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A Systematic Review and Stage-Based Taxonomy of Lean-Sustainability Integration in Modular Off-Site Construction

Helia Rasouli[1], Amirhossein Mehdipoor[2], Silvio Melhado[3], and Ivanka Iordanova[4]

Abstract

Question: What are the current research topics, patterns, and trends concerning Lean-sustainability integration in modular off-site construction? What are the critical research gaps, challenges, and opportunities for advancing Lean-enabled sustainability in MOC across manufacturing and on-site assembly/construction stages?

Purpose: To synthesize and structure the state of knowledge on Lean-sustainability integration in MOC, with a stage-based focus on barriers, opportunities, and the role of digital enablers.

Research Method: Systematic Literature Review of 71 peer-reviewed journal articles (2004–2024), combining bibliometric mapping with qualitative thematic coding across off-site manufacturing and on-site assembly stages.

Findings: Research emphasizes economic outcomes, shows moderate attention to environmental outcomes, and gives limited treatment to social sustainability. Barriers are stage-dependent: manufacturing challenges relate to standardization and production system design, while on-site assembly emerges as a key bottleneck due to variability, coordination complexity, and workforce constraints. Digital tools (e.g., BIM, analytics, simulation, and integrated delivery approaches) are frequently positioned as enablers but are rarely connected explicitly to sustainability outcomes in a unified framework.

Limitations: The review is limited to journal articles and does not empirically validate findings through case studies or field interventions; coding outcomes depend on available reporting detail in the literature.

[1] Department of Construction Engineering, École de Technologie Supérieure (ÉTS), Montréal, Canada helia.rasouli.1@ens.etsmtl.ca

[2] Construction Research Centre, National Research Council of Canada, Ottawa, Canada amirhossein.mehdipoor@nrc-cnrc.gc.ca

[3] Department of Construction Engineering, École de Technologie Supérieure (ÉTS), Montréal, Canada Silvio.Melhado@etsmtl.ca

[4] Department of Construction Engineering, École de Technologie Supérieure (ÉTS), Montréal, Canada Ivanka.Iordanova@etsmtl.ca

Implications: Advancing sustainable modular construction requires stage-specific Lean strategies and clearer linking of Lean practices and digital enablers to Triple Bottom Line outcomes, especially social sustainability in both factory and site contexts.

Value for authors: Provides a stage-based taxonomy that helps practitioners anticipate where Lean implementation typically breaks down (especially during assembly), and where digital practices can be prioritized to reduce variability, improve coordination, and strengthen sustainability performance.

Keywords: Modular Off-Site Construction; Lean Construction; Sustainable Development; Triple Bottom Line; BIM; Digital Enablers

Paper type: Full paper

Introduction

This review is positioned within the Lean Construction body of knowledge, focusing on how Lean principles and practices can be operationalized across modular production and installation to reduce waste and increase value generation across the Triple Bottom Line. Modular Off-Site Construction (MOC) has emerged as a transformative alternative to conventional construction, offering substantial benefits in speed, quality, and resource efficiency. Unlike traditional on-site building approaches, MOC transfers a significant portion of production activities to controlled manufacturing environments, enabling greater precision, reduced waste, and improved productivity. These advantages directly support Sustainable Development (SD) objectives, as modularization can minimize construction waste, reduce material usage, and shorten project timelines (Kamali et al., 2018). Despite these benefits, the adoption of MOC remains hindered by persistent challenges such as transportation limitations, design rigidity, supply-chain fragmentation, and low stakeholder familiarity (Hussein & Zayed, 2021).These constraints limit the full realization of MOC's sustainability potential, underscoring the need for integrated frameworks that enhance process efficiency and support the Triple Bottom Line (TBL).

Lean Management (LM), grounded in waste elimination, continuous improvement, and value delivery, has become an influential philosophy for optimizing construction processes. Although initially developed for manufacturing environments, Lean principles closely align with off-site modular workflows due to their emphasis on flow reliability, standardization, and minimization of variability. Tools such as 5S, Kaizen, Just-in-Time (JIT), Value Stream Mapping (VSM), Kanban, and the Last Planner System (LPS) have demonstrated notable improvements in productivity, quality, and coordination within construction projects (Du et al., 2023; Naeemah & Wong, 2022).However, the integration of Lean with MOC remains fragmented, with many studies addressing Lean, modularization, and sustainability as separate research streams rather than a unified domain (Jin et al., 2018; McDermott et al., 2023; Peiris et al., 2023).

A key gap in current literature lies in the limited understanding of how Lean principles influence sustainability outcomes in modular off-site contexts. Previous reviews show that most studies prioritize economic sustainability such as cost, productivity, and schedule performance while environmental and particularly social sustainability remain underexplored (Carvajal-Arango et al., 2019; Goh & Goh, 2019). Social sustainability outcomes such as workforce well-being, occupational health, training, ergonomics, and collaborative culture (Ciannella & Santos, 2022) have received comparatively less attention, despite being critical to both Lean philosophy and factory-based construction environments (Naeemah & Wong, 2022). This imbalance reveals a lack of holistic frameworks that integrate Lean practices across all three TBL dimensions in MOC.

Furthermore, emerging research highlights the growing role of digital technologies such as Building Information Modelling (BIM), Integrated Project Delivery (IPD), simulation modelling, production analytics, and digital supply-chain systems in enabling Lean implementation within off-site construction (Jin et al., 2018; Mellado & Lou, 2020; Peiris et al., 2023). Yet these digital enablers are rarely examined in conjunction with sustainability or Lean principles in modular settings. Instead, the literature often treats digitalization as a parallel but isolated improvement domain. As a result, there is limited knowledge on how digital Lean tools mitigate barriers to MOC adoption, improve sustainability performance, or enhance modular manufacturing and on-site assembly workflows.

Several recent studies emphasize the importance of addressing implementation challenges that hinder Lean–MOC integration. These challenges include inconsistent communication, resistance to change, shortages of skilled labor, lack of standardization, supply-chain variability, technical complexity, and organizational misalignment (Hussein & Zayed, 2021; McDermott et al., 2023; Montazeri et al., 2025). However, these barriers have not been systematically categorized for the two distinct stages of MOC, off-site manufacturing and on-site assembly even though the nature and severity of challenges differ substantially between controlled factory workflows and site-based installation environments. The absence of a stage-based analysis represents a critical knowledge gap that prevents researchers and practitioners from tailoring Lean strategies to the unique constraints of each phase.

Given these gaps, the integration of Lean, sustainability, and digitalization within MOC remains a fragmented research domain lacking a structured and comprehensive synthesis. While studies such as Carvajal-Arango et al. (2019) provide valuable insights into Lean–sustainability linkages, they do not differentiate between off-site and on-site modular processes, nor do they incorporate digital process-improvement tools that have grown rapidly in recent years. In this context, “on-site construction” denotes activities carried out at the project site either as part of off-site construction processes or within conventional on-site projects that employ specific construction methods (Montazeri et al., 2025).Addressing these gaps is essential to advance both theoretical understanding and practical implementation of Lean-enabled sustainable modular construction.

To respond to these needs, this study conducts a comprehensive systematic literature review (SLR) supported by bibliometric analysis and qualitative coding to investigate the integration of Lean management and sustainable development in MOC. This review aims to answer two research questions:

(a) What are the current research topics, patterns, and trends concerning Lean–sustainability integration in modular off-site construction?

(b) What are the critical research gaps, challenges, and opportunities for advancing Lean-enabled sustainability in MOC across manufacturing and on-site assembly/construction stages?

The findings of this review provide a structured analysis of emerging themes, stage-specific challenges, sustainability implications, and the role of digital Lean enablers. Ultimately, this work establishes a conceptual foundation for developing a stage-based taxonomy and integrated framework to optimize Lean implementation for sustainable modular off-site construction.

Literature Review

Lean Construction: Principles, Tools, and Alignment with Modular Off-Site Construction

Lean Construction (LC), founded on the principles of the Toyota Production System (TPS), seeks to reduce waste, increase workflow reliability, and enhance value for the end user. Koskela (1993) Transformation–Flow–Value (TFV) theory provides the conceptual underpinning for LC by framing construction as a production system that must minimize variability and maximize predictability. In practice, LC has evolved into a suite of tools and methods designed to improve planning, coordination, and process stability. Prominent Lean tools include 5S, Just-in-Time (JIT), Value Stream Mapping (VSM), Kaizen, Kanban, Standard Work, and the Last Planner System® (LPS®) (Naeemah & Wong, 2022).

In traditional construction, the fragmented nature of projects often leads to inefficiencies such as rework, delays, material waste, and miscommunication among stakeholders. Lean offers structured approaches to mitigate these issues through continuous improvement, visual management, collaborative planning, and waste reduction strategies (Du et al., 2023). These principles are particularly relevant to manufacturing-based production systems, where repetitive workflows and controlled environments enable the implementation of takt planning, pull mechanisms, and production line balancing.

This makes LC highly compatible with Modular Off-Site Construction (MOC). In MOC, a significant portion of production is shifted to a factory environment where modules or components are fabricated before being transported to the construction site. This shift enables the adoption of Lean practices such as standardized workstations, streamlined supply chains, and flow-based production scheduling (Kamali et al., 2018). As demonstrated by Hussein and Zayed (2021), modular manufacturing benefits from process stability, reduced variability, and shortened cycle times all core goals of Lean.

However, despite these synergies, Lean implementation in MOC is far from straightforward. The off-site manufacturing stage resembles a controlled factory system, while the on-site assembly stage still operates under traditional construction conditions, with exposure to delays, subcontractor fragmentation, and external uncertainties. This dual nature complicates the application of Lean tools uniformly across the MOC lifecycle. Several studies emphasize barriers such as resistance to change, lack of skilled workers, absence of performance metrics, limited standardization, and communication gaps between factory and site teams (McDermott et al., 2023; Naeemah & Wong, 2022).These barriers play different roles at the manufacturing and assembly stages, suggesting a need for stage-specific Lean strategies gap that this study addresses systematically.

Sustainable Development in Modular Construction

Sustainable Development (SD) is commonly conceptualized through the Triple Bottom Line (TBL), which emphasizes economic, environmental, and social performance. In the construction industry, SD is increasingly prioritized due to high levels of waste generation, energy consumption, and greenhouse gas emissions. Modular Off-Site Construction has been recognized as a promising method for improving sustainability outcomes. By transferring production to factories, MOC can reduce material waste, improve precision, enhance worker safety, and decrease overall project durations (Kamali et al., 2018).

Environmental sustainability benefits arise from controlled material usage, reduced rework, minimized site disturbance, and optimization of transportation and logistics. Several studies show that modularization can reduce embodied carbon and construction waste through standardized component production, precision cutting, and closed-loop recycling (Goh & Goh, 2019).Moreover, environmental performance is enhanced when modular design is integrated with digital modelling tools such as BIM and energy simulation (Peiris et al., 2023).

Economic sustainability is predominantly linked to improved productivity, reduced construction time, minimized defects, and enhanced cost predictability. Lean practices, when integrated with modular workflows, further reduce variability and increase reliability, thereby amplifying economic benefits (Du et al., 2023). Studies also highlight the role of supply-chain stability, repeatability, and design standardization in lowering production costs and enabling economies of scale (McDermott et al., 2023).

Despite progress in environmental and economic domains, **social sustainability** remains the least explored dimension in MOC and in the broader Lean–sustainability literature. This aligns with findings from (Carvajal-Arango et al., 2019; Ciannella & Santos, 2022), who observed a significant underrepresentation of social SD indicators in Lean construction research. Social sustainability includes factors such as worker well-being, training and upskilling, ergonomics, safety, and community impact. While modular construction offers improved ergonomics and safer working conditions in controlled factory environments, barriers such as lack of training, unfamiliarity with modular workflows, and cultural resistance impede the achievement of social SD outcomes (Hussein & Zayed, 2021; Naeemah & Wong, 2022).

The literature clearly demonstrates a gap: sustainability in MOC is predominantly evaluated through economic and environmental lenses, with social aspects poorly articulated and rarely linked to Lean principles. This reinforces the importance of a holistic, integrated framework that considers all three TBL dimensions.

Lean-Sustainability Integration: Prior Studies and Remaining Gaps

Lean and sustainability research has expanded substantially, emphasizing synergies among waste reduction, resource efficiency, workflow reliability, and improved project performance (Carvajal-Arango et al., 2019; Goh & Goh, 2019).Lean practices such as Value Stream Mapping (VSM), 5S, Kaizen, and the Last Planner System® (LPS ®) support sustainable development (SD) by reducing waste and cycle times, enhancing collaboration, and promoting continuous improvement. However, existing reviews highlight the absence of structured frameworks that explicitly link Lean practices to sustainability outcomes in Modular and Off-Site Construction (MOC).

To address this gap, Lean Construction principles proposed by Koskela (1992) including waste reduction, variability control, cycle-time reduction, process simplification, transparency, continuous improvement, and benchmarking, provide a relevant foundation. This production philosophy aims to improve process efficiency and effectiveness, ensure timely delivery, prevent defects, and enhance productivity, underpinned by the dual pillars of respect for people and continuous improvement (Cherrafi et al., 2016).

Carvajal-Arango et al. (2019) offer the most influential review, systematically examining the economic, environmental, and social sustainability impacts of Lean practices. While their sustainability indicator framework is valuable, it was not designed for modular off-site workflows and does not distinguish between factory-based manufacturing and on-site assembly, limiting its applicability to MOC.

Other studies examine the integration of Lean with BIM, IPD, and digital modelling tools (Jin et al., 2018; Peiris et al., 2023), but largely at a conceptual level without assessing sustainability outcomes. Similarly, studies on modular adoption barriers (Hussein & Zayed, 2021; McDermott et al., 2023) do not explicitly link these challenges to Lean or sustainability frameworks.

Overall, the literature provides fragmented insights into Lean–SD integration in MOC, lacking systematic barrier classification, stage-specific analysis, and integration of digital Lean enablers gaps that limit practical implementation.

Digitalization and Lean Integration in Modular Off-Site Construction

Digital technologies play an increasingly critical role in enabling efficient modular workflows. BIM supports design coordination, clash detection, production sequencing, and logistics planning. Simulation tools allow optimization of factory production lines, assembly processes, and transportation routes (Peiris et al., 2023). Digital supply-chain platforms improve visibility, reduce uncertainties, and synchronize module delivery. Integrated Project Delivery (IPD) enhances collaboration, information sharing, and decision-making (Mellado & Lou, 2020; Moradi et al., 2022a-03-07).

These digital tools align closely with Lean objectives. For example, BIM supports value flow transparency, simulation models improve takt planning, and digital dashboards reduce process variability. However, digitalization is often discussed separately from Lean and sustainability. Few studies explore how digital technologies enable Lean-driven sustainability outcomes in MOC. Despite these contributions, the literature remains fragmented, particularly regarding stage-specific challenges in modular construction and their implications for Lean and sustainability integration. These gaps motivate the systematic review presented in the following sections.

Methodology

This study adopts a Systematic Literature Review (SLR) approach integrating both bibliometric analysis and qualitative thematic synthesis to ensure a comprehensive understanding of the relationships among Lean Construction (LC), Modular Off-Site Construction (MOC), and Sustainable Development (SD). SLRs provide a transparent and replicable structure for identifying, screening, and analyzing relevant literature across interconnected domains (Xiao & Watson, 2019).Bibliometric mapping complements this process by revealing structural patterns, publication trends, and emerging themes within the academic discourse.

VOSviewer a widely used bibliometric mapping tool is employed to visualize keyword networks, co-authorship patterns, and source clustering. As highlighted by Van Eck & Waltman (2010) VOSviewer offers robust capabilities for constructing and interpreting bibliometric networks, enabling clear identification of research hotspots and gaps. This tool enhances the interpretative accuracy of findings and supports evidence-driven identification of future research opportunities.

To ensure comprehensive coverage, Scopus was selected as the primary database due to its extensive indexing of peer-reviewed journals in engineering, construction management, sustainability science, and industrialized construction. Scopus is also compatible with VOSviewer bibliometric export formats, improving workflow efficiency and analytical reliability (Hu et al., 2019). Additional verification searches were carried out using Web of Science (WoS) and Engineering Village to mitigate database bias. *Figure 1* shows the complete PRISMA flow diagram summarizing the identification, screening, eligibility assessment, and inclusion stages for the 71 articles reviewed.

Search Strategy

The search strategy was developed iteratively, drawing on foundational studies in Lean construction and modularization to identify relevant keywords. Core search terms included:

"Lean Construction", "Lean Management", "Modular Construction", "Off-Site Construction", "Prefabrication", "Industrialized Construction", "Sustainable Development", and "Sustainability".

These terms were combined using Boolean operators into the final search string:

(Lean OR "Lean Management")

AND (Sustainability OR Sustainable Development OR Green)

AND (Construction OR "Modular Construction" OR "Off-Site Construction" OR MOC)

The search was conducted for English-language studies published between 2004 and 2024, capturing the contemporary period during which modularization and Lean practices expanded significantly. This initial query returned 550 records.

Screening and Eligibility Assessment

Screening followed the PRISMA 2020 guidelines to ensure methodological rigor and transparency. *Figure 1* presents the PRISMA flow diagram reflecting each step of the literature selection process. A multi-stage filtering procedure was applied:

- <u>Step 1 — Initial Filtering:</u> Records were refined by: Language (English), Document type (journal articles only), Subject area (Engineering, Energy, Environmental Science), Year range (2004–2024). This reduced the dataset to 394 records.
- <u>Step 2 — Title and Abstract Screening:</u> Articles were reviewed for relevance to Lean, modular/off-site construction, or sustainability. A total of 279 records were excluded for reasons such as: Duplication, not being journal articles, Lack of relevance to the three core themes.
- <u>Step 3 — Full-Text Assessment:</u> The remaining 115 studies were assessed in detail to determine conceptual alignment with all three domains: Lean, Sustainability, Modular/off-site construction. A total of 50 articles were excluded at this stage for not sufficiently addressing the intersection of these domains.
- <u>Step 4 — Final Selection and Snowballing:</u> This screening process resulted in 65 eligible studies. To improve completeness, backward snowballing was applied, reviewing reference lists of key papers to identify additional relevant studies. Following established SLR practice, snowballing enhances coverage, especially in emerging interdisciplinary fields (Jayawardana et al., 2023). This process yielded 6 additional studies, resulting in a total dataset of: 71 included studies.

Data Extraction and Analysis

The final set of 71 studies was analyzed using an integrated approach:

- (a) Bibliometric Analysis: Bibliometric data (authors, affiliations, keywords, sources) were exported into VOSviewer for mapping: Keyword co-occurrence networks, most relevant sources, Country and institutional contributions, Authors' publication trajectories. This quantitative lens enabled visualization of dominant themes and global research activity across Lean–MOC–SD interactions.
- (b) Qualitative Coding (NVivo): A thematic coding procedure was conducted to extract insights across three analytical layers: Lean-related challenges and enablers like: communication issues, organizational resistance, lack of expertise or standardization. Sustainability dimensions (TBL): economic (cost, productivity, schedule), environmental (waste, emissions, materials), social (training, safety, ergonomics). Digital enablers (BIM integration, simulation, digital supply-chain tools, IPD-supported collaboration).

This dual-method approach bibliometric and thematic coding ensures both macro-level patterns and micro-level insights are captured, enabling a richer understanding of how Lean and sustainability converge within modular off-site contexts.

Categorization into Core Themes

All included studies were classified under three central domains:

- Lean Practices in MOC
- Sustainability Impacts in MOC
- Integration of Lean, Sustainability, and Modular Construction

This categorization emphasized intersections between these domains and supported the development of the stage-based taxonomy introduced in next sections.

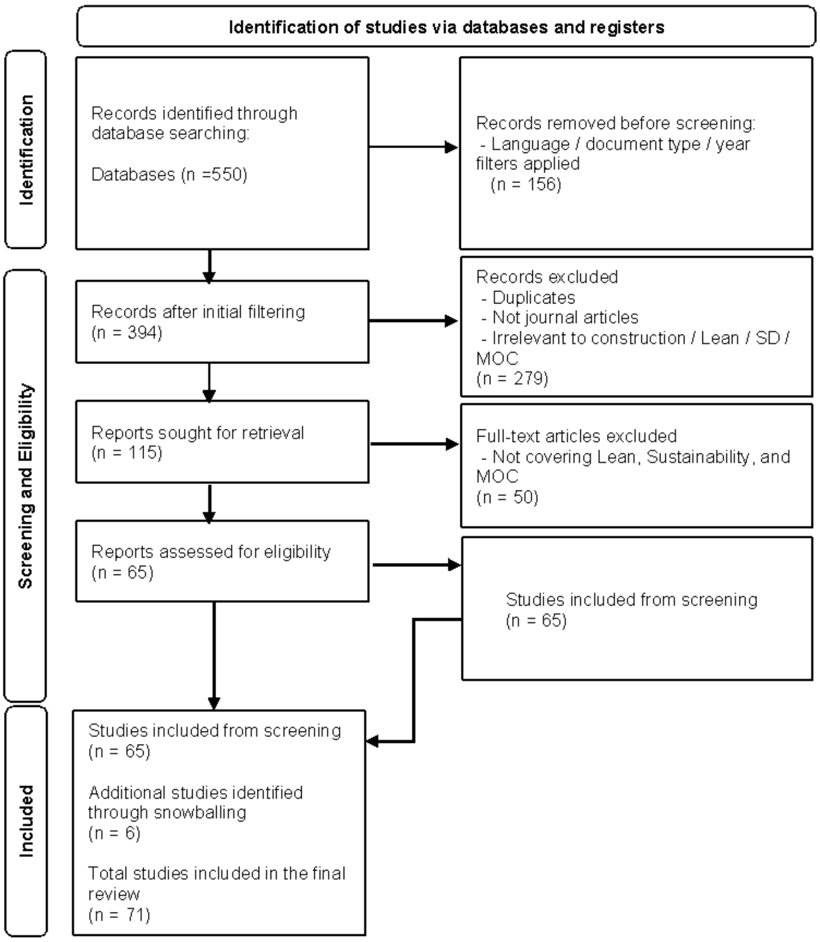

Figure 1. Literature Search and Evaluation for Inclusion

Result

Bibliometric result

A bibliometric analysis was conducted to describe publication trends, geographical contributions, and prominent research outlets in the intersection of Lean Construction, Modular Off-Site Construction, and Sustainable Development. These results provide an overview of the evolution and structure of the research domain and support the identification of thematic patterns discussed in subsequent sections. The annual scientific production from 2004 to 2024 shows a steady increase in publications, reflecting growing academic interest in industrialized construction, Lean practices, and sustainability. A notable rise in output occurs after 2015, coinciding with increased global attention to modular construction and the adoption of Lean methodologies in off-site manufacturing. Keyword analysis provides insight into dominant themes and conceptual linkages. The most frequently occurring keywords include lean construction, sustainability, prefabrication, modular construction, off-site construction, BIM, performance, optimization, and waste reduction.

The co-occurrence network Figure 2 reveals clear thematic clusters involving Lean practices, modular systems, and performance-driven sustainability goals. These clusters suggest that research has increasingly focused on integrating Lean methodologies with off-site fabrication processes and sustainability evaluation frameworks.

Figure 2. Keyword Co-occurrence Map (Generated with VOS Viewer)

Peaks in specific years align with high-profile special issues on industrialized construction and sustainability-focused construction management conferences. *Figure 3* presents the annual publication trend.

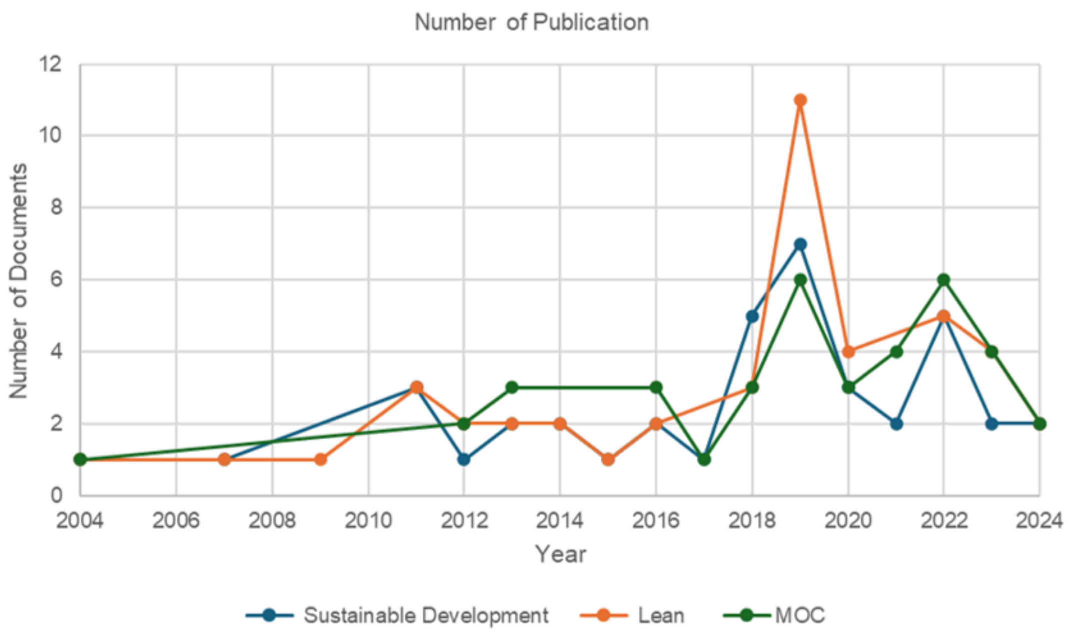

Figure 3. Articles Published Between 2004 and 2024 (Annual Publication Trend)

A total of 31 countries contributed to the reviewed literature. The most productive regions include the United States (31 publications), China (28), Australia (23), the United

Kingdom (17), Canada (15), and India (15). These nations have strong research ecosystems in construction technology, modular systems, and Lean adoption. Emerging contributions are also observed from Brazil, Malaysia, Ireland, Chile, and Turkey, reflecting a wider global uptake of modular and Lean principles. The distribution indicates that research is globally diverse, with substantial contributions from North America, Asia, and Oceania. *Figure 4* displays the geographical distribution of publications.

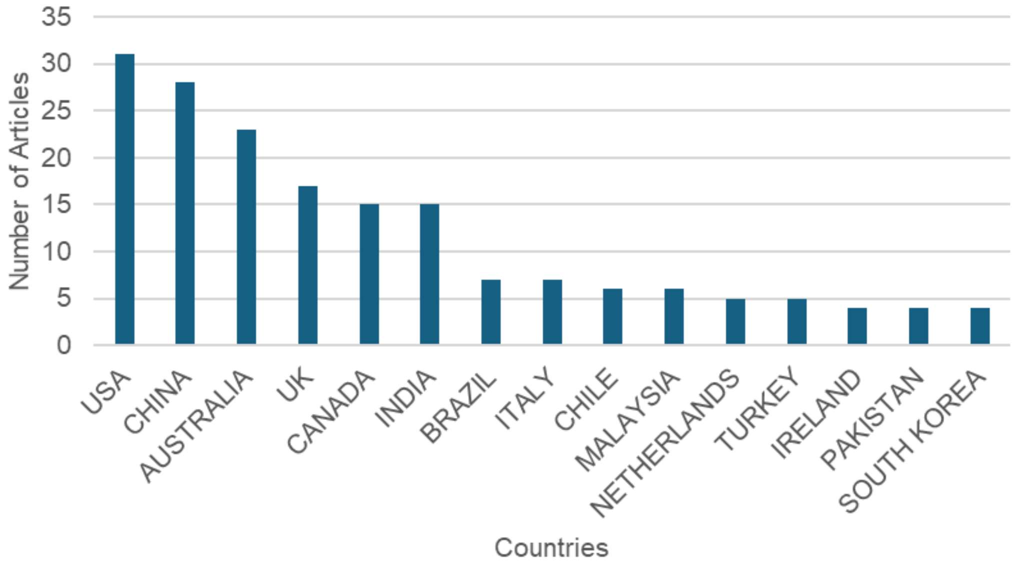

Figure 4. Pioneer Countries in Publication

The most influential journals include the Journal of Cleaner Production, Automation in Construction, Journal of Construction Engineering and Management, and Sustainability, all of which regularly publish work on Lean, sustainability, and industrialized construction. These journals account for a large share of the reviewed publications, indicating their central role in shaping scholarly discourse in this domain.

Author productivity indicates repeated contributions from scholars specializing in Lean, off-site construction, and performance improvement, including Arashpour, Demirkesen and Al-Hussein, who have published extensively on modular manufacturing and Lean-enabled project delivery.

Figure 5 summarizes the most relevant sources, while *Figure 6* illustrates authors' publication trajectories.

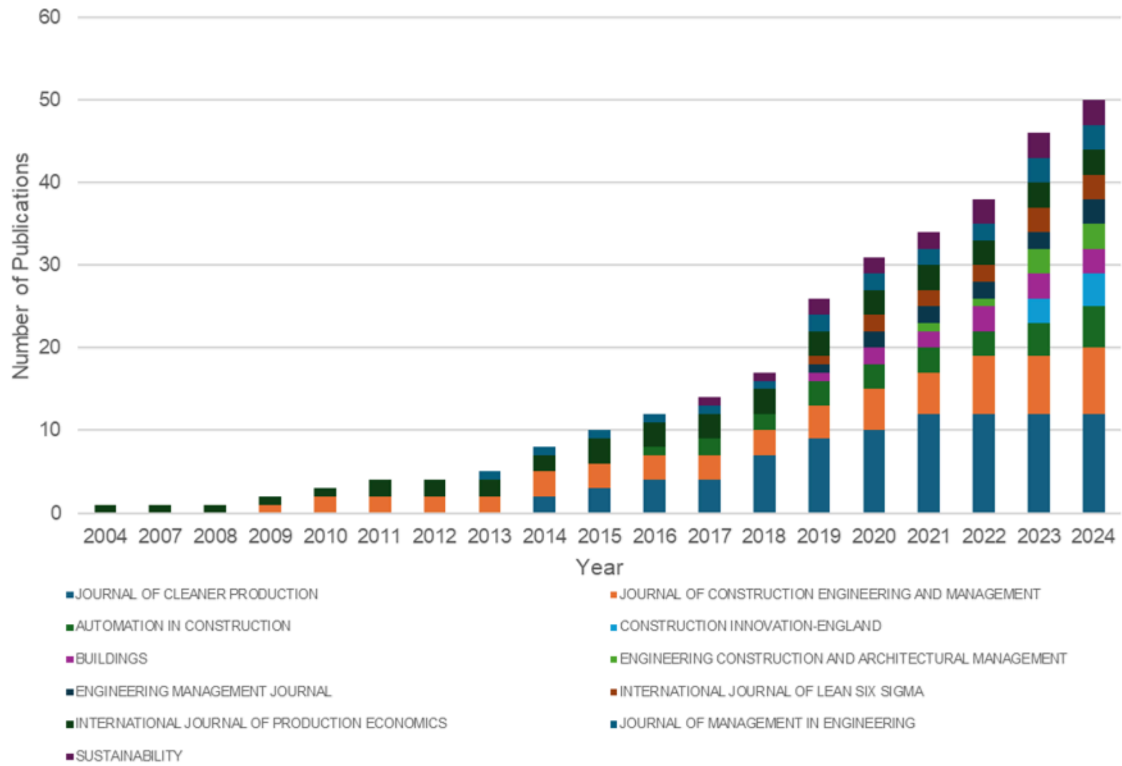

Figure 5. Number of Articles Collected by Journal

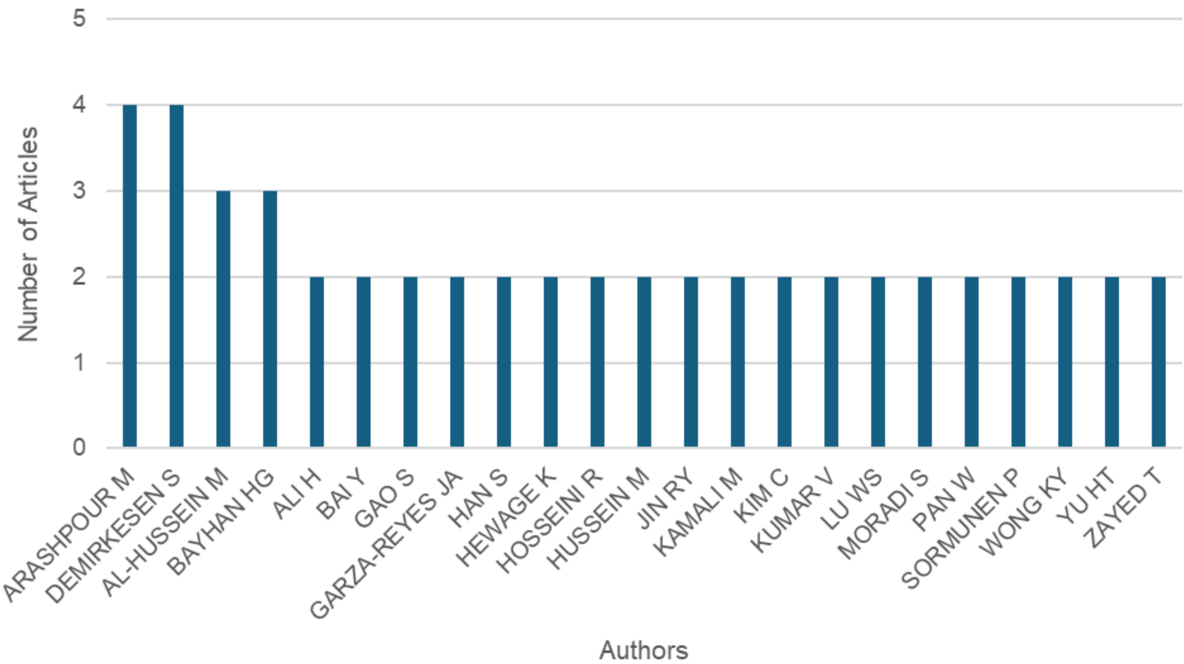

Figure 6. Frequency of Publications per Author

Lean Implementation Challenges in Modular Off-Site Construction

The core objective of this review was to examine how Lean Management principles are challenged within the two main stages of Modular Off-Site Construction (MOC): off-site manufacturing and on-site assembly. The literature shows that while modularization enables controlled production environments that should theoretically support Lean practices, significant barriers continue to restrict Lean adoption and limit sustainability outcomes. To capture these constraints comprehensively, a detailed qualitative coding analysis was conducted across all 71 selected articles. Challenges were classified into thematic categories and mapped to the MOC stage in which they primarily occur. *Figure 7* and *Figure 8* present the coding frequencies for manufacturing and assembly challenges, and *Table 1* summarizes the supporting references for each challenge category.

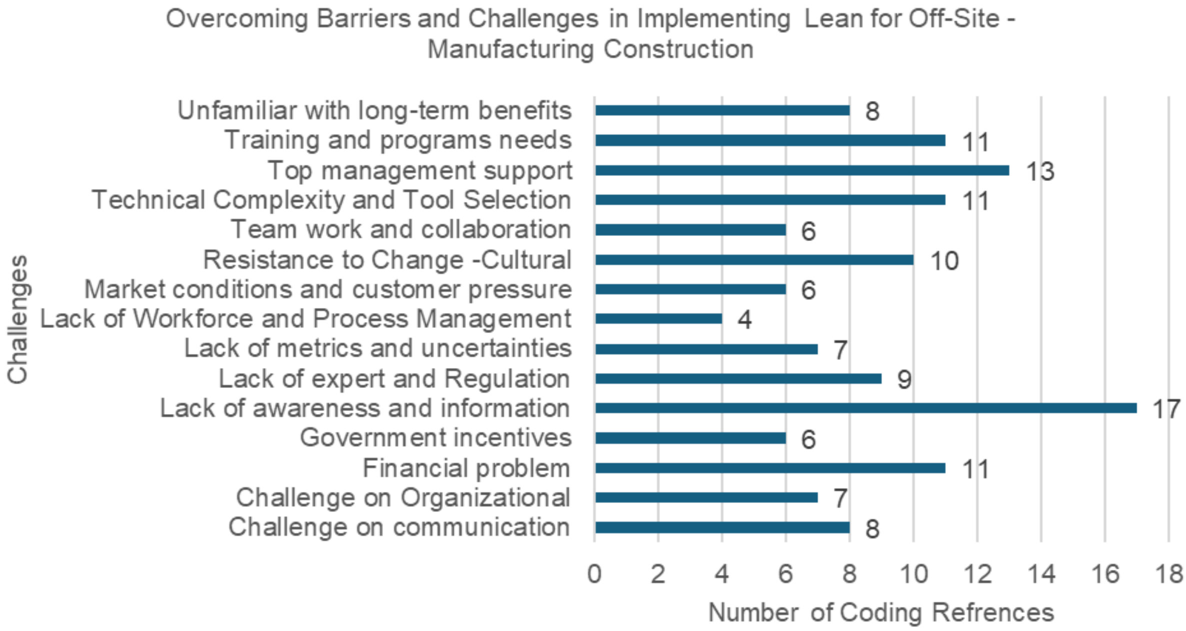

Figure 7. Lean Adoption Challenges Identified in the Off-Site Manufacturing Stage

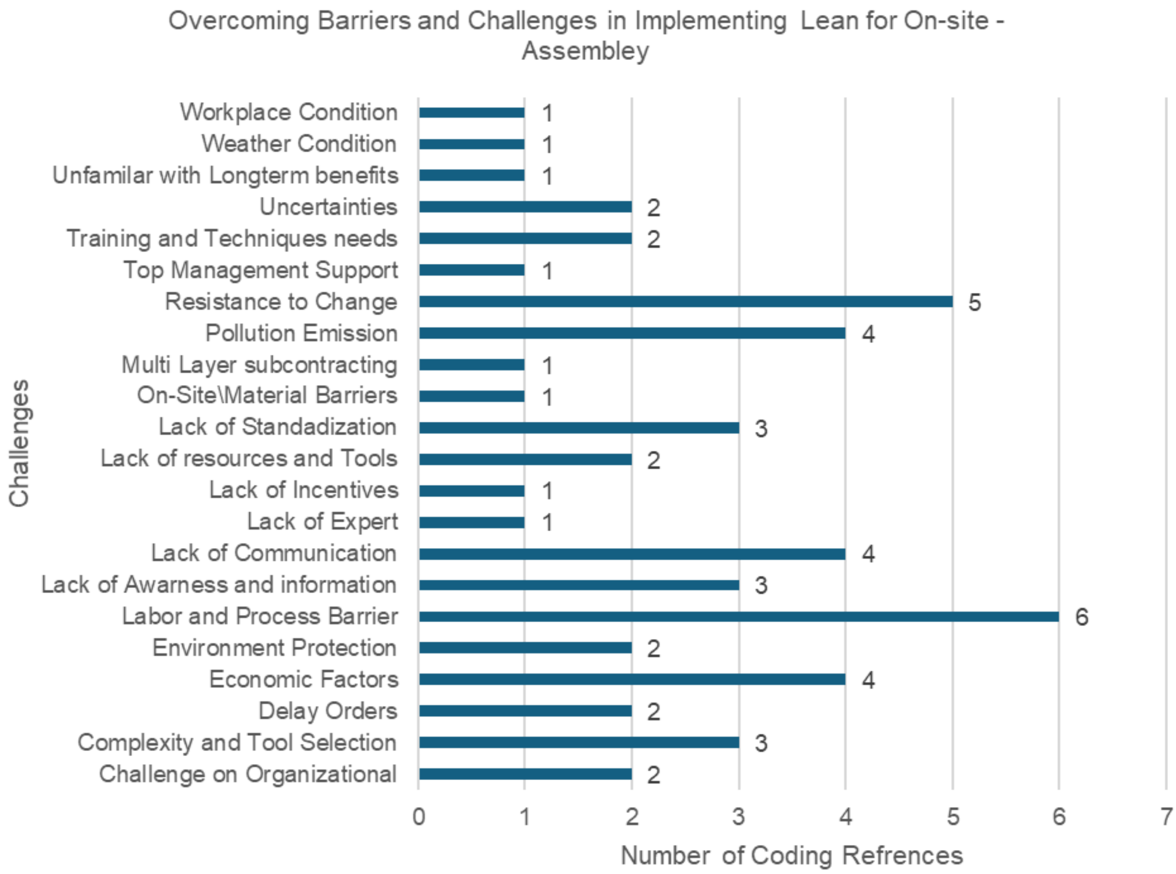

Figure 8. Lean Adoption Challenges Identified in the On-Site Assembly Stage

Table 1: Identified Barriers to Lean Management Adoption Across Modular Off-Site Construction Stages

Challenge	Category	Description	Off-site Manufacturing - Supporting Studies	On-site Assembly - Supporting Studies
Challenge in Communication	Organizational / Communication	Ineffective information flow and poor communication among stakeholders causing delays, errors, and rework. Absence of effective communication channels during on-site Lean execution.	(Ballard & Howell, 1995; Caiado et al., 2018; Demirkesen, Wachter, Oprach, & Haghsheno, 2019; Demirkesen & Bayhan, 2022; Sarhan & Fox, 2013; Singh et al., 2024; Wong & Wong, 2014a)	(Ahmed & Sobuz, 2019; Bayhan et al., 2019; Singh et al., 2024; Yuan et al., 2020)
Organizational Challenges	Organizational	Structural and managerial barriers such as unclear roles, siloed processes, and poor coordination.	(Ahmed & Sobuz, 2019; Cherrafi et al., 2016; Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019; Maware et al., 2024; Singh et al., 2024;	(Negi et al., 2024; Yuan et al., 2020)

Challenge	Category	Description	Off-site Manufacturing - Supporting Studies	On-site Assembly - Supporting Studies
			Terreno et al., 2019; Wong & Wong, 2014a)	
Financial Problems	Economic / Financial	Budget limitations, cost overruns, or insufficient financial resources to support Lean implementation.	(Bayhan et al., 2019; Cherrafi et al., 2016; Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019; Demirkesen & Bayhan, 2020, 2022; Maware et al., 2024; Moradi et al., 2022a-03-07; Salama et al., 2024; Sarhan & Fox, 2013; Singh et al., 2024; Terreno et al., 2019)	-
Government Incentives Lack	Regulatory / Institutional	Absence of supportive policies, subsidies, or government-driven incentives to adopt Lean or modular practices.	(Bayhan et al., 2019; Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019; Demirkesen & Bayhan, 2022; Jayawardana et al., 2023; Moradi & Kähkönen, 2022; Singh et al., 2024)	-
Lack of Awareness & Information	Organizational / Knowledge	Stakeholders lack understanding of Lean principles, benefits, and implementation requirements.	(Ahmed & Sobuz, 2019; Bayhan et al., 2019; Cherrafi et al., 2016; Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019; Demirkesen & Bayhan, 2020, 2022; Hussein et al., 2021; Jayawardana et al., 2023; Maqbool et al., 2019; Maware et al., 2024; Mellado & Lou, 2020; Moradi & Kähkönen, 2022; Negi et al., 2024; Pan & Pan, 2023a; Sarhan & Fox, 2013; Shah & Ward, 2007; Singh et al., 2024; Song & Liang, 2011; Terreno et al., 2019)	(Ahmed & Sobuz, 2019; Singh et al., 2024; Yuan et al., 2020)
Lack of Experts & Regulation	Workforce / Regulatory	Shortage of qualified personnel and lack of clear regulatory frameworks guiding Lean or modular adoption.	(Caiado et al., 2018; Demirkesen & Bayhan, 2020, 2022; Jayawardana et al., 2023; Maqbool et al., 2019; Maware et al., 2024; Moradi & Kähkönen, 2022; Pan & Pan, 2023b; Singh et al., 2024)	(Yuan et al., 2020)

Challenge	Category	Description	Off-site Manufacturing - Supporting Studies	On-site Assembly - Supporting Studies
Lack of Metrics & Uncertainty	Technical / Measurement	Absence of performance indicators and uncertainty in expected process outcomes.Variability in site conditions and unpredictability affecting Lean flow.	(Bayhan et al., 2019; Cherrafi et al., 2016; Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019; Pan & Pan, 2023b; Sarhan & Fox, 2013; Singh et al., 2024; Wong & Wong, 2014a)	(Mossman & Sarhan, 2021; Singh et al., 2024)
Lack of Workforce / Process Management	Workforce / Management	Ineffective planning, workforce allocation, and supervision of Lean processes.	(Ahmed & Sobuz, 2019; Caiado et al., 2018; Demirkesen & Bayhan, 2020, 2022)	-
Market Conditions / Customer Pressure	Economic / External	Limited customer acceptance and market resistance to Lean or industrialized construction.	(Ahmed & Sobuz, 2019; Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019; McDermott et al., 2023; Singh et al., 2024; Wong & Wong, 2014b)	-
Resistance to Change (Cultural)	Cultural / Organizational	Behavioral and cultural reluctance to adopt new Lean methods and eliminate traditional practices.	(Bayhan et al., 2019; Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019; Innella et al., 2019; Maware et al., 2024; Mellado & Lou, 2020; Moradi & Kähkönen, 2022; Pan & Pan, 2023b; Salama et al., 2024; Sarhan & Fox, 2013; Singh et al., 2024)	(Ahmed & Sobuz, 2019; Bayhan et al., 2019; Negi et al., 2024; Singh et al., 2024; Yuan et al., 2020)
Teamwork & Collaboration Issues	Organizational / Collaboration	Poor cross-functional cooperation leading to workflow fragmentation.	(Ahmed & Sobuz, 2019; Ballard & Howell, 2003; Demirkesen, Wachter, Oprach, & Haghsheno, 2019; Moradi & Kähkönen, 2022; Sarhan & Fox, 2013; Singh et al., 2024)	-
Technical Complexity & Tool Selection	Technical	Difficulty selecting, integrating, and standardizing Lean tools, digital systems, and technical interfaces.Additional technical challenges specific to on-site implementation of Lean tools and systems.	(Ahmed & Sobuz, 2019; Caiado et al., 2018; Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019; Demirkesen & Bayhan, 2020; Hussein et al., 2021; Maqbool et al., 2019; Mellado & Lou, 2020; Pan & Pan, 2023b; Singh et al., 2024; Terreno et al., 2019)	(Ahmed & Sobuz, 2019; Singh et al., 2024; Yuan et al., 2020)

Challenge	Category	Description	Off-site Manufacturing - Supporting Studies	On-site Assembly - Supporting Studies
Top Management Support Lack	Organizational / Leadership	Weak leadership commitment, unclear vision, and insufficient support for Lean transformation.	(Ahmed & Sobuz, 2019; Bayhan et al., 2019; Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019; Innella et al., 2019; Maware et al., 2024; Mellado & Lou, 2020; Moradi et al., 2022a-03-07; Pan & Pan, 2023b; Sarhan & Fox, 2013; Singh et al., 2024; Terreno et al., 2019; Wong & Wong, 2014b)	(Yuan et al., 2020)
Training / Programs Needed	Workforce / Skills	Need for structured Lean training, upskilling, and competency development.Need for site-specific Lean techniques and practical skills.	(Ahmed & Sobuz, 2019; Assaad et al., 2022; Demirkesen & Bayhan, 2020; Maqbool et al., 2019; Pan & Pan, 2023b; Sarhan & Fox, 2013; Singh et al., 2024; Song & Liang, 2011; Terreno et al., 2019; Wong & Wong, 2014b)	(Ahmed & Sobuz, 2019; Yuan et al., 2020)
Unfamiliar with Long-term Benefits	Cultural / Adoption	Limited awareness of long-term Lean benefits such as waste reduction and lifecycle performance.	(Aziz & Hafez, 2013; Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019; Demirkesen & Bayhan, 2020; Maware et al., 2024; Moradi et al., 2022a-03-07; Singh et al., 2024)	(Yuan et al., 2020)
Delay Orders	Operational	Late delivery or delayed instructions disrupting workflow and Lean flow.	-	(McDermott et al., 2023; Singh et al., 2024)
Economic Factors	Economic	Economic instability, inflation, or market risks affecting Lean adoption.	-	(Ahmed & Sobuz, 2019; Carvajal-Arango et al., 2019; Singh et al., 2024; Yuan et al., 2020)
Environmental Protection	Environmental	Environmental regulations and requirements related to resource efficiency, waste reduction, and minimizing environmental impacts that influence Lean adoption.	-	(Singh et al., 2024; Yuan et al., 2020)

Challenge	Category	Description	Off-site Manufacturing - Supporting Studies	On-site Assembly - Supporting Studies
Labor & Process Barriers	Workforce	Workforce resistance, lack of discipline, or incompatible on-site practices hindering Lean flow.	-	(Bayhan et al., 2019; Demirkesen, Wachter, Oprach, Haghsheno, et al., 2019; Minh et al., 2019; Negi et al., 2024; Singh et al., 2024; Yuan et al., 2020)
Lack of Incentives	Regulatory	No incentive for contractors to adopt Lean or modular systems.	-	(Yuan et al., 2020)
Lack of Resources & Tools	Operational	Insufficient tools, equipment, or supporting resources for Lean-based workflows.	-	(Singh et al., 2024; Yuan et al., 2020)
Lack of Standardization	Technical / Process	Variability in on-site procedures and component interfaces undermining Lean consistency.	-	(Ahmed & Sobuz, 2019; Negi et al., 2024; Yuan et al., 2020)
Material Barriers	Supply Chain	Challenges with material availability, compatibility, or delivery.	-	(Yuan et al., 2020)
Multi-layer Subcontracting	Organizational	Excessive subcontracting layers complicating Lean coordination and responsibility.	-	(Yuan et al., 2020)
Pollution / Emission	Environmental	Emissions, waste, and environmental impacts during on-site processes.	-	(Caldarelli et al., 2022; Carvajal-Arango et al., 2019; Cherrafi et al., 2016; Song & Liang, 2011)
Weather Conditions	Environmental	Weather-related interruptions limiting Lean continuity during installation.	-	(Yuan et al., 2020)

Challenge	Category	Description	Off-site Manufacturing - Supporting Studies	On-site Assembly - Supporting Studies
Workplace Conditions	H&S / Environment	Safety risks, ergonomic issues, and site constraints limiting Lean implementation.	-	(Yuan et al., 2020)

Challenges in Off-Site Manufacturing

Off-site manufacturing exhibits the highest concentration of Lean-related constraints in literature. The most frequently coded challenges include lack of awareness and information, resistance to change, training and skills gaps, technical complexity, and financial pressures. Lack of awareness and insufficient understanding of Lean concepts is the most frequently identified barrier, with extensive support across studies such as Song (2011), Terreno et al. (2019), Cherrafi et al. (2016). These studies highlight that many modular manufacturers lack structured processes, Lean metrics, or standardized methods for continuous improvement, leading to inconsistent workflows and low process transparency.

Resistance to organizational or cultural change is another widespread challenge (Innella et al., 2019; Mellado & Lou, 2020; Pan & Pan, 2023b).These studies emphasize that organizations transitioning from traditional construction to modular workflows face entrenched habits, reluctance to redesign processes, and limited buy-in for Lean-based interventions.

Skills and training challenges are consistently reported (Demirkesen & Bayhan, 2022; Mellado & Lou, 2020; Song & Liang, 2011). These limitations reduce the effective use of Lean tools such as takt planning, value stream mapping (VSM), and continuous improvement cycles. The modular workforce often lacks experience with production-line thinking, contributing to workflow variability and inefficiencies.

The implementation of Lean tools in modular factories is further constrained by technical complexity in production lines, uncertain processes, and challenges in selecting appropriate Lean methods. This barrier is reported across multiple studies (Caiado et al., 2018). Problems include difficulty integrating pull systems, selecting suitable visual management methods, and adapting Lean tools to high-customization modular projects.

Organizational fragmentation (Demirkesen & Bayhan, 2022; Terreno et al., 2019) and financial pressures (Moradi & Kähkönen, 2022; Terreno et al., 2019) further limit Lean uptake. Several studies highlight market pressures, unstable demand, and customer-driven variability as drivers of production instability (Ahmed & Sobuz, 2019; McDermott et al., 2023; Wong & Wong, 2014b) Overall, manufacturing-stage challenges primarily concern organizational readiness, cultural resistance, workforce capability, and technical barriers related to modular production system design. These constraints collectively restrict Lean's effectiveness in creating stable, predictable off-site production flows.

Challenges in On-Site Assembly

On-site assembly operates in a more uncertain and variable environment compared to factory settings. The literature identifies several assembly-specific challenges that hinder Lean implementation, with the most prominent being labor and process barriers, resistance to change, lack of awareness, lack of standardization, and environmental or site-related constraints.

Labor coordination, sequencing issues, and unfamiliarity with modular installation techniques are frequently cited (Demirkesen & Bayhan, 2022; Yuan et al., 2020).These challenges create bottlenecks in assembly workflows, reduce takt reliability, and increase rework, making it difficult to sustain Lean principles such as continuous flow and waste minimization.

Resistance to change also presents a significant barrier on the assembly side, particularly among site crews who may prefer traditional construction methods. This issue is highlighted by Yuan et al. (2020), Negi et al. (2024) and Singh et al. (2024), who note that Lean-standardized workflows developed in the factory often do not translate smoothly to the site due to entrenched practices and limited engagement.

Limited understanding of Lean installation practices and lack of standardized assembly procedures are common barriers (Singh et al., 2024). Additionally, communication issues between factory and site teams contribute to delays and errors during installation (Singh et al., 2024; Yuan et al., 2020).

Environmental conditions, including weather impacts, site access limitations, and pollution further complicate Lean implementation (Caldarelli et al., 2022; Song & Liang, 2011). These conditions introduce variability that directly affects standardization and flow-based planning.

Sustainability Findings in Modular Off-Site Construction

Sustainability is a central theme in both the Lean and modular construction domains; however, the extent to which the three dimensions of Sustainable Development (economic, environmental, and social) are represented in existing research varies considerably. To better understand these patterns, all 71 selected articles were coded according to the Triple Bottom Line (TBL) framework. The distribution of sustainability themes is shown in *Figure 9*, highlighting the relative emphasis each dimension receives within literature.

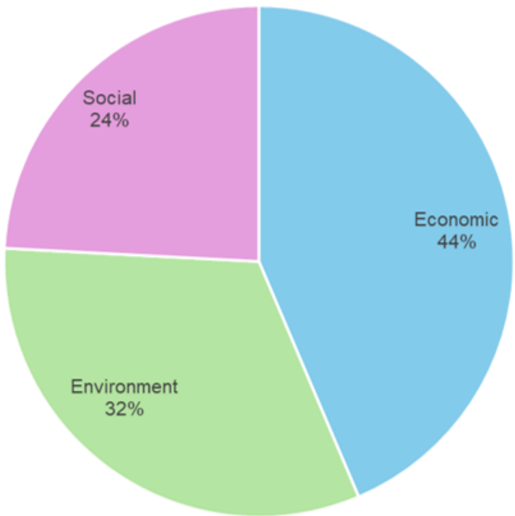

Figure 9. Distribution of Sustainability Dimensions Addressed in the Reviewed Literature (Economic, Environmental, and Social)

Economic sustainability is the most frequently addressed dimension, comprising 44% of coded references. As in previous Lean construction reviews (Carvajal-Arango et al., 2019), literature prioritizes productivity, cost reduction, schedule reliability, and waste minimization benefits that align closely with Lean practices such as takt planning and continuous improvement. This emphasis reflects industry priorities around efficiency and cost competitiveness, particularly given the high initial investment and market pressures associated with MOC.

Environmental sustainability accounts for 32% of findings, with studies focusing on waste reduction, embodied carbon, energy performance, and transport-related emissions. MOC inherently reduces material waste and site disturbance through factory precision and standardization, and these benefits can be strengthened through Lean tools that stabilize processes. However, environmental gains are often treated as secondary outcomes of efficiency rather than explicit sustainability targets (Kamali et al., 2018).

Social sustainability is the least represented dimension, at only 24%, echoing patterns noted in prior literature (Hussein & Zayed, 2021). Although modular factories can improve ergonomics, safety, and working conditions, social issues such as training, upskilling, cultural resistance, and labor transitions between factory and site environments remain underexplored. This gap is noteworthy, given Lean's emphasis on respect for people and workforce empowerment.

Overall, the TBL distribution reveals three insights:

- economic considerations dominate Lean–MOC research.
- environmental aspects receive moderate but indirect attention; and
- social sustainability is significantly understudied. Moreover, no existing work differentiates sustainability outcomes across off-site manufacturing and on-site assembly, underscoring the need for stage-specific frameworks.

These findings underscore the need for a more balanced and holistic framework linking Lean practices with sustainability outcomes across the full MOC lifecycle. This gap motivates the stage-specific Lean Taxonomy introduced in next section.

Discussion

This discussion synthesizes the findings from the systematic review and positions them within the broader body of Lean and modular construction literature. The goal is to interpret how Lean principles interact with the unique characteristics of Modular Off-Site Construction (MOC), how stage-dependent challenges restrict sustainability outcomes, and how the proposed taxonomy advances current theoretical and practical understanding. Consistent with prior reviews in Lean-sustainability research (e.g., Carvajal-Arango et al., 2019; Hussein & Zayed, 2021), this discussion emphasizes conceptual relationships rather than repeating descriptive statistics presented earlier.

Lean Implementation in Off-Site Manufacturing: Interpretation Through Literature

Prefabricated construction introduces demanding managerial and production requirements that traditional construction management practices cannot fully accommodate. Lean principles have long been recognized as theoretically compatible with prefabrication due to their shared emphasis on waste reduction, flow improvement, and value generation. Numerous studies highlight substantial economic benefits derived from Lean in modular manufacturing including productivity increases, reduced lead times, minimized waste, and higher throughput (Innella et al., 2019; Nahmens & Ikuma, 2012).However, the present review reveals that achieving these benefits in practice remains challenging, as shown in *Figure 10*.

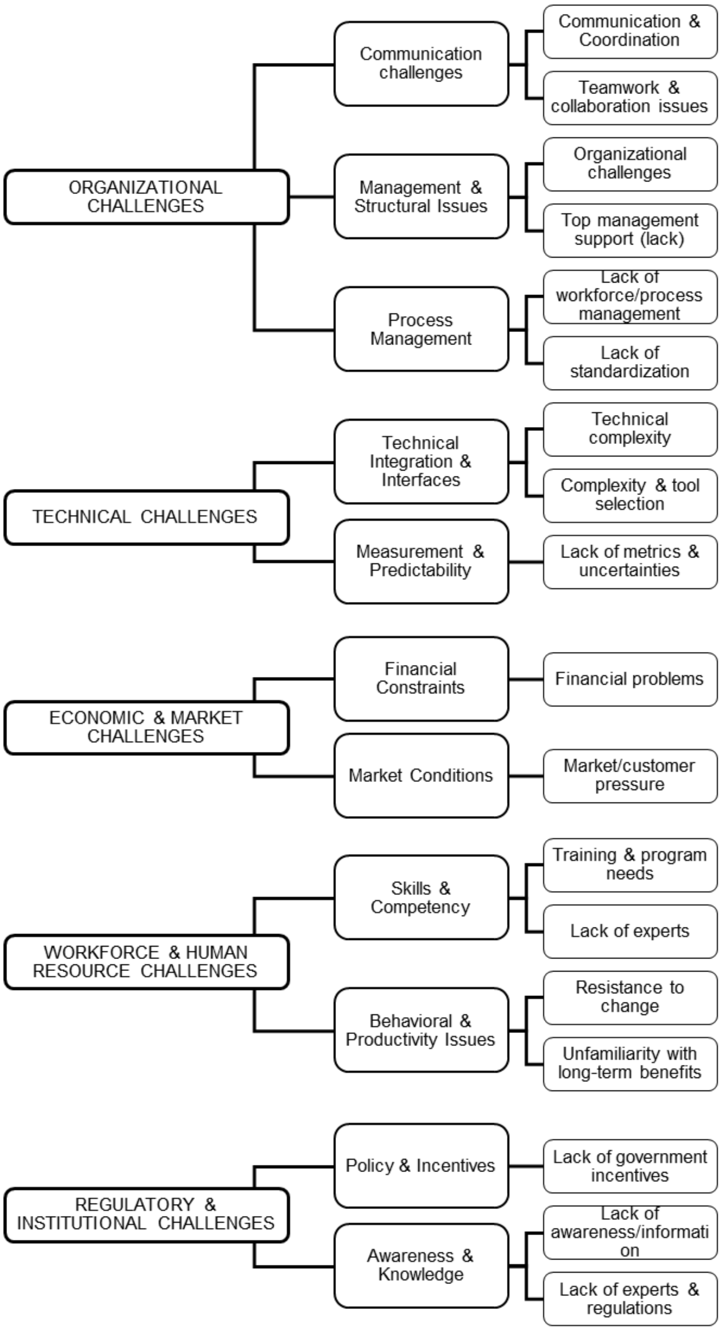

Figure 10. Taxonomy of Barriers to Lean Adoption Across Manufacturing Stage of MOC

Organizational and cultural barriers remain prominent. Studies such as Sarhan and Fox, (2013), Caiado et al. (2018), and Cherrafi et al. (2016) demonstrate that without strong managerial commitment, shared understanding, and cultural readiness, Lean tools lose effectiveness. In modular factories, these issues manifest as inconsistent training, fragmented communication, and limited standardization factors also identified by Demirkesen and Bayhan (2022) and Mellado et al. (2020). These findings support the argument that cultural and behavioral readiness remains a foundational requirement for Lean adoption, even in controlled manufacturing environments where Lean would theoretically excel.

Technical integration also plays a central role. Challenges such as system complexity, tool selection, and interface coordination (Wong & Wong, 2014a) restrict modular factories from achieving stable workflows a core Lean objective. This aligns with Martínez-Jurado and Moyano-Fuentes, (2014) who warn that certain Lean tools, such as JIT, can introduce vulnerabilities if supply chain or production interfaces are unstable.

A major insight from this review, extending beyond prior Lean–construction studies, is that Lean's success in off-site manufacturing is not automatic, despite environmental conditions being favorable for Lean. The combination of organizational immaturity, cultural resistance, and technical inconsistencies undermines Lean's potential and directly weakens sustainability outcomes. This nuance absent in prior reviews demonstrates that modular factories require tailored Lean frameworks rather than direct transfer of manufacturing-based Lean models.

Lean Implementation in On-Site Assembly: Constraints in a Variable Environment

In contrast to the controlled nature of modular factories, on-site assembly is defined by variability, resource fragmentation, and environmental unpredictability. These conditions introduce unique challenges that differ substantially from those in manufacturing, as reflected in *Figure 11*.This distinction is rarely made in prior Lean or modular construction reviews, representing a key conceptual contribution of this work. The assembly stage exhibits challenge similar to those of conventional construction, as activities are performed on-site. However, the required competencies and skill sets differ, as trades must possess specialized knowledge for modular installation, and expert personnel are needed to effectively implement Lean construction principles on-site.

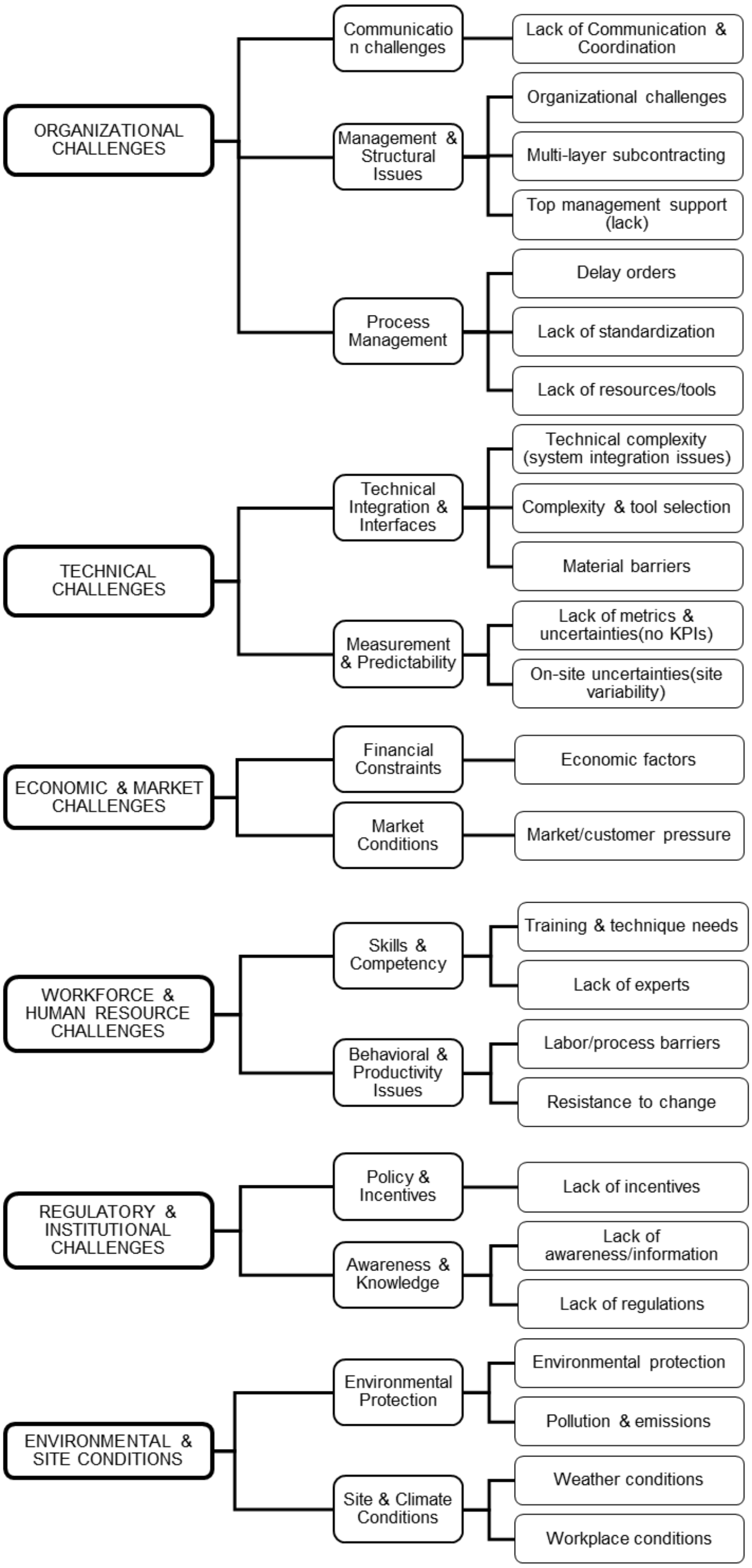

Figure 11. Taxonomy of Barriers to Lean Adoption Across On-site Stage of MOC

Communication and coordination issues represent some of the most critical assembly challenges, consistent with findings in (Ahmed & Sobuz, 2019; Yuan et al., 2020). Unlike factory settings, modular assembly involves subcontractors with diverse capabilities, inconsistent work rhythms, and dependencies between trades. These characteristics inhibit the reliable flow that Lean requires. Negi et al. (2024) similarly note that misaligned production assembly interfaces disrupt synchronization and create waste, supporting this study's stage-based interpretation.

Environmental and site conditions such as weather, accessibility constraints, and site-specific variability further limit the applicability of Lean in assembly. Martínez-Jurado and Moyano-Fuentes (2014) emphasize that while JIT can improve production flow, it can also increase environmental and logistical burdens when applied in unstable environments. These insights explain why Lean benefits achieved in manufacturing rarely transfer seamlessly to assembly.

Workforce and skills-related issues amplify assembly-stage instability. Studies such as Khaw et al. (2022) and Singh et al. (2024) highlight that workers at the assembly stage often lack modular-specific competencies, leading to rework, installation delays, and inconsistent adherence to standardized processes. These findings align with Demirkesen and Bayhan (2020), who note that MOC differs significantly from traditional manufacturing due to its variability, dynamic stakeholder interactions, and site constraints.

The review's findings suggest a major theoretical contribution: the assembly stage is the primary bottleneck in Lean–MOC integration, not manufacturing. This contrasts with earlier studies, which treated Lean challenges generically and did not consider stage-specific differences. Recognizing assembly as the critical constraint point helps explain why Lean–sustainability integration remains limited in practice.

Linking Lean Challenges to Sustainability Performance

A notable contribution of this review is its integration of Lean challenges with sustainability performance across the Triple Bottom Line. Prior research identifies strong economic and environmental synergies between Lean and sustainability (Goh & Goh, 2019; Kamali et al., 2018), yet often treats these synergies conceptually. This study shows empirically how stage-specific Lean barriers directly restrict sustainability outcomes.

Economic performance is undermined by manufacturing issues such as lack of workflow stability, inadequate training, and technical complexity contradicting the well-documented productivity benefits of Lean (Innella et al., 2019). Assembly issues such as rework, delays, and coordination breakdowns further increase cost variability. These findings confirm Kamali et al.'s (2018) argument that economic sustainability is the most accessible but also the most vulnerable dimension when operational inefficiencies persist.

Environmental gains achieved in manufacturing such as waste reduction and precision are weakened by assembly disruptions. Rework, improper handling, and site inefficiencies introduce emissions and waste that offset factory-level environmental benefits. This mirror concerns raised by Martínez-Jurado and Moyano-Fuentes (2014), who noted that supply chain instability can compromise environmental outcomes even when Lean tools are applied correctly.

Consistent with Hussein and Zayed (2021) and Kamali et al. (2018), this review finds that social sustainability remains the least developed TBL dimension. Training gaps, resistance to change, labor/process barriers, and ergonomics concerns limit Lean's "respect for people" philosophy in both manufacturing and assembly. Scholars such as Gbadamosi et al., (2019) argue that integrating human-centered design with Lean could strengthen social sustainability a direction supported by the present findings.

The primary theoretical and practical contribution of this study lies in its stage-based taxonomy of Lean challenges. Prior frameworks classify Lean barriers broadly but do not differentiate between off-site and on-site contexts (e.g., Demirkesen & Bayhan, 2022). The proposed taxonomy introduces four major contributions: Clear distinction between manufacturing and assembly challenges, Integration of organizational, technical, workforce, regulatory, and environmental issues, Direct mapping to sustainability outcomes, Alignment with the digitalization agenda.

Conclusion

Lean management and modular off-site construction (MOC) emerge from different historical and industrial traditions, yet both philosophies share a common objective: improving efficiency, reducing waste, and delivering greater value throughout construction processes. The findings of this review confirm that Lean and MOC are conceptually compatible and, when effectively integrated, can generate substantial economic, environmental, and social benefits. As observed in previous studies, Lean contributes to reduced waste, improved flow, enhanced productivity, and higher quality, while modularization enables standardization, precision, and safer working environments. However, despite these synergies, the practical integration of Lean and sustainability within modular construction remains inconsistent and highly dependent on contextual and stage-specific conditions. A central insight from this research is that Lean implementation does not occur uniformly across the modular construction lifecycle. Instead, challenges differ significantly between off-site manufacturing and on-site assembly, each presenting distinct technical, organizational, and operational constraints. Off-site manufacturing benefits from controlled environments but is hindered by limited Lean awareness, cultural resistance, inconsistent training, and technical integration issues. Conversely, on-site assembly remains vulnerable to coordination complexity, site variability, subcontractor fragmentation, and environmental conditions. These differences demonstrate that Lean principles cannot simply be transferred from manufacturing to construction; they require stage-based adaptation aligned with modular workflows and constraints. This study's most significant contribution is the development of a stage-based Lean–Sustainability Taxonomy, which classifies Lean-related barriers at each modular stage and links them to sustainability implications across the Triple Bottom Line. Economic benefits remain the most prominent in the literature, while environmental advantages are recognized but less frequently measured. Social sustainability continues to be the least addressed dimension, echoing earlier.

By explicitly mapping Lean constraints to sustainability outcomes, this research provides a clearer foundation for understanding why sustainability gains often fail to materialize consistently across modular projects. Moreover, the taxonomy highlights digitalization as a cross-stage enabler. Studies emphasize the need for Manufacturing Execution and Control (MEC) systems, BIM-enabled coordination, and simulation tools to support Lean decision-making. The taxonomy identifies where such technologies can mitigate bottlenecks, especially at the assembly stage where uncertainty is highest. This integration of Lean, sustainability, and digitalization aligns with the emerging trajectory of industrialized construction research.

Nonetheless, several gaps remain. First, although the literature widely acknowledges the potential of Lean to support sustainability, empirical evidence linking specific Lean tools to social sustainability outcomes is limited. Worker well-being, ergonomics, communication quality, and job satisfaction central elements of Lean's "respect for people" principle are still underexplored in modular contexts. Second, the environmental impacts of certain Lean practices, such as JIT logistics, require more nuanced assessment, as they may inadvertently increase emissions if not carefully managed. Third, a more standardized approach to measuring sustainability across modular projects is necessary, as existing assessments employ heterogeneous indicators that complicate comparison and synthesis. Despite these limitations, the review provides a structured and theoretically grounded perspective on how Lean can support sustainability within MOC, while also clarifying the barriers that must be addressed to unlock its full potential. By offering a taxonomy that integrates Lean principles, system constraints, sustainability considerations, and digital enablers, this research contributes a practical and conceptual foundation for improving modular construction performance.

Ultimately, Lean and modular construction share strong potential synergies, but their integration must be guided by a deeper understanding of stage-specific constraints, human and organizational factors, and the need for digital support systems. Future research should prioritize empirical validation of the taxonomy, develop social sustainability metrics relevant to modular environments, and explore how digital Lean strategies can bridge gaps between factory and site. Addressing these areas will help advance a more holistic, sustainable, and resilient model for industrialized construction.

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