders to support lean and MOC, they need to see the numbers. If you can't show ROI or monetary gains, it won't fly" (Int-8)*. This reinforces the importance of financial transparency and value alignment when applying Lean practices. Another significant improvement emerged from the inclusion of Construction 4.0 technologies, which experts identified as enablers of cost efficiency and process accuracy. As one participant mentioned, *"Digital tools are becoming essential. From planning to prefabrication, the gains in accuracy and time saved directly cut costs" (Int-4)*. These insights led to the incorporation of smart technologies in the economic dimension of the final framework.

In summary, Lean practices serve as strategic levers for driving economic sustainability in Modular Off-Site Construction by improving schedule reliability, optimizing cost efficiency, and strengthening productivity outcomes especially when supported by digital tools and early-stage planning. The integration of digital tools and refinement of economic metrics further support the strategic alignment of Lean principles with financial performance and stakeholder value.

4.6.3 Environmental dimension

Among the three sustainability dimensions, the environmental aspect received the slightly lowest mean score (4.02) in terms of Lean's perceived influence, as shown in Table 4.9. Despite this, experts emphasized the growing importance of aligning Modular Off-Site Construction (MOC) practices with broader environmental sustainability goals. The Environmental dimension is composed of five key metrics Figure 4.8: Material Consumption

(F9), Energy Consumption (F10), Water Consumption (F11), Waste (F8), and Atmospheric Impact (F7).

Material Consumption (F9) ranked highest in this category (MS = 4.31), followed by Waste (F8), highlighting Lean's role in resource efficiency. As one expert noted, *"Waste in materials isn't just a cost issue, it's an environmental one. When lean minimizes material usage, we're not just saving money, we're reducing our footprint" (Int-2)*. Lean principles such as Elimination of Waste, Standardization, and Flow were commonly mentioned as enablers of improved ecological performance Figure 4.11.

Experts also emphasized tools like Value Stream Mapping (VSM), Kaizen, and 5S for identifying inefficiencies and reducing material waste, aligning with studies by (Francis & Thomas, 2019) and (Vieira & Cachadinha, 2011). Additionally, Visual Management and Target Value Design (TVD) were noted for their role in environmental monitoring. One interviewee shared, *"We've recently started using Andon lines and visual boards not just for quality, but to flag emissions and energy leaks during modular operations" (Int-9).*

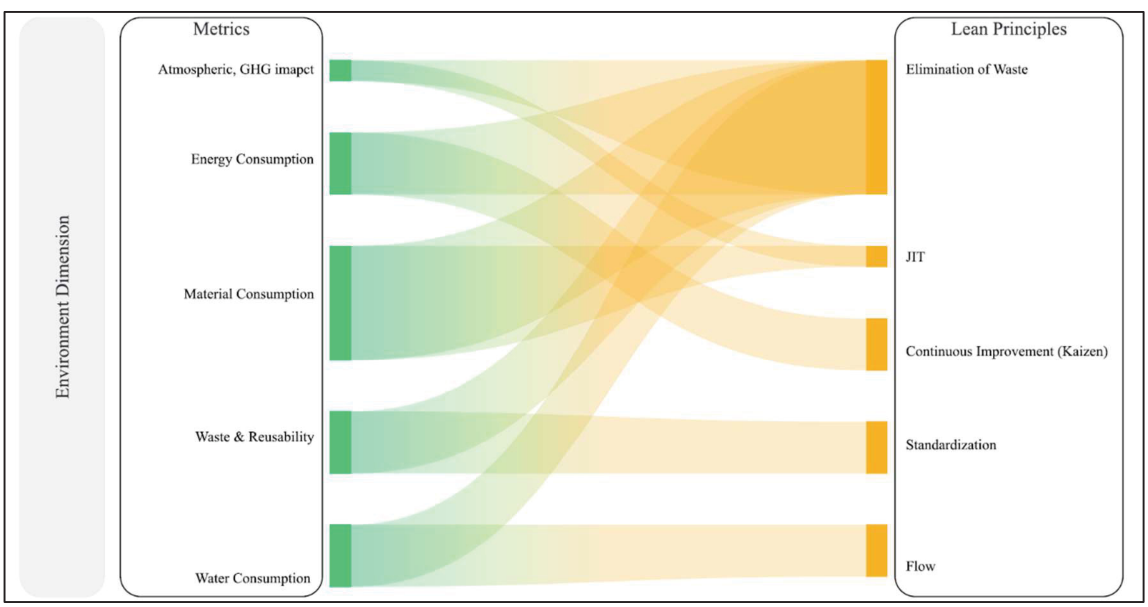

Figure 4.11 Mapping of lean principles to environment dimension of SD metrics in MOC projects

Kanban was identified as a versatile tool supporting both workflow efficiency and environmental impact control by regulating prefabricated deliveries and minimizing over-ordering. In terms of Energy Consumption (F10), experts referenced low-energy machinery, setup time reduction via SMED, and energy audits as effective strategies, consistent with (Demirkesen & Bayhan, 2020).

Water Consumption (F11) and Atmospheric Impact (F7) received lower scores, yet interviewees acknowledged the emerging potential of Lean tools such as Closed-Loop Systems and JIT to address these metrics. However, several experts cautioned that poorly managed JIT implementation may increase transport emissions, echoing warnings in the literature (Khodeir & Othman, 2018). Based on expert feedback, two key modifications were made to the framework. First, the label "Atmospheric" was revised to "GHG and Atmospheric Impact" to improve clarity and alignment with measurable sustainability indicators. Second, the previously separate metrics of Waste and Reusability were merged into "Waste & Reusability", reflecting industry trends toward circular practices and resource recovery.

In conclusion, although Lean's influence on environmental sustainability in MOC received slightly lower emphasis compared to economic and social dimensions, it nonetheless demonstrates strong and growing relevance. Notably, Lean practices contribute meaningfully to waste reduction, improved material flow, and enhanced energy efficiency. The integration of digital monitoring tools and updated environmental metrics into the framework reflects industry efforts to make environmental impacts more measurable and actionable. These developments reinforce the importance of embedding Lean principles as a key enabler of holistic sustainability in Modular Off-site Construction.

4.7 Conclusion

This study explored the integration of Lean Management (LM) principles with Sustainable Development (SD) goals in the context of Modular and Off-Site Construction (MOC), with a focus on the manufacturing and on-site assembly stages, critical phases for operational efficiency and sustainability that remain underrepresented in research. Using a mixed-methods approach combining a systematic literature review, expert interviews, and quantitative analysis, the study developed a conceptual framework linking Lean tools to sustainability metrics across the economic, environmental, and social dimensions. The results demonstrate that Lean practices have a significant and multi-dimensional impact on sustainability in MOC. Notably, the social dimension, which has often been overlooked in earlier studies, was identified as the most significantly influenced by Lean tools. Practices such as Visual Management, Kaizen, and cross-training were found to support worker safety, communication, inclusivity, and organizational cohesion, underscoring the centrality of "Respect for People" as a pillar of Lean thinking within the collaborative and fragmented environments typical of MOC projects. Economically, Lean tools like Just-in-Time, Value Stream Mapping, and the Last Planner System were validated as effective enablers of cost efficiency, schedule reliability, and productivity. Environmentally, Lean contributed mainly to reducing material waste and improving resource efficiency, though some practices showed potential environmental trade-offs when poorly managed.

Based on expert feedback, several refinements were introduced to enhance both the theoretical robustness and practical applicability of the framework. Notable adjustments include: (i) the addition of IDEA (Inclusivity, Diversity, Equity, and Accessibility) principles to the social dimension, (ii) the integration of Construction 4.0 technologies and monetary value alignment in the economic metrics, and (iii) the refinement of environmental indicators such as renaming "Atmospheric" to "GHG and Atmospheric Impact" and merging "Waste" with "Reusability." These modifications reflect real-world priorities identified by industry professionals, thereby transforming the initial framework into a more actionable and context-sensitive tool for guiding sustainable Lean implementation in Modular and Off-Site Construction.

However, certain limitations should be acknowledged. The relatively small expert panel size (n=13), despite geographical diversity, limits the generalizability of findings. Additionally, while the framework's logical structure was well-received, experts noted the need for more detailed, context-specific examples to aid real-world application. Variability in digital maturity across different firms and regions was also identified as a constraint, as was the challenge of adapting to evolving sustainability benchmarks that differ across policy environments and regions.

Building on these insights, future research should focus on developing case-based operational playbooks tailored to different types of MOC projects, piloting simplified or modular versions of Lean tools in settings with limited digital infrastructure and testing integrated Lean-digital strategies such as Lean+BIM applications in real-world projects. Furthermore, there is a need for the creation of long-term metrics to monitor social sustainability outcomes, including labor conditions, safety, and stakeholder inclusion. Institutional support mechanisms and training structures could also enhance Lean and sustainability capacity across project lifecycles. Overall, this study provides an important foundation for more people-centered, digitally enhanced, and context-sensitive Lean strategies in MOC, bridging gaps between theory and practice and contributing to the broader goal of sustainable transformation in the construction industry.

4.7.1 Theoretical and practical contributions and validation

The contributions of this research lie in developing a matrix-based visualization of Lean impacts across all sustainability dimensions, proposing a practitioner-validated framework that addresses the integrated role of Lean in supporting sustainability, and specifically highlighting the often-underrepresented social impacts. By integrating end-user insights and recognizing cross-functional stakeholder needs, this study offers both theoretical and practical contributions, adaptable model that aligns Lean thinking with digital technologies and emerging circular construction models, advancing the practical relevance of Lean in sustainable MOC practices. The contributions are supported by expert validation and visual data analysis.

Theoretical Contributions

The study proposes a framework that systematically links Lean practices to sustainability dimensions (economic, environmental, social), with a specific focus on production and assembly phases (area often underexplored in the literature). It provides a matrix-based visualization of the dual (positive and negative) impacts of Lean tools on SD, enhancing theoretical understanding of trade-offs in Lean applications. The research contributes to the academic knowledge base by highlighting the significant impact of Lean practices on the social dimension, such as worker well-being, inclusion, and communication dimensions frequently overlooked in previous studies. The framework also sets a foundation for future research, enabling the development of metrics and strategies for evaluating Lean implementation across construction contexts.

Practical Contributions

The framework has the potential to serve as organizations, helping managers align Lean strategies with sustainability targets. It facilitates gap analysis by allowing practitioners to assess current practices in productivity, waste reduction, and social well-being on construction projects. It promotes improved communication and collaboration among stakeholders through a shared understanding of how Lean supports sustainability. It can be used as a training and teaching aid for students and professionals, guiding the application of Lean thinking in modular and digital construction environments.

Validation through Expert Feedback

Validation was conducted via semi-structured interviews with 13 industry experts. The results confirm the framework's practical relevance and usability: As shown in Figure 4.12, 84% of respondents recommended the adoption of the framework in MOC projects.

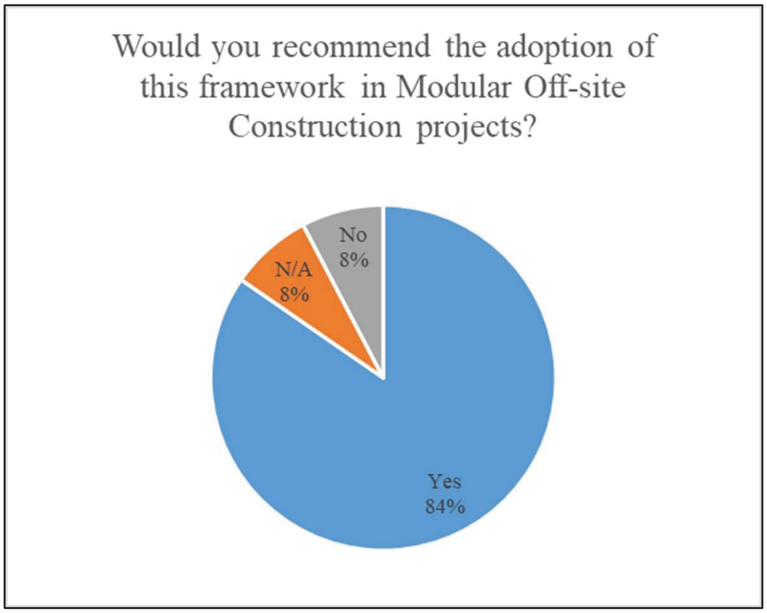

Figure 4.12 Experts recommend adopting the framework in Modular Off-site Construction projects

In Figure 4.13, most participants rated the framework's effectiveness between 4 and 5 (where 1 = not effective and 5 = very effective), reflecting strong agreement on its real-world applicability.

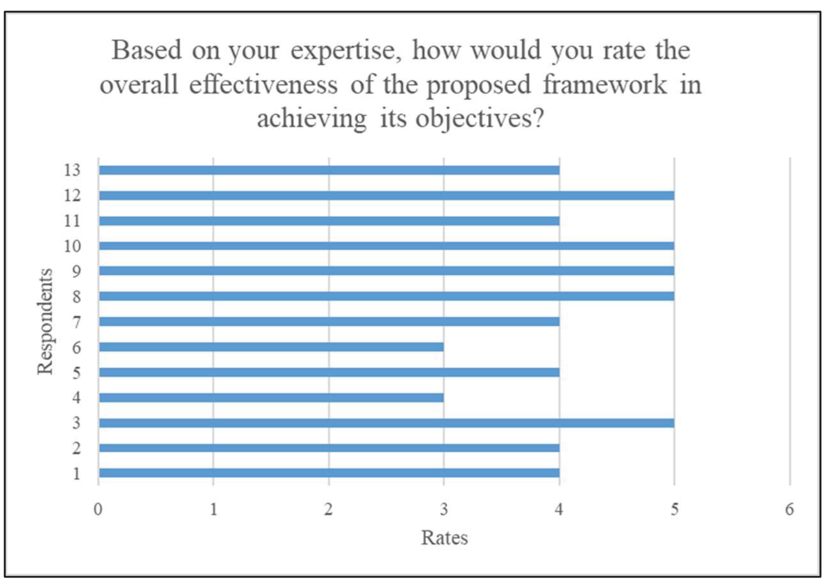

Figure 4.13 Experts' ratings of the framework's effectiveness

Interviewees also confirmed the framework's ability to capture contextual trade-offs, particularly in environmental impacts (e.g., logistics effects of Just-in-Time) and in social areas where tools like Visual Management and Kaizen directly support inclusivity and worker satisfaction. This combination of theoretical innovation and empirical validation enhances the robustness of the framework and confirms its relevance across both academic and professional settings.

CONCLUSION

This thesis sets out to explore the integration of Lean Management (LM) principles with Sustainable Development (SD) goals in the context of Modular Off-Site Construction (MOC), focusing on the manufacturing and on-site assembly stages. Through a mixed-methods approach, the research developed and validated a conceptual framework that links Lean tools to key sustainability metrics across the economic, environmental, and social dimensions.

The first paper, presented in Chapter 3, provides a systematic literature review and bibliometric analysis of 71 scholarly studies published between 2004 and 2024. This paper highlights major gaps in existing research, including the underrepresentation of the social dimension of sustainability and the limited evaluation of both the positive and negative impacts of Lean practices across all SD dimensions. It also reveals that on-site assembly remains significantly less explored than production in the current body of literature, despite being a critical phase in MOC delivery.

Building on these findings, the second paper (Chapter 4) introduces a framework that was co-developed and refined through expert interviews and quantitative scoring. The framework identifies which Lean tools most significantly impact sustainability, and in which stages they are most applicable. Notably, this study found that while Lean has traditionally been associated with economic efficiency, experts ranked social sustainability as the most positively impacted dimension by Lean practices especially tools like Visual Management, Kaizen, and Respect for People. Tools supporting productivity and time management (e.g., LPS, Kanban, VSM) were also recognized as essential to economic gains, while waste reduction and material flow optimization underlined Lean's contribution to environmental outcomes.

This master's thesis advances both academic understanding and industry practice by developing an evidence-based, expert-informed framework that maps Lean practices to SD goals in MOC. The framework provides practitioners with clear guidance on which tools to prioritize and in which stages of MOC they are most effective. It also offers researchers a foundation for further empirical exploration, especially concerning under-addressed areas like worker well-being, inclusivity, and digital-lean integration. By emphasizing the value of human-centered lean strategies and the need for balanced attention to all three SD dimensions, this thesis contributes to a more holistic and actionable pathway for achieving sustainable transformation in modular construction.

Regarding the research limitations, this study has a few limitations to consider:

Methodological Constraints: Using NVivo software for data coding may introduce subjectivity or overlook nuances that alternative analytical methods could capture

Sample Size and Selection Bias: The sample size (n=13), though geographically diverse, limits the generalizability of findings.

Dynamic Policy Landscape: The evolving and region-specific nature of sustainability benchmarks limited the ability to apply a universal framework across all MOC projects.

Neglected Tech Integration: Limited attention was given to emerging technologies like AI, BIM and IoT in Lean-MOC applications, suggesting a future research need.

Practical Gaps: Experts highlighted the need for real-world examples to enhance the framework's usability.

RECOMMENDATIONS

Based on the findings and expert insights gained through this research, the following recommendations are proposed to support the implementation and future refinement of Lean practices in Modular Off-Site Construction (MOC) aligned with sustainability goals:

Expand Research on Underexplored Dimensions

Promote deeper investigation into Lean's impact on social sustainability, particularly in areas like inclusivity, worker empowerment, and health and safety. Investigate the long-term and dynamic effects of Lean practices across the full construction lifecycle, especially during on-site assembly.

Enhance Lean Tool Adaptation for MOC

Develop stage-specific guidelines to optimize Lean tools for on-site assembly, where adaptability and stakeholder collaboration are key. Establish best practices that reflect the dual nature of Lean tools emphasizing not only their productivity benefits but also their potential social and environmental trade-offs.

Support Digital-Integrated Lean Practices

Encourage the integration of BIM, IoT, and digital monitoring with Lean methods to improve visibility, traceability, and impact measurement. Develop digital dashboards that visualize the triple bottom line impacts of Lean implementation in MOC projects.

Strengthen Training and Capacity Building

Invest in training programs focused on Lean for MOC, emphasizing hands-on learning, social sustainability, and cross-functional collaboration. Build awareness around less visible tools like Choosing by Advantages (CBA), Target Value Design (TVD), and closed-loop systems to broaden adoption.

Foster Industry–Academia Collaboration

Initiate joint research pilots and real-world implementation studies to test the framework in diverse modular construction contexts. Co-develop toolkits, templates, and assessment models with industry partners to bridge the gap between theory and practice.

Incentivize Sustainable Lean Transformation

Encourage policy support and procurement incentives for projects demonstrating measurable sustainability gains through Lean-MOC integration. Advocate for life-cycle-oriented sustainability metrics that help stakeholders justify investment in Lean-based process innovation.

Encourage Transparency Through Case Studies

Create a repository of successful Lean-MOC project cases that illustrate tangible gains in cost, time, emissions, or workforce well-being. Develop storytelling formats videos, visuals, infographics that highlight the human, environmental, and financial value created by Lean practices.

APPENDIX A

LEAN-MOC CONCEPTUAL FRAMEWORK QUESTIONNAIRE – CHAPTER 4

Dear Interviewee, thank you for participating in this interview. The purpose of this Interview is to validate a framework that that integrates Lean management principles with the key dimensions of Sustainable Development (SD) within the context of Modular Off-site Construction (MOC). This framework addresses economic, environmental, and social impacts, applying selected lean tools and best practices across stages of production or manufacturing and on-site assembly.

The lean tools and best practices included in this framework have been identified through an extensive review of relevant literature. While there are numerous tools available for lean management, this framework highlights the top tools and practices found to be most impactful in our research. Your insights and expertise are invaluable for assessing the framework's relevance, feasibility, and effectiveness in real-world applications.

Figure 4I.1, Figure AI.2 and Figure AI.3 presents our proposed framework. You may refer to the end of this questionnaire for a brief definition of each lean principle applied, as well as lean tools and best practices.

Please rest assured that your responses will remain confidential and your identity will not be disclosed at any point. Your participation is entirely voluntary, and you may withdraw at any stage. Your knowledge and expertise are greatly appreciated.

Please be informed that this interview has been developed within the context of an academic research project performed by Helia Rasouli under the supervisions of Prof. Melhado and Prof. Ivanka Iordanova from the École de Technologie Supérieure (ÉTS). The answers that you will provide will be anonymized and may be presented in publications, conferences, research reports or in a thesis.

For any further information, please contact: helia.rasouli.1@ens.etsmtl.ca

Semi-Structured Survey and Questionnaire:

Section 1: Demographic Information

- Name:
- Position/Title:
- Organization:
- Years of Experience in Construction Industry:
- Years of Experience with Lean Management:
- Years of Experience with Modular Off-site Construction (MOC):

SD Dimension	Metrics and Impacts	Lean Principles Applied	Lean Tools and Best Practices		
			In General	Lean Production	Lean Assembly on Site
Economic (D1)	Budget (F1)	Value, Value Stream, Pull, Elimination of Waste	**5S (Sort, Set in order, Shine, Standardize, Sustain)** for workspace efficiency, **Value Stream Mapping (VSM)** for process optimization**, Target Value Design t**o align costs with client value**, SMED** to reduce setup times and costs.	Apply 5S and VSM to eliminate non-value-adding activities and optimize resource use	Control on-site costs by identifying value-adding steps and avoiding unnecessary expenditures
	Construction and Delivery Time (F2)	Flow, Just-In-Time (JIT), Elimination of Waste	**Last Planner System** to reduce delays, **Kanban** for workflow management,**Lean Project Delivery** System for integrated project phases, **JIT** for inventory control.	Use Kanban for seamless material flow and Last Planner to avoid bottlenecks	Use JIT to deliver materials just-in-time for on-site assembly and prevent delays
	Productivity (F3)	Continuous Improvement (Kaizen), Perfection	**Visual Management (Andon Line)** to highlight and address issues quickly**.Kaizen strategy** to achieve continuous and incremental improvements	Perform Gemba Walks in production to find and address inefficiencies	Apply Kaizen for incremental on-site assembly improvements
	Quality (F4)	Standardization, Perfection	**Poka Yoke (Error Proofing)** to prevent defects, **Six Sigma** for process optimization.	Six Sigma to ensure uniform quality in prefabrication.	Ensure quality control measures are followed during assembly
	Uncertainties and Risks (F5)	Respect for People, Flow, Elimination of Waste	**Visual Management** to track risk-related tasks**.Poka Yoke (Error Proofing)** to prevent human errors, **Kanban** for managing workflow interruptions.	Poka Yoke, and Visual Management to preempt production risks and prevent errors.	Conduct Daily Huddles, use Kanban to manage on-site workflow interruptions, and use Visual Management to track tasks and address issues quickly.
	Value Creation (F6)	Value, Flow, Perfection	**Value Stream Mapping (VSM)** to align production steps with client value, **Poka-Yoke** for error-proofing**, Pull Strategy** to match production with demand.	Focus on value-added steps using VSM in production to maximize customer value	Ensure final assembly aligns with value creation goals

Figure AA.1 Framework linking Lean tools and best practices with economic SD dimensions and modular construction phases

SD Dimension	Metrics and Impacts	Lean Principles Applied	Lean Tools and Best Practices		
			In General	Lean Production	Lean Assembly on Site
Environmental (D2)	Atmospheric (F7)	Elimination of Waste, Just-In-Time (JIT)	**5S to organize and reduce unnecessary movements.Visual Management (Andon Line) to** monitor emission sources, **Target Value Design** to align production with environmental goals.**Kanban** for workflow efficiency,	Reduce emissions through energy-efficient equipment and Green Supply Chain initiatives,Visual Management to monitor emission sources.	Minimize emissions with low-emission transport for modular assembly, Visual Management to monitor emission sources.
	Energy Consumption (F8)	Elimination of Waste, Continuous Improvement (Kaizen)	**Energy Audits and Visual Management** to identify usage reduction, **Energy-Efficient Technologies** for optimized energy use**, SMED** to reduce energy wastage during setup,**Target Value Design** to align energy use with production targets..	Perform energy audits and Visual Management in prefabrication and optimize energy usage,Target Value Design to minimize unnecessary energy use.	Implement energy-saving practices with Kanban to manage on-site energy efficiency and Visual Management to monitor energy consumption during assembly
	Material Consumption (F9)	Elimination of Waste, Just-In-Time (JIT)	**Target Value Design to** align material use with client need**s, IPD** for collaborative optimization.		Implement JIT to receive materials in exact quantities needed
	Waste (F10)	Elimination of Waste, Standardization	**Waste Reduction Programs** to minimize waste, **Recycling Initiatives** to reuse materials, **Visual Management** to monitor and track waste levels.	Establish waste reduction and recycling initiatives in prefabrication	Set up waste management practices on-site to control excess materials
	Water Consumption (F11)	Elimination of Waste, Flow	**Water Management System** to track usage, **Closed-Loop Water System** to conserve resources**, Visual Management** to ensure compliance.**Target Value Design** to align water usage with production needs.	Use Closed-Loop Systems and Visual Management to conserve water in production	Implement efficient water practices with Kanban to control on-site water use and Visual Management to track compliance with water-saving goals.

Figure AA.2 Framework linking Lean tools and best practices with environment SD dimensions and modular construction phases

SD Dimension	Metrics and Impacts	Lean Principles Applied	Lean Tools and Best Practices		
			In General	Lean Production	Lean Assembly on Site
Social (D3)	Employee Skills (Training and Learning) (F12)	Respect for People, Continuous Improvement (Kaizen)	**Training Programs** for skill improvement, **Cross-Training** for flexibility,**Visual Management to** monitor progress.	Offer regular training sessions and Kaizen activities to improve production efficiency and encourage ongoing learning.	Provide on-site training for specialized assembly skills
	Influence in the Organization (F13)	Respect for People, Value Stream	**Employee Empowerment Programs** to encourage participation, **Kaizen for** continuous involvement in process improvement**. IPD to** foster collaboration.	Empower employees to contribute to decision-making for improved production and involve them in continuous improvement through Kaizen.	Foster team collaboration on-site to support employee influence and use IPD to ensure integrated collaboration.
	Relationships and Communication (F14)	Respect for People, Value Stream	**Team-building exercises**, **Collaborative Planning Tools** for open communication.**Visual Management (Andon Line)** to provide real-time feedback, **Kanban** to streamline communication across tasks.	Promote teamwork and effective communication in production, and use Visual Management to provide real-time updates.	Enhance coordination on-site for smooth workflows, supported by Kanban and Visual Management for task tracking.
	Safety and Health (F15)	Respect for People, Standardization, Continuous Improvement (Kaizen)	**Safety Training Programs**, **Safety Inspections** to ensure safe work practices**, Visual Management (Andon Line) to** highlight hazards**, 5S** to maintain an organized and safe workspace.	Maintain standardized safety protocols during production with Visual Management to monitor risks and 5S to keep areas organized.	Regular on-site safety checks and Visual Management to track and address hazards in real-time.
	Working Conditions (F16)	Respect for People, Perfection, Continuous Improvement (Kaizen)	**Ergonomics Assessment** for optimal work conditions, **Work Environment Improvement Programs** for a better workspace, Visual Management for monitoring conditions, Kaizen to continuously improve workplace ergonomics.	Enhance production workspace ergonomics for improved conditions, using Kaizen for ongoing improvements.	Ensure comfortable and safe on-site work environment, with Visual Management to monitor conditions regularly.

Figure AA.3 Framework linking Lean tools and best practices with social SD dimensions and modular construction phase

Section 2: Framework Validation

Instructions: Please rate the following aspects of the conceptual framework on a scale of 1 to 5, where 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, and 5 = Strongly Agree. Provide additional comments where applicable.

1. Clarity and Structure

The framework is presented in a clear and organized structure.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

2. Comprehensiveness

The framework comprehensively covers the key dimensions of Sustainable Development (Economic, Environmental, and Social).

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comment

3. Relevance

The Lean principles and tools included in the framework are relevant to Modular Off-site Construction.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

4. Practical Application

The framework provides practical and actionable insights for implementing Lean management in MOC.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

5. Integration of Sustainable Development Dimensions

The framework has the potential to help integrating the economic, environmental, and social dimensions of Sustainable Development into Modular and off-site construction.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

Section 3: Assessment of Impacts

Economic Dimension

1. Budget

The framework contributes to addressing budget management through Lean principles.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

2. Construction and Delivery Time

The framework has the potential to help reducing construction and delivery time.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

3. Productivity

The framework potential to enhance the productivity in MOC.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

4. Quality

The framework potential to support high-quality standards in production and assembly.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

5. Uncertainties and Risks

The framework potential to effectively mitigate uncertainties and risks.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

6. Value Creation

The framework potential to enhance value creation for stakeholders.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

Environmental Dimension

1. Atmospheric Impact

The framework can help reducing atmospheric emissions.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

2. Energy Consumption

The framework promotes energy-efficient practices.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

3. Material Consumption

The framework potential to optimize material usage and reduce waste.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

4. Waste

The framework potential to effectively minimize waste generation.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

5. Water Consumption

The framework promotes efficient water usage.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral

- 4. Agree
- 5. Strongly Agree

Comments:

Social Dimension

1. Employee Skills (Training and Learning)

The framework supports employee training and skill development.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

2. Influence in the Organization

The framework potential to empower employees and enhance their influence in the organization.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

3. Relationships and Communication

The framework potential to improve relationships and communication within the organization.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

4. Safety and Health

The framework potential to ensure safety and health standards are maintained.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

5. Working Conditions

The framework promotes better working conditions.

- 1. Strongly Disagree
- 2. Disagree
- 3. Neutral
- 4. Agree
- 5. Strongly Agree

Comments:

Section 4: Open-Ended Questions

Strengths and Weaknesses

- What do you consider to be the main strengths of the proposed framework?
- What do you consider to be the main weaknesses or areas for improvement in the proposed framework?

Practical Implementation

- In your view, how feasible is it to implement this framework in real-world MOC projects?
- What challenges do you foresee in the practical application of this framework?

Additional Lean Tools and Practices

- Are there any additional Lean tools or best practices that you believe should be included in the framework?
- If yes, please specify and explain their relevance.

Sustainable Development Integration

- Are there any specific aspects of Sustainable Development that you feel are not adequately addressed?

General Feedback

- Do you have any other comments or suggestions for improving the framework?

Section 5: Expert Validation

Overall Assessment

Based on your expertise, how would you rate the overall effectiveness of the proposed framework in achieving its objectives?

- 1.(Very Ineffective)
- 2.(Ineffective)
- 3.(Neutral)
- 4.(Effective)
- 5.(Very Effective)

Comments:

Recommendation
Would you recommend the adoption of this framework in Modular Off-site Construction projects?

- Yes
- No

LEAN PRINCIPLES

1. Value: The importance of delivering what the customer wants and is willing to pay for.
2. Value Stream: The entire process flow from raw materials to the delivery of the final product to the customer.
3. Pull: Producing only what is needed when it is needed, based on customer demand.
4. Elimination of Waste: Removing any activity or process that does not add value to the product or service.
5. Flow: Ensuring that work processes move smoothly and continuously without interruptions or delays.
6. Just-In-Time (JIT): Producing and delivering products in precise quantities and at the exact time they are needed.
7. Continuous Improvement (Kaizen): Ongoing efforts to improve products, services, or processes incrementally.
8. Perfection: Striving for a state where every process adds value and there is no waste.
9. Standardization: Establishing consistent methods and procedures to ensure quality and efficiency.
10. Respect for People: Valuing and empowering employees, encouraging their involvement in problem-solving and improvement efforts.

LEAN TOOLS AND BEST PRACTICES

1. 5S (Sort, Set in Order, Shine, Standardize, Sustain): A workplace organization method to improve efficiency and safety.
2. Value Stream Mapping (VSM): A tool to visualize and analyze the flow of materials and information required to bring a product to the customer.
3. Target Value Design: A method to align project costs with the value desired by the client.
4. SMED (Single-Minute Exchange of Dies): A technique to reduce setup times and costs in manufacturing processes.
5. Last Planner System: A collaborative planning process to reduce delays in project delivery.
6. Kanban: A visual workflow management tool to optimize the flow of work.

7. Lean Project Delivery System: An integrated approach to manage project phases efficiently.
8. Just-In-Time (JIT): A strategy to control inventory by producing only what is needed, when it is needed.
9. Visual Management (Andon Line): A system to highlight and address issues quickly through visual signals.
10. Kaizen: A strategy for continuous and incremental improvements.
11. Poka Yoke (Error Proofing): Techniques to prevent defects and errors in processes.
12. Six Sigma: A methodology for process optimization and reducing variability.
13. Visual Management: Tools to track and monitor tasks and processes visually.
14. Pull Strategy: A method to match production with actual demand.
15. Energy Audits: Assessments to identify opportunities for reducing energy usage.
16. Energy-Efficient Technologies: Technologies designed to optimize energy use.
17. Material Tracking System: A system to monitor material consumption.
18. Integrated Project Delivery (IPD): A collaborative approach to optimize project outcomes.
19. Waste Reduction Programs: Initiatives to minimize waste generation.
20. Recycling Initiatives: Programs to reuse materials and reduce waste.
21. Water Management System: A system to track and manage water usage.
22. Closed-Loop Water System: A system to conserve water by recycling it within the process.
23. Training Programs: Programs to improve employee skills.
24. Cross-Training: Training employees in multiple skills for flexibility.
25. Employee Empowerment Programs: Initiatives to encourage employee participation and involvement.
26. Team-Building Exercises: Activities to improve team cohesion and communication.
27. Collaborative Planning Tools: Tools to facilitate open communication and planning.
28. Safety Training Programs: Programs to ensure safe work practices.
29. Safety Inspections: Regular checks to ensure workplace safety.
30. Ergonomics Assessment: Evaluations to ensure optimal work conditions.
31. Work Environment Improvement Programs: Initiatives to enhance the workplace environment

LIST OF BIBLIOGRAPHICAL REFERENCES

Abdulmalek, F. A., & Rajgopal, J. (2007). Analyzing the benefits of lean manufacturing and value stream mapping via simulation: A process sector case study. *International Journal of Production Economics*, *107*(1), 223–236. https://doi.org/10.1016/j.ijpe.2006.09.009

Andersson, N., & Lessing, J. (2017). The Interface between Industrialized and Project Based Construction. *Procedia Engineering*, *196*, 220–227. https://doi.org/10.1016/j.proeng.2017.07.193

Arashpour, M., Bai, Y., Aranda-mena, G., Bab-Hadiashar, A., Hosseini, R., & Kalutara, P. (2017). Optimizing decisions in advanced manufacturing of prefabricated products: Theorizing supply chain configurations in off-site construction. *Automation in Construction*, *84*, 146–153. https://doi.org/10.1016/j.autcon.2017.08.032

Assaad, R. H., El-adaway, I. H., Hastak, M., & LaScola Needy, K. (2022). The Impact of Offsite Construction on the Workforce: Required Skillset and Prioritization of Training Needs. *Journal of Construction Engineering and Management*, *148*(7), 04022056. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002314

Attouri, E., Lafhaj, Z., Ducoulombier, L., & Linéatte, B. (2022). Development of decision-making tool for construction method selection: Choosing and optimizing offsite construction. *Modular and Offsite Construction (MOC) Summit Proceedings*, 25–33. https://doi.org/10.29173/mocs261

Aziz, R. F., & Hafez, S. M. (2013). Applying lean thinking in construction and performance improvement. *Alexandria Engineering Journal*, *52*(4), 679–695. https://doi.org/10.1016/j.aej.2013.04.008

Ballard, G., & Howell, G. (2003). Lean project management. *Building Research & Information*, *31*(2), 119–133. https://doi.org/10.1080/09613210301997

Batwara, A., Sharma, V., Makkar, M., & Giallanza, A. (2023). Towards smart sustainable development through value stream mapping – a systematic literature review. *Heliyon*, *9*(5), e15852. https://doi.org/10.1016/j.heliyon.2023.e15852

Belekoukias, I., Garza-Reyes, J. A., & Kumar, V. (2014). The impact of lean methods and tools on the operational performance of manufacturing organisations. *International Journal of Production Research*, *52*(18), 5346–5366. https://doi.org/10.1080/00207543.2014.903348

Bertelsen, K., & Koskela, L. (2004). *CONSTRUCTION BEYOND LEAN: A NEW UNDERSTANDING OF CONSTRUCTION MANAGEMENT*.

Bhatia, A. P. S., Moselhi, O., & Han, S. (2023, July 7). *Optimized Production Scheduling for Modular Construction Manufacturing*. 40th International Symposium on Automation and Robotics in Construction, Chennai, India. https://doi.org/10.22260/ISARC2023/0038

Blismas, N., & Wakefield, R. (2009). Drivers, constraints and the future of offsite manufacture in Australia. *Construction Innovation*, *9*(1), 72–83. https://doi.org/10.1108/14714170910931552

Boyd, N., Khalfan, M. M. A., & Maqsood, T. (2013). Off-Site Construction of Apartment Buildings. *Journal of Architectural Engineering*, *19*(1), 51–57. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000091

Bridi, M. E., Ceolin, E. D., Granja, A. D., & Formoso, C. T. (2019). *Modularity in the Construction Industry: A Systematic Mapping Study*. 737–748. https://doi.org/10.24928/2019/0178

Caiado, R., Nascimento, D., Quelhas, O., Tortorella, G., & Rangel, L. (2018). TOWARDS SUSTAINABILITY THROUGH GREEN, LEAN AND SIX SIGMA INTEGRATION AT SERVICE INDUSTRY: REVIEW AND FRAMEWORK. *Technological and Economic Development of Economy*, *24*(4), 1659–1678. https://doi.org/10.3846/tede.2018.3119

Caldarelli, V., Filipponi, M., Saetta, S., & Rossi, F. (2022). Lean and green production for the modular construction. *Procedia Computer Science*, *200*, 1298–1307. https://doi.org/10.1016/j.procs.2022.01.331

Carvajal-Arango, D., Bahamón-Jaramillo, S., Aristizábal-Monsalve, P., Vásquez-Hernández, A., & Botero, L. F. B. (2019). Relationships between lean and sustainable construction: Positive impacts of lean practices over sustainability during construction phase. *Journal of Cleaner Production*, *234*, 1322–1337. https://doi.org/10.1016/j.jclepro.2019.05.216

Cherrafi, A., Elfezazi, S., Chiarini, A., Mokhlis, A., & Benhida, K. (2016). The integration of lean manufacturing, Six Sigma and sustainability: A literature review and future research directions for developing a specific model. *Journal of Cleaner Production*, *139*, 828–846. https://doi.org/10.1016/j.jclepro.2016.08.101

Da C., T., Milberg, C., & Walsh, K. D. (2012). Exploring lean construction practice, research, and education. *Engineering, Construction and Architectural Management*, *19*(5), 512–525. https://doi.org/10.1108/09699981211259595

Das, B., Sanchez-Rivas, J. M., Garcia-Diaz, A., & MacDonald, C. A. (2010). A computer simulation approach to evaluating assembly line balancing with variable operation times. *Journal of Manufacturing Technology Management*, *21*(7), 872–887. https://doi.org/10.1108/17410381011077964

De Paula, N., & Melhado, S. (2018). Sustainability in Management Processes: Case Studies in Architectural Design Firms. *Journal of Architectural Engineering*, *24*(4), 05018005. https://doi.org/10.1061/%28ASCE%29AE.1943-5568.0000326

De Sordi, J. O. (2021). *Design Science Research Methodology: Theory Development from Artifacts*. Springer International Publishing. https://doi.org/10.1007/978-3-030-82156-2

Deming, W. E. (1994). *Out of the crisis: Quality, productivity and competitive position* (19th. printing). Cambridge Univ. Pr.

Demirkesen, S., & Bayhan, H. G. (2020). A Lean Implementation Success Model for the Construction Industry. *Engineering Management Journal*, *32*(3), 219–239. https://doi.org/10.1080/10429247.2020.1764834

Demirkesen, S., & Bayhan, H. G. (2022). Critical Success Factors of Lean Implementation in the Construction Industry. *IEEE Transactions on Engineering Management*, *69*(6), 2555–2571. https://doi.org/10.1109/TEM.2019.2945018

Demirkesen, S., Wachter, N., Oprach, S., & Haghsheno, S. (2019). *Identifying Barriers in Lean Implementation in the Construction Industry*. 157–168. https://doi.org/10.24928/2019/0151

Demirkesen, S., Wachter, N., Oprach, S., Haghsheno, S., Demirkesen, S., Wachter, N., Oprach, S., & Haghsheno, S. (2019). Identifying Barriers in Lean Implementation in the Construction Industry. *27th Annual Conference of the International Group for Lean Construction (IGLC)*, 157–168. https://doi.org/10.24928/2019/0151

Denzin, N. K., & Lincoln, Y. S. (Eds.). (2018). *The SAGE handbook of qualitative research* (Fifth edition). SAGE.

DiCicco-Bloom, B., & Crabtree, B. F. (2006). The qualitative research interview. *Medical Education*, *40*(4), 314–321. https://doi.org/10.1111/j.1365-2929.2006.02418.x

Dieste, M., Panizzolo, R., & Garza-Reyes, J. A. (2020). Evaluating the impact of lean practices on environmental performance: Evidences from five manufacturing companies. *Production Planning & Control*, *31*(9), 739–756. https://doi.org/10.1080/09537287.2019.1681535

Dransfield, E., Morrot, G., Martin, J.-F., & Ngapo, T. M. (2004). The application of a text clustering statistical analysis to aid the interpretation of focus group interviews. *Food Quality and Preference*, *15*(5), 477–488. https://doi.org/10.1016/j.foodqual.2003.08.004

Du, J., Zhang, J., Castro-Lacouture, D., & Hu, Y. (2023). Lean manufacturing applications in prefabricated construction projects. *Automation in Construction*, *150*, 104790. https://doi.org/10.1016/j.autcon.2023.104790

Durdyev, S., & Ismail, S. (2019). Offsite Manufacturing in the Construction Industry for Productivity Improvement. *Engineering Management Journal*, *31*(1), 35–46. https://doi.org/10.1080/10429247.2018.1522566

Enshassi, M. S. A., Walbridge, S., West, J. S., & Haas, C. T. (2019). Integrated Risk Management Framework for Tolerance-Based Mitigation Strategy Decision Support in Modular Construction Projects. *Journal of Management in Engineering*, *35*(4), 05019004. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000698

Firoozi, M., & Heravi, G. (2013). *A LEAN APPROACH TO INDUSTRIALIZED AND MODULAR HOMEBUILDINTG: IDENTIFICATION AND ASSESSMENT OF WASTES IN MASS-HOUSING PROJECTS*.

Francis, A., & Thomas, A. (2019). *Integrating Lean Construction and Sustainability via a System Dynamics Framework*. 1187–1196. https://doi.org/10.24928/2019/0187

Fuenzalida, C., Fischer, B., Arroyo, P., & Salvatierra, J. L. (2016). *EVALUATING ENVIRONMENTAL IMPACTS OF CONSTRUCTION OPERATION BEFORE AND AFTER THE IMPLEMENTATION OF LEAN TOOLS*.

Gao, S., Jin, R., & Lu, W. (2020). Design for manufacture and assembly in construction: A review. *Building Research & Information*, *48*(5), 538–550. https://doi.org/10.1080/09613218.2019.1660608

Gbadamosi, A.-Q., Mahamadu, A.-M., Oyedele, L. O., Akinade, O. O., Manu, P., Mahdjoubi, L., & Aigbavboa, C. (2019). Offsite construction: Developing a BIM-Based optimizer for assembly. *Journal of Cleaner Production*, *215*, 1180–1190. https://doi.org/10.1016/j.jclepro.2019.01.113

Gladwin, T. N., Kennelly, J. J., & Krause, T.-S. (1995). Shifting Paradigms for Sustainable Development: Implications for Management Theory and Research. *The Academy of Management Review*, *20*(4), 874. https://doi.org/10.2307/258959

Global Construction Outlook. (2015). *Global Construction Outlook 2020, "Global construction market worth $10.3 trillion in 2020," 2015.*

Goh, M., & Goh, Y. M. (2019). Lean production theory-based simulation of modular construction processes. *Automation in Construction*, *101*, 227–244. https://doi.org/10.1016/j.autcon.2018.12.017

Hallam, C. R. A., Valerdi, R., & Contreras, C. (2018). Strategic lean actions for sustainable competitive advantage. *International Journal of Quality & Reliability Management*, *35*(2), 481–509. https://doi.org/10.1108/IJQRM-10-2016-0177

Han, Y., Yan, X., & Piroozfar, P. (2022). An overall review of research on prefabricated construction supply chain management. *Engineering, Construction and Architectural Management*. https://doi.org/10.1108/ECAM-07-2021-0668

Heravi, G., & Firoozi, M. (2017). Production process improvement of buildings' prefabricated steel frames using value stream mapping. *The International Journal of Advanced Manufacturing Technology*, *89*(9–12), 3307–3321. https://doi.org/10.1007/s00170-016-9306-9

Hevner, A. R., March, S. T., Park, J., & Ram, S. (2004). *Design Science in Information Systems Research*.

Heyvaert, M., Maes, B., & Onghena, P. (2013). Mixed methods research synthesis: Definition, framework, and potential. *Quality & Quantity*, *47*(2), 659–676. https://doi.org/10.1007/s11135-011-9538-6

Hu, X., Chong, H.-Y., & Wang, X. (2019). Sustainability perceptions of off-site manufacturing stakeholders in Australia. *Journal of Cleaner Production*, *227*, 346–354. https://doi.org/10.1016/j.jclepro.2019.03.258

Hussain, S., Zhu, F., Ali, Z., & Xu, X. (2017). Rural Residents' Perception of Construction Project Delays in Pakistan. *Sustainability*, *9*(11), 2108. https://doi.org/10.3390/su9112108

Hussein, M., Eltoukhy, A. E. E., Karam, A., Shaban, I. A., & Zayed, T. (2021). Modelling in off-site construction supply chain management: A review and future directions for sustainable modular integrated construction. *Journal of Cleaner Production*, *310*, 127503. https://doi.org/10.1016/j.jclepro.2021.127503

Hussein, M., & Zayed, T. (2021). Critical factors for successful implementation of just-in-time concept in modular integrated construction: A systematic review and meta-analysis. *Journal of Cleaner Production*, *284*, 124716. https://doi.org/10.1016/j.jclepro.2020.124716

Ikram, A. H., Salah, O., & Ali, H. (2022). The impact of Lean & Green Supply Chain Practices on Sustainability: Literature Review and Conceptual Framework. *Logforum*, *18*(1), 1–13. https://doi.org/10.17270/J.LOG.2022.684

Innella, F., Arashpour, M., & Bai, Y. (2019). Lean Methodologies and Techniques for Modular Construction: Chronological and Critical Review. *Journal of Construction Engineering and Management*, *145*(12), 04019076. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001712

Jackson, K. (2019). *Qualitative data analysis with NVivo* (3rd edition). SAGE Publications.

Jang, J., Ahn, S., Cha, S. H., Cho, K., Koo, C., & Kim, T. W. (2021). Toward productivity in future construction: Mapping knowledge and finding insights for achieving successful offsite construction projects. *Journal of Computational Design and Engineering*, *8*(1), 1–14. https://doi.org/10.1093/jcde/qwaa071

Jasti, N. V. K., & Kodali, R. (2016). Validity and reliability of lean enterprise frameworks in Indian manufacturing industry. In *PROCEEDINGS OF THE INSTITUTION OF MECHANICAL ENGINEERS PART B-JOURNAL OF ENGINEERING MANUFACTURE* (Vol. 230, Issue 2, pp. 354–363). SAGE PUBLICATIONS LTD. https://doi.org/10.1177/0954405414555736

Jayawardana, J., Kulatunga, A. K., Jayasinghe, J. A. S. C., Sandanayake, M., & Zhang, G. (2023). Environmental Sustainability of Off-Site Construction in Developed and Developing Regions: A Systematic Review. *Journal of Architectural Engineering*, *29*(2), 04023008. https://doi.org/10.1061/JAEIED.AEENG-1420

Jiang, Y., Zhao, D., Wang, D., & Xing, Y. (2019). Sustainable Performance of Buildings through Modular Prefabrication in the Construction Phase: A Comparative Study. *Sustainability*, *11*(20), 5658. https://doi.org/10.3390/su11205658

Jin, R., Gao, S., Cheshmehzangi, A., & Aboagye-Nimo, E. (2018). A holistic review of off-site construction literature published between 2008 and 2018. *Journal of Cleaner Production*, *202*, 1202–1219. https://doi.org/10.1016/j.jclepro.2018.08.195

Jørgensen, B., & Emmitt, S. (2008). Lost in transition: The transfer of lean manufacturing to construction. *Engineering, Construction and Architectural Management*, *15*(4), 383–398. https://doi.org/10.1108/09699980810886874

Kallio, H., Pietilä, A., Johnson, M., & Kangasniemi, M. (2016). Systematic methodological review: Developing a framework for a qualitative semi-structured interview guide. *Journal of Advanced Nursing*, *72*(12), 2954–2965. https://doi.org/10.1111/jan.13031

Kamali, M., & Hewage, K. (2016). Life cycle performance of modular buildings: A critical review. *Renewable and Sustainable Energy Reviews*, *62*, 1171–1183. https://doi.org/10.1016/j.rser.2016.05.031

Kamali, M., Hewage, K., & Milani, A. S. (2018). Life cycle sustainability performance assessment framework for residential modular buildings: Aggregated sustainability indices. *Building and Environment*, *138*, 21–41. https://doi.org/10.1016/j.buildenv.2018.04.019

Karimi, S., & Iordanova, I. (2021). Integration of BIM and GIS for Construction Automation, a Systematic Literature Review (SLR) Combining Bibliometric and Qualitative Analysis. *Archives of Computational Methods in Engineering*, *28*(7), 4573–4594. https://doi.org/10.1007/s11831-021-09545-2

Khodeir, L. M., & Othman, R. (2018). Examining the interaction between lean and sustainability principles in the management process of AEC industry. *Ain Shams Engineering Journal*, *9*(4), 1627–1634. https://doi.org/10.1016/j.asej.2016.12.005

Kim, T. K. (2017). Understanding one-way ANOVA using conceptual figures. *Korean Journal of Anesthesiology*, *70*(1), 22. https://doi.org/10.4097/kjae.2017.70.1.22

Ko, C.-H., & Kuo, J.-D. (2015). MAKING FORMWORK CONSTRUCTION LEAN. *Journal of Civil Engineering and Management*, *21*(4), 444–458. https://doi.org/10.3846/13923730.2014.890655

Kong, L., Li, H., Luo, H., Ding, L., & Zhang, X. (2018). Sustainable performance of just-in-time (JIT) management in time-dependent batch delivery scheduling of precast construction. *Journal of Cleaner Production*, *193*, 684–701. https://doi.org/10.1016/j.jclepro.2018.05.037

Koranda, C., Chong, W. K., Kim, C., Chou, J.-S., & Kim, C. (2012). An investigation of the applicability of sustainability and lean concepts to small construction projects. *KSCE Journal of Civil Engineering*, *16*(5), 699–707. https://doi.org/10.1007/s12205-012-1460-5

Korb, S. (2016). *"RESPECT FOR PEOPLE" AND LEAN CONSTRUCTION: HAS THE BOAT BEEN MISSED?*

Koskela, L. (1993, May 26). *Lean Production in Construction*. 10th International Symposium on Automation and Robotics in Construction, Houston, TX, USA. https://doi.org/10.22260/ISARC1993/0007

Lee, D., & Lee, S. (2021). Digital Twin for Supply Chain Coordination in Modular Construction. *Applied Sciences*, *11*(13), 5909. https://doi.org/10.3390/app11135909

Lee, S., Jang, Y., Yi, J.-S., & Son, J. (2023). Identifying Critical Risk Factors and Management Activities for Effective Offsite Construction Projects during Construction Phase. *Journal of Management in Engineering*, *39*(4), 04023018. https://doi.org/10.1061/JMENEA.MEENG-5310

Leksic, I., Stefanic, N., & Veza, I. (2020). The impact of using different lean manufacturing tools on waste reduction. In *ADVANCES IN PRODUCTION ENGINEERING & MANAGEMENT* (Vol. 15, Issue 1, pp. 81–92). UNIV MARIBOR, FAC MECHANICAL ENGINEERING. https://doi.org/10.14743/apem2020.1.351

Lewins, A., & Silver, C. (2009). *Using software in qualitative research: A step-by-step guide* (Reprinted). SAGE.

Li, L., Luan, H., Yin, X., Dou, Y., Yuan, M., & Li, Z. (2022). Understanding Sustainability in Off-Site Construction Management: State of the Art and Future Directions. *Journal of Construction Engineering and Management*, *148*(11), 03122008. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002396

Liker, J. K. (2003). *Toyota way: 14 management principles from the world's greatest manufacturer* (First edition). McGraw-Hill Education.

Liker, J. K., & Choi, T. Y. (2004). Building Deep Supplier Relationships. *Harvard Business Review*.

Lombardo, S., Hindenes, A., Aslesen, S., Reff, S., Lombardo, S., Hindenes, A., Aslesen, S., & Reff, S. (2023). Sustainability as Target Value – a Parametric Approach. *31st Annual Conference of the International Group for Lean Construction (IGLC 31)*, 445–453. https://doi.org/10.24928/2023/0127

Lu, H., Wang, H., Xie, Y., & Wang, X. (2018). Study on construction material allocation policies: A simulation optimization method. *Automation in Construction*, *90*, 201–212. https://doi.org/10.1016/j.autcon.2018.02.012

Lu, N., & Liska, R. W. (2008). Designers' and General Contractors' Perceptions of Offsite Construction Techniques in the United State Construction Industry. *International Journal of Construction Education and Research*, *4*(3), 177–188. https://doi.org/10.1080/15578770802494565

Mandala, R. S. K., & Nayaka, R. R. (2023). A state of art review on time, cost and sustainable benefits of modern construction techniques for affordable housing. *Construction Innovation*. https://doi.org/10.1108/CI-03-2022-0048

Maqbool, Y., Rafique, M. Z., Hussain, A., Ali, H., Javed, S., Amjad, M. S., Khan, M. A., Mumtaz, S., Haider, S. M., & Atif, M. (2019). An Implementation Framework to Attain 6R-Based Sustainable Lean Implementation—A Case Study. *IEEE Access*, *7*, 117561–117579. https://doi.org/10.1109/ACCESS.2019.2936056

Marjaba, G. E., & Chidiac, S. E. (2016). Sustainability and resiliency metrics for buildings – Critical review. *Building and Environment*, *101*, 116–125. https://doi.org/10.1016/j.buildenv.2016.03.002

Martínez-Jurado, P. J., & Moyano-Fuentes, J. (2014). Lean Management, Supply Chain Management and Sustainability: A Literature Review. *Journal of Cleaner Production*, *85*, 134–150. https://doi.org/10.1016/j.jclepro.2013.09.042

McDermott, O., ODwyer, K., Noonan, J., Trubetskaya, A., & Rosa, A. (2023). The development of a lean six sigma and BIM framework for enhancing off-site manufacturing. *International Journal of Lean Six Sigma*. https://doi.org/10.1108/IJLSS-02-2023-0020

Mehdipoor, A., Iordanova, I., & Al-Hussein, M. (2025). *Enhancing the Manufacturing Process in Light-Gauge Steel Off-Site Construction Using Semiautomation*.

Mellado, F., & Lou, E. C. W. (2020). Building information modelling, lean and sustainability: An integration framework to promote performance improvements in the construction industry. *Sustainable Cities and Society*, *61*, 102355. https://doi.org/10.1016/j.scs.2020.102355

Meng, X. (2019). Lean management in the context of construction supply chains. *International Journal of Production Research*, *57*(11), 3784–3798. https://doi.org/10.1080/00207543.2019.1566659

Minh, K. S., Zailani, S., Iranmanesh, M., & Heidari, S. (2019). Do lean manufacturing practices have negative impact on job satisfaction? In *INTERNATIONAL JOURNAL OF LEAN SIX SIGMA* (Vol. 10, Issue 1, pp. 257–274). EMERALD GROUP PUBLISHING LTD. https://doi.org/10.1108/IJLSS-11-2016-0072

Moghadam, M. (2014). *Moghadam_Mansooreh_Fall-202013.pdf*.

Moghadam, M., & Al-Hussein, M. (2013). *RESOURCE OPTIMIZATION FOR MODULAR CONSTRUCTION THROUGH VALUE STREAM MAP IMPROVEMENT*.

Moghadam, M., Alwisy, A., & Al-Hussein, M. (2012). Integrated BIM/Lean Base Production Line Schedule Model for Modular Construction Manufacturing. *Construction Research Congress 2012*, 1271–1280. https://doi.org/10.1061/9780784412329.128

Moradi, S., & Kähkönen, K. (2022). Sustainability Indicators in Building Construction Projects through the Lens of Project Delivery Elements. *IOP Conference Series: Earth and Environmental Science*, 022032. https://doi.org/10.1088/1755-1315/1101/2/022032

Moradi, S., Kähkönen, K., & Sormunen, P. (2022a-03-07). Analytical and Conceptual Perspectives toward Behavioral Elements of Collaborative Delivery Models in Construction Projects. *Buildings*, *12*(3), 316. https://doi.org/10.3390/buildings12030316

Moradi, S., & Sormunen, P. (2023). Integrating lean construction with BIM and sustainability: A comparative study of challenges, enablers, techniques, and benefits. *Construction Innovation*, *24*(7), 188–203. https://doi.org/10.1108/CI-02-2023-0023

Mossman, A., & Sarhan, S. (2021). Synchronising Off-Site Fabrication with On-Site Production in Construction. *Construction Economics and Building*, *21*(3). https://doi.org/10.5130/AJCEB.v21i3.7638

Mostafa, S., Chileshe, N., & Abdelhamid, T. (2016). Lean and agile integration within offsite construction using discrete event simulation: A systematic literature review. *Construction Innovation*, *16*(4), 483–525. https://doi.org/10.1108/CI-09-2014-0043

Naeemah, A. J., & Wong, K. Y. (2022). Positive impacts of lean manufacturing tools on sustainability aspects: A systematic review. *Journal of Industrial and Production Engineering*, *39*(7), 552–571. https://doi.org/10.1080/21681015.2022.2041742

Nahmens, I., & Ikuma, L. H. (2012). Effects of Lean Construction on Sustainability of Modular Homebuilding. *Journal of Architectural Engineering*, *18*(2), 155–163. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000054

Negi, P., Thakur, G., Singh, R., Gehlot, A., Thakur, A. K., Gupta, L. R., Priyadarshi, N., & Twala, B. (2024). Perception of lean construction implementation barriers in the indian prefabrication sector. *Heliyon*, *10*(16), e36458. https://doi.org/10.1016/j.heliyon.2024.e36458

Ng, R., Low, J. S. C., & Song, B. (2015). Integrating and implementing Lean and Green practices based on proposition of Carbon-Value Efficiency metric. *Journal of Cleaner Production*, *95*, 242–255. https://doi.org/10.1016/j.jclepro.2015.02.043

Nóbrega Júnior, C. L., & Melhado, S. B. (2008). Lean design management in architectural designs developed in the city of João Pessoa –analysis with focus in the process of elaboration and description of the solution. *CIB W096 Architectural Management and CIB TG49 Architectural Engineering Conference (São Paulo, Brazil, Nov. 04-08, 2008)*, 343–350. http://www.irbnet.de/daten/iconda/CIB10499.pdf

Nunes, T. L. M., & Melhado, S. B. (2025). The Effects of Incorporating Artificial Intelligence (AI) into Lean Construction. In A. Francis, E. Miresco, & S. Melhado (Eds.), *Advances in Information Technology in Civil and Building Engineering* (Vol. 628, pp. 833–841). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-84208-5_64

Ogunbiyi, O., Goulding, J. S., & Oladapo, A. (2014). An empirical study of the impact of lean construction techniques on sustainable construction in the UK. *Construction Innovation*, *14*(1), 88–107. https://doi.org/10.1108/CI-08-2012-0045

Ohno, T., & Ohno, T. (2008). *Toyota production system: Beyond large-scale production*. 143.

Ostertagová, E., & Ostertag, O. (2013). Methodology and Application of One-way ANOVA. *American Journal of Mechanical Engineering*.

Pan, W., & Pan, M. (2023). Rethinking lean synergistically in practice for construction industry improvements. *Engineering, Construction and Architectural Management*, *30*(7), 2669–2690. https://doi.org/10.1108/ECAM-04-2021-0346

Peiris, A., Hui, F. K. P., Duffield, C., Wang, J., Gil Garcia, M., Chen, Y., & Ngo, T. (2023). Digitalising modular construction: Enhancement of off-site manufacturing productivity via a manufacturing execution & control (MEC) system. *Computers & Industrial Engineering*, *178*, 109117. https://doi.org/10.1016/j.cie.2023.109117

Peltokorpi, A., Olivieri, H., Granja, A. D., & Seppänen, O. (2018). Categorizing modularization strategies to achieve various objectives of building investments. *Construction Management and Economics*, *36*(1), 32–48. https://doi.org/10.1080/01446193.2017.1353119

Quale, J., Eckelman, M. J., Williams, K. W., Sloditskie, G., & Zimmerman, J. B. (2012). Construction Matters: Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. *Journal of Industrial Ecology*, *16*(2), 243–253. https://doi.org/10.1111/j.1530-9290.2011.00424.x

Rahima Shabeen, S., & Aravind Krishnan, K. (2022). Application of lean manufacturing using value stream mapping (VSM) in precast component manufacturing: A case study. *Materials Today: Proceedings*, *65*, 1105–1111. https://doi.org/10.1016/j.matpr.2022.04.159

Rosenbaum, S., Toledo, M., & González, V. (2014). Improving Environmental and Production Performance in Construction Projects Using Value-Stream Mapping: Case Study. *Journal of Construction Engineering and Management*, *140*(2), 04013045. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000793

Ryan, G. W., & Bernard, H. R. (2003). Techniques to Identify Themes. *Field Methods*, *15*(1), 85–109. https://doi.org/10.1177/1525822X02239569

Sacks, R., Koskela, L., Dave, B. A., & Owen, R. (2010). Interaction of Lean and Building Information Modeling in Construction. *Journal of Construction Engineering and Management*, *136*(9), 968–980. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000203

Salama, T., & Said, H. (2023). Agility assessment framework for modular and offsite construction. *Construction Innovation*. https://doi.org/10.1108/CI-09-2022-0238

Sarhan, S., & Fox, A. (2013). *Barriers to Implementing Lean Construction in the UK Construction Industry*. *6*, 1–17.

Sartal, A., Llach, J., Vazquez, X. H., & de Castro, R. (2017). How much does Lean Manufacturing need environmental and information technologies? In *JOURNAL OF MANUFACTURING SYSTEMS* (Vol. 45, pp. 260–272). ELSEVIER SCI LTD. https://doi.org/10.1016/j.jmsy.2017.10.005

Singh, A., Kumar, V., Mittal, A., & Verma, P. (2024). Identifying critical challenges to lean construction adoption. *Construction Innovation*, *24*(1), 67–105. https://doi.org/10.1108/CI-09-2022-0229

Singh, J., Singh, H., & Kumar, A. (2020). Impact of lean practices on organizational sustainability through green supply chain management – an empirical investigation. *International Journal of Lean Six Sigma*, *11*(6), 1035–1068. https://doi.org/10.1108/IJLSS-06-2017-0068

Skjott Linneberg, M., & Korsgaard, S. (2019). Coding qualitative data: A synthesis guiding the novice. *Qualitative Research Journal*, *19*(3), 259–270. https://doi.org/10.1108/QRJ-12-2018-0012

Solaimani, S., Haghighi Talab, A., & Van Der Rhee, B. (2019). An integrative view on Lean innovation management. *Journal of Business Research*, *105*, 109–120. https://doi.org/10.1016/j.jbusres.2019.07.042

Souza, J. P. E., & Alves, J. M. (2018). Lean-integrated management system: A model for sustainability improvement. *Journal of Cleaner Production*, *172*, 2667–2682. https://doi.org/10.1016/j.jclepro.2017.11.144

Stump, B., & Badurdeen, F. (2012). Integrating lean and other strategies for mass customization manufacturing: A case study. *Journal of Intelligent Manufacturing*, *23*(1), 109–124. https://doi.org/10.1007/s10845-009-0289-3

Sui Pheng, L., & Hui Fang, T. (2005). Modern-day lean construction principles: Some questions on their origin and similarities with Sun Tzu's *Art of War*. *Management Decision*, *43*(4), 523–541. https://doi.org/10.1108/00251740510593530

Tavakol, M., & Dennick, R. (2011). Making sense of Cronbach's alpha. *International Journal of Medical Education*, *2*, 53–55. https://doi.org/10.5116/ijme.4dfb.8dfd

Taylor, H. (2005). A Critical Decision Interview Approach to Capturing Tacit Knowledge: Principles and Application. *International Journal of Knowledge Management*, *1*(3), 25–39. https://doi.org/10.4018/jkm.2005070102

Terreno, S., Asadi, S., & Anumba, C. (2019). An Exploration of Synergies between Lean Concepts and BIM in FM: A Review and Directions for Future Research. *Buildings*, *9*(6), 147. https://doi.org/10.3390/buildings9060147

Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, *84*(2), 523–538. https://doi.org/10.1007/s11192-009-0146-3

Vieira, A. R., & Cachadinha, N. (2011). *Lean Construction and Sustainability—Complementary Paradigms? A Case Study*.

Vom Brocke, J., Hevner, A., & Maedche, A. (2020). Introduction to Design Science Research. In J. Vom Brocke, A. Hevner, & A. Maedche (Eds.), *Design Science Research. Cases* (pp. 1–13). Springer International Publishing. https://doi.org/10.1007/978-3-030-46781-4_1

Wang, M., Wang, C. C., Sepasgozar, S., & Zlatanova, S. (2020). A Systematic Review of Digital Technology Adoption in Off-Site Construction: Current Status and Future Direction towards Industry 4.0. *Buildings*, *10*(11), 204. https://doi.org/10.3390/buildings10110204

Womack, J. P., & Jones, D. T. (1997). Lean Thinking—Banish Waste and Create Wealth in your Corporation. *Journal of the Operational Research Society*, *48*(11), 1148–1148. https://doi.org/10.1038/sj.jors.2600967

Wong, L. (2008). *DATA ANALYSIS IN QUALITATIVE RESEARCH: A BRIEF GUIDE TO USING NVIVO*. *3*(1).

Wuni, I. Y., & Shen, G. Q. (2020). Barriers to the adoption of modular integrated construction: Systematic review and meta-analysis, integrated conceptual framework, and strategies. *Journal of Cleaner Production*, *249*, 119347. https://doi.org/10.1016/j.jclepro.2019.119347

Xiao, Y., & Watson, M. (2019). Guidance on Conducting a Systematic Literature Review. *Journal of Planning Education and Research*, *39*(1), 93–112. https://doi.org/10.1177/0739456X17723971

Yang, M. G. (Mark), Hong, P., & Modi, S. B. (2011). Impact of lean manufacturing and environmental management on business performance: An empirical study of manufacturing firms. In *INTERNATIONAL JOURNAL OF PRODUCTION ECONOMICS* (Vol. 129, Issue 2, pp. 251–261). ELSEVIER. https://doi.org/10.1016/j.ijpe.2010.10.017

Yu, H., Al-Hussein, M., Al-Jibouri, S., & Telyas, A. (2013). Lean Transformation in a Modular Building Company: A Case for Implementation. *Journal of Management in Engineering*, *29*(1), 103–111. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000115

Yu, H., Tweed, T., Al-Hussein, M., & Nasseri, R. (2009). Development of Lean Model for House Construction Using Value Stream Mapping. *Journal of Construction*

Engineering and Management, *135*(8), 782–790. https://doi.org/10.1061/(ASCE)0733-9364(2009)135:8(782)

Zaalouk, A., & Han, S. (2022). Lean-Based Integrated Approach for Manual Work Design Optimization in Modular Construction. *Construction Research Congress 2022*, 335–344. https://doi.org/10.1061/9780784483985.034

Zhang, Y., Lei, Z., Han, S., Bouferguene, A., & Al-Hussein, M. (2020). Process-Oriented Framework to Improve Modular and Offsite Construction Manufacturing Performance. *Journal of Construction Engineering and Management*, *146*(9), 04020116. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001909