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Evolution of Technological Integration in Lean Construction: A Systematic Literature Review on Waste Elimination and Value Generation

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Abstract: The construction industry continues to experience a persistent productivity gap compared to manufacturing, largely due to fragmented workflows, high variability, and systemic waste. Lean Construction (LC), derived from the Toyota Production System, was introduced to address these challenges by emphasizing waste elimination, continuous improvement, value generation, and respect for people. However, the effectiveness of lean implementation has been constrained by the limited capability of traditional, manually driven lean tools to manage the complexity of modern construction projects. This study presents a systematic literature review investigating the evolution of technological integration in Lean Construction and its role in operationalizing lean principles for waste elimination and value creation. Peer-reviewed publications published between 1992 and 2025 were analyzed and classified into four technological evolution phases: Stabilization (1990s), Collaboration (2000s), Flow and Integration (2010s), and Lean 4.0 and Intelligence (2020s). The findings reveal that digital technologies progressively transform lean philosophy from a conceptual framework into a data-driven production system. Technologies such as BIM, cloud platforms, sensing systems, artificial intelligence, and digital twins enhance real-time visibility, standardized work, continuous flow, and predictive control, while systematically addressing the Eight Wastes (TIMWOODS). Technological integration shifts Lean Construction from reactive management toward proactive, system-level optimization. Despite these advancements, barriers including cultural resistance, high implementation costs, workforce skill gaps, and regulatory limitations persist, particularly in developing economies. This review contributes to theory and practice by mapping the historical trajectory of lean–technology integration and identifying future research directions for technology- enabled waste elimination and value generation in construction.

Key Words: Lean Construction; Digital Technologies; Technological Integration; Waste Elimination; Value Generation; Lean 4.0; Systematic Literature Review.

Objectives: The objective of this study is to systematically review the evolution of technological integration in Lean Construction from 1992 to 2025. The study aims to classify this evolution into distinct technological phases and examine how digital technologies operationalize core Lean Construction principles, particularly waste elimination and value generation. In addition, it investigates how technology-enabled lean practices address the Eight Wastes (TIMWOODS) framework and identifies key benefits, challenges, and research gaps associated with implementing technology-driven Lean Construction in contemporary construction practice.

1-Introduction

The construction industry is a fundamental driver of economic growth and infrastructure development worldwide; however, it has consistently underperformed in terms of productivity when compared with manufacturing and other production- oriented sectors. While manufacturing has achieved substantial productivity gains through standardization, automation, and data-driven production systems, construction productivity it has remained stagnant or has declined in many regions (Egan, 1998; Koskela, 1992). This productivity gap is widely attributed to fragmented workflows, high variability, poor coordination among stakeholders, and the prevalence of non-value-adding activities across construction processes. These inefficiencies manifest in persistent project delivery challenges, including cost overruns, schedule delays, quality defects, safety incidents, and excessive waste of materials and labor. Traditional construction management approaches primarily focus on activity-level control, contractual compliance, and short-term cost optimization. Such approaches often fail to address construction as an integrated production system characterized by complex interdependencies, uncertainty, and weak information flows, particularly in large and complex projects(Flyvbjergetal.,2003). Lean Construction (LC) emerged as an alternative production management philosophy that conceptualizes construction as a value-generating production system rather than a collection of isolated

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tasks. Derived from the Toyota Production System, Lean Construction emphasizes waste elimination, continuous improvement, value generation from the client's perspective, and respect for people (Ohno, 1988; Womack&Jones,1996). Despite demonstrated benefits, the implementation of Lean Construction has often been constrained by the limited capability of traditional, manually driven lean tools to cope with the increasing complexity and information demands of contemporary construction projects. Recent advancements in digital technologies have created new opportunities to enhance Lean Construction implementation by enabling real-time data capture, improved visualization, enhanced collaboration, and system-level optimization. Technologies such as Building Information Modeling (BIM), cloud-based platforms, sensing technologies, artificial intelligence, and digital twins are increasingly being integrated with lean practices. However, existing research largely examines these technologies individually, offering limited understanding of how technological integration systematically reinforces lean principles over time. Accordingly, this study presents a systematic literature review examining the evolution of technological integration in Lean Construction from 1992to2025. The study aims to classify major phases of lean–technology evolution and to analyze how digital technologies operationalize lean principles to support waste elimination and value generation in construction.

2. Literature Review

2.1 Lean Construction Theory and Principles

Lean Construction originates from the Toyota Production System, which redefined production as a system focused on value creation, waste elimination, continuous improvement, and respect for people (Ohno, 1988; Womack & Jones, 1996). The transfer of lean thinking from manufacturing to construction was formalized by Koskela (1992), who introduced the Transformation– Flow–Value (TFV) theory. Unlike traditional construction management approaches that view production solely as the transformation of inputs into outputs, TFV emphasizes workflow reliability and value generation as equally critical dimensions. Within the lean framework, waste is not limited to material loss but includes any activity that does not add value from the client's perspective. Waste in construction is commonly categorized using the Eight Wastes (TIMWOODS) framework: Transportation, Inventory, Motion, Waiting, Overproduction, Over processing, Defects, and non-utilized skills or talent (Ohno, 1988). These wastes are pervasive in construction projects and contribute significantly to productivity losses, cost overruns, and environmental impacts. The operationalization of lean principles in construction has been supported by tools such as the Last Planner System (LPS), pull planning, take-time planning, and continuous improvement cycles. These tools aim to improve planning reliability, reduce variability, and foster collaboration among project participants (Ballard,2000; Ballard&Howell,2003). However, early lean implementations relied heavily on manual data collection and paper-based reporting, which limited scalability, transparency, and real-time learning.

2.2 Limitations of Traditional Lean Implementation

Despite its conceptual strengths, Lean Construction has faced significant implementation challenges in practice. Traditional lean tools often depend on periodic meetings, manual constraint tracking, and subjective performance assessment. Such approaches are insufficient for managing the complexity, uncertainty, and dynamic nature of modern construction projects, particularly large-scale and infrastructure projects (Sacks et al., 2010). The reliance on delayed feedback restricts the ability of project teams to identify deviations early and respond proactively. Consequently, lean practices frequently become reactive rather than preventive, undermining core principles such as continuous flow, error proofing, and system-level optimization. These limitations have led researchers to recognize the need for technological enablers to support lean implementation more effectively.

2.3 Technological Integration in Lean Construction

The integration of digital technologies with Lean Construction has evolved progressively over the past three decades. Early adoption focused on basic digital tools such as spreadsheets and scheduling software to stabilize planning and control processes. These tools enabled data-driven tracking of planning reliability metrics such as Percent Plan Complete (PPC), marking an initial shift from intuition-based to evidence-based decision-making (Ballard & Howell, 2003). The introduction of Building Information Modeling (BIM) represented a significant milestone in lean–technology integration. BIM enabled enhanced visualization, automated clash detection, and multidisciplinary coordination, thereby reducing design-related rework and waste (Eastmanetal.,2011; Sacks et al., 2010). Cloud-based collaboration platforms further supported lean objectives by centralizing project information and reducing waiting and over-processing waste associated with fragmented

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communication (Dave et al., 2013). Subsequent technological advancements, including 4D/5D BIM, sensing technologies, drones, RFID, and automated site monitoring, enhanced real-time visibility of construction processes and enabled tighter integration between design, planning, and execution. These technologies supported key lean principles such as continuous flow, Just-In-Time delivery, visualization, and error proofing by providing timely and accurate production data.

2.4 Lean4.0andIntelligentProduction Systems

More recently, Lean Construction has entered the era of Lean 4.0, characterized by the convergence of lean principles with Industry 4.0 technologies such as artificial intelligence, digital twins, robotics, and predictive analytics. AI-driven systems enable proactive identification of schedule risks, resource bottle necks, and quality issues, shifting lean implementation from reactive learning to predictive waste prevention (Moradi & Arashpour, 2023). Digital twins establish real-time, bidirectional data exchange between physical construction site and virtual models, allowing system-level optimization and informed decision-making (Sacks et al., 2020). These technologies extend lean principles beyond process improvement toward intelligent, adaptive, and autonomous production systems. However, their adoption remains uneven, with barriers including high implementation costs, workforce skill gaps, cultural resistance, and regulatory constraints, particularly in developing economies.

2.5 Research Gaps

Although prior studies have examined various digital tools and technologies in the context of Lean Construction, most research focuses on individual technologies or isolated applications. There is limited systematic synthesis that traces the historical evolution of lean–technology integration and explicitly analyzes how technological advancements reinforce core lean principles and address the Eight Wastes(TIMWOODS)frame work overtime. This gap highlights the need for a comprehensive, phase-based review that connects technological evolution with lean philosophy, waste elimination, and value generation.

3-Methodology

This study adopts a systematic literature review methodology to examine the evolution of technological integration in Lean Construction and its role in waste elimination and value generation. A systematic approach was selected to ensure methodological rigor, transparency, and reproducibility, and to provide a comprehensive synthesis of peer-reviewed research on lean–technology integration in the construction industry. The review covers publications from 1992 to 2025, corresponding to the emergence of Lean Construction theory and its subsequent technological evolution. A comprehensive search was conducted using major academic databases widely recognized in construction management research, including Scopus, Web of Science, ScienceDirect, ASCE Library, and Taylor& Francis Online. The search strategy employed combinations of keywords related to Lean Construction and digital technologies, such as "Lean Construction, lean production, waste elimination, value generation, Building Information Modeling(BIM), digital technologies," "Industry 4.0," "artificial intelligence," and "digital twins." The search was limited to peer-reviewed journal articles published in English to ensure academic quality and consistency. Clear inclusion and exclusion criteria were applied to select relevant studies. Articles were included if they explicitly addressed Lean Construction principles and examined the application or integration of digital or emerging technologies in construction, with reported implications for waste reduction, value generation, workflow reliability, or production performance. Studies focusing solely on manufacturing or non- construction industries, addressing technology adoption without reference to lean principles, or lacking sufficient methodological or conceptual detail were excluded. Duplicate records were removed, followed by a two-stage screening process involving title-and-abstract review and full-text assessment to ensure alignment with the study objectives. Relevant information was systematically extracted from the selected studies, including publication year, research focus, type of technology, lean principles addressed, and reported outcomes. To enable structured analysis, the literature was classified into four technological evolution phases: Stabilization(1990s), Collaboration (2000s), Flow and Integration (2010s), and Lean 4.0 and Intelligence (2020s). Each study was analyzed to examine how technological tools operationalize core Lean Construction principles such as waste elimination, value generation, continuous improvement, standardized work, respect for people, continuous flow, visualization, and error proofing and how these impacts align with the Eight Wastes (TIMWOODS) framework. To enhance validity and reliability, findings were triangulated across multiple sources and evaluated against established Lean Construction theories. Cross-phase comparisons were conducted to examine how similar lean principles were enabled by different technologies over time. Only studies supported by empirical evidence or wellestablished theoretical arguments were included in the synthesis, ensuring methodological rigor consistent with the expectations of high-quality construction management journals.

4. Results and Findings

The systematic literature review reveals a clear and progressive evolution in the integration of digital technologies with Lean Construction principles over the period 1992–2025. The reviewed studies consistently demonstrate that technological integration strengthens the practical implementation of lean philosophy by enabling data-driven planning, enhanced collaboration, continuous flow, and predictive control. Based on the synthesis of the selected literature, the evolution of lean–technology integration is classified into four distinct phases: Stabilization, Collaboration, Flow and Integration, and Lean4.0 and Intelligence. Each phase is characterized by dominant technologies, specific lean functions, and distinct impacts on waste elimination and value generation.

4.1 Phase1: Stabilization(1990s–Early2000s)

The Stabilization phase represents the initial digitization of Lean Construction practices. During this period, basic digital tools such as spreadsheets, databases, and CPM scheduling software were used to support planning reliability, documentations, and baseline scheduling. These tools primarily enabled the measurement and standardization of lean practices rather than real-time optimization.

Table1Digital tools and lean impacts during the Stabilization phase

Tech-Tool	Function	Impact
Excel Databases	(Tracking PPC) and Variance Analysis.	Continuous Improvement: Established the First data-driven feedback loops for learning from failure.
CPM Software (MS Project/Primavera)	Creating the Master Schedule that feeds into Phase/ Pulb Planning.	Standardized Work: Created a predictable baseline for all trades to align their work.
Digital Document Management	Transitioning from physical blue prints to a digital Single Source of Truth.	Waste Reduction: Drastically reduced Waiting and Defects caused by outdated drawings.

The findings indicate that spreadsheets enabled systematic tracking of Last Planner System commitments, transforming Percent Plan Complete (PPC) from anecdotal reporting into measurable performance data. CPM software provided standardized master schedules that supported trade coordination and reduced variability. Digital document management systems reduced waiting and defect waste by minimizing reliance on outdated drawings. Although these tools relied on manual data input and lacked real-time responsiveness, they established the foundation for data-informed continuous improvement and standardized work in Lean Construction.

4.2 Phase2: Collaboration(2000s)

The Collaboration phase marked a significant shift toward multidisciplinary coordination and shared information environments. The introduction of Building Information Modeling (BIM), cloud-based collaboration platforms, and mobile technologies enabled lean practices to extend beyond planning into design coordination and real-time communication.

Table2 Collaborative technologies and lean impacts during the Collaboration phase

Tech-Tool	Function	Impact
BIM	TVD and automated Clash Detection.	Value Generation: Maximized value by Resolving errors in the virtual world before the actual work starts.
Cloud Collaboration Platforms	Digitalizing the LPS (Touch plan, v Planner).	Respect for People: Empowered "Last Planners"(foremen)to update their own plans in real-time.
Laser Scanning(LiDAR)	As-builtverificationand Comparing site data to The BIM model.	Error Proofing (Poka-Yoke):Identifies defects immediately, preventing the waste of Rework.

The literature shows that BIM-supported practices such as Target Value Design and automated clash detection significantly reduced design-related rework and enhanced value generation by resolving conflicts in the virtual environment. Cloud-based platforms centralized project information, reducing waiting and over-processing waste caused by fragmented communication. Mobile technologies empowered frontline supervisors to update plans and constraints in real time, reinforcing the lean principle of respect for people and enabling more effective Gemba Walks. This phase reflects a cultural shift in lean implementation, where transparency, collaboration, and decentralized decision-making became central.

4.3 Phase3: Flow and Integration (2010s)

The Flow and Integration phase is characterized by the embedding of lean principles directly into construction workflows through real-time data capture and system integration. Technologies such as 4D/5D BIM, IoT sensors, drones, RFID, and laser scanning enabled tighter coordination between design, planning, and site execution.

Table3Flow-orientedtechnologiesandleanimpactsduringtheFlowandIntegrationphase

Tech-Tool	Function	Impact on Lean
4D/5D Modeling	Integrating Time(4D)and Cost (5D) into BIM for Takt-time planning.	Continuous Flow: Allowed trades to move through the Building like an assembly line without overlapping.
IoT & RFID Sensors	E-Kanban systems for tracking Material from the factory to the point of use.	Just-In-Time(JIT): Eliminated the waste of Inventory and Transportation.
Drones& 360° Cameras	Automated site monitoring and Progress tracking(OpenSpace).	Gemba Walks: Enhanced the "Go and See" principle With 100% site visibility from any location.

The findings indicate that 4D/5D BIM enabled takt-time planning and synchronized trade movement, supporting continuous flow and reducing work overlap. RFID and IoT technologies facilitated Just-In-Time material delivery, minimizing inventory and transportation waste. Drones and 360-degree cameras enhanced visualization of work-in-progress, Allowing remote and continuous Gemba Walks. Laser scanning and LiDAR functioned as digital poka-yoke mechanisms by identifying deviations between planned and actual work early, thereby preventing defect-related waste. This phase demonstrates the operationalization of lean principles at scale through integrated digital systems.

4.4 Phase4:Lean4.0andIntelligence(2020s)

The most recent phase reflects the convergence of Lean Construction with Industry 4.0 technologies, resulting in intelligent, predictive, and system-level optimization. Artificial intelligence, digital twins, robotics, augmented reality, and additive manufacturing extend lean principles beyond process improvement toward proactive waste prevention.

Table 4 Intelligent technologies and lean impacts in the Lean4.0 phase

Tech-Tool	Function	Impact
AI & Machine Learning	Predictive analytics to identify schedule bottlenecks before they happen.	Moves from reactive learning to proactive prevention of waste.
Digital Twins	Bidirectional data flow between the site and model for real-time simulation.	Allows for systemic optimization rather than just fixing individual tasks.
Construction Robotics	Automated brick laying or layout (e.g., Dusty Robotics).	Removes human variability, ensuring perfect quality (Zero Defects) every time.
Mixed Reality (AR/MR)	Overlaying digital instructions directly onto the physical workspace.	Let'spracticeacomplextaskin3D, reducing the waste of "Non-utilized Talent."

There viewed studies indicate that AI-driven analytics enable early identification of schedule bottlenecks and resource constraints, shifting continuous improvement from reactive learning to proactive prevention. Digital twins establish bidirectional data flows between physical sites and virtual models, enabling system-wide optimization rather than isolated problem-solving. Robotics ensures standardized work and consistent quality by reducing human variability, while AR/VR technologies enhance workforce capability through immersive training, addressing the waste of non-utilized talent. This phase represents the full realization of Lean 4.0 as an intelligent production system.

4.5 Cross-Phase Synthesis of Waste Elimination

Across all phases, technological integration progressively expanded the scope and depth of waste elimination. Early phases primarily addressed waiting and variability, while later phases targeted inventory, transportation, defects, overproduction, and underutilized skills at a system level.

Table5 comparison of traditional and technology-enabled lean tools across TIMWOODS wastes

Waste type	Traditional	Modern	Measurable Impact
Transportation	Manual Logs	IoT & RFID Sensors	22%reductioninmaterial movement costs.
Inventory	Physical Lists	BIM-Integrated Supply Chains	30%reduction in on-site storage requirements.
Motion	Site Walks	Drones&360°Vision (AI)	18%improvement in field productivity.
Waiting	Weekly Meetings	Cloud-Based Real-Time Dashboards	15% reduction in crew idle time.
Over-production	Push Scheduling	4DBIM/Takt-Time Planning	Elimination of trade stacking and work overlaps.
Over-processing	Paper Drawings	Digital Twins	Single-source truth prevents duplicate data entry.
Defects	Site Inspections	Mixed Reality (AR)& Robotics	45%reduction in rework and design clashes.
Skills	Oral Training	VR First-Run Studies	35%better utilization of specialized labor.

The synthesis confirms that technological maturity directly correlates with lean maturity, enabling a transition from basic waste identification to predictive and preventive waste management aligned with the TIMWOODS framework.

4.6 Evolution of Lean–Technology Maturity

To visually represent the progression of lean maturity enabled by technology, a conceptual model was developed illustrating the transition from stabilization to intelligent lean systems.

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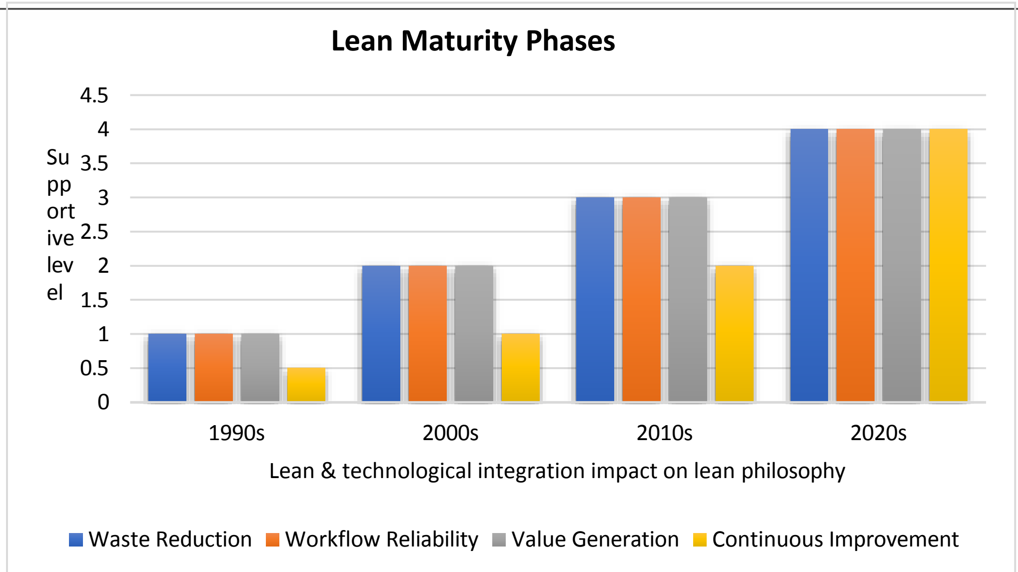

Figure1 Evolution of lean maturity across technological phases

The figure2 illustrates how lean practices evolve from measurement and standardization toward predictive, autonomous, and system-optimized production systems.

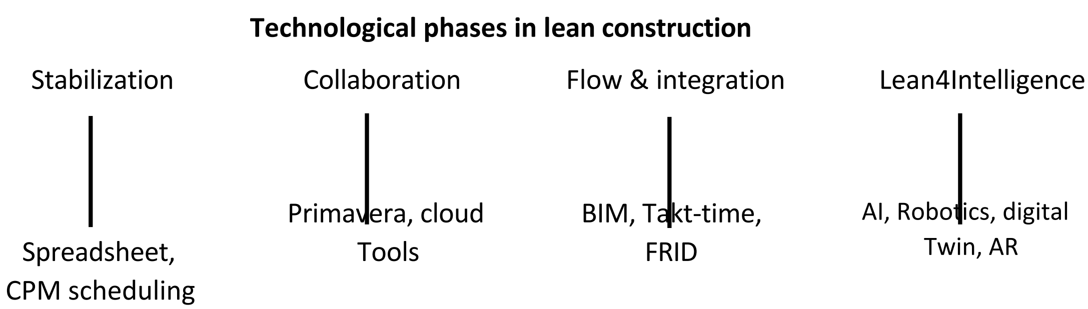

Figure2 Technological phases and associated lean tools

5. Discussion

This systematic literature review demonstrates a clear and structured evolution in the integration of digital technologies with Lean Construction over the past three decades. The findings indicate that technological integration has progressively enhanced the operationalization of lean principles, shifting Lean Construction from basic measurement and stabilization toward predictive, intelligent, and system-level production optimization. The identification off our distinct technological phases Stabilization, Collaboration, Flow and Integration, and Lean 4.0 and Intelligence confirms that lean– technology integration is not a static or tool-specific phenomenon, but rather an evolutionary process aligned with advancements in information processing, automation, and data analytics. This phased progression is consistent with earlier observations that lean maturity in construction develops incrementally rather than through one-time tool adoption (Ballard& Howell, 2003; Sacks et al., 2010). From a theoretical standpoint, the findings strongly reinforce and extend the Transformation Flow Value (TFV) theory proposed by Koskela (1992).

Early technological applications primarily supported the transformation dimension of production by improving task execution, schedule control, and planning reliability through tools such as spreadsheets and CPM software. However, as digital technologies evolved, the emphasis increasingly shifted toward the flow dimension by reducing variability, enhancing coordination, and enabling Just-In-Time material delivery. Technologies such as BIM, real-time sensing systems, and automated progress tracking directly support flow reliability by improving transparency and synchronizing interdependent activities (Eastman et al.,2011;Sacksetal.,2010).MorerecentIndustry4.0 technologies further strengthen the value dimension by enabling predictive control, continuous learning, and system-wide optimization, thereby operationalizing lean principles that were previously difficult to implement using manual approaches (Sacks et al., 2020; Moradi & Arashpour, 2023). The findings also extend existing Lean Construction literature by synthesizing fragmented research on individual technologies into a coherent, phase-based framework. Previous studies have predominantly examined specific tools such as BIM, RFID, or artificial intelligence in isolation, often focusing on localized efficiency improvements or single-project applications (Dave et al., 2013; Tezel et al., 2018). While these studies demonstrate the potential benefits of individual technologies, they provide limited insight into how technological integration systematically reinforces lean philosophy over time. In contrast, this review demonstrates that the effectiveness of digital technologies in Lean Construction depends not only on the tools themselves, but also on their alignment with lean maturity, production system thinking, and organizational readiness. By explicitly linking technological phases to the Eight Wastes (TIMWOODS) framework, this study advances prior work by showing how different technologies progressively address multiple forms of waste at a system level rather than in isolation (Ohno, 1988; Womack&Jones,1996). From a practical perspective, the results highlight important implications for construction practitioners, managers, and policymakers.

The findings suggest that technology adoption should not be treated as an end in itself, but rather as a strategic enabler of Lean Construction principles. Organizations that adopt advanced digital tools without a foundational lean culture risk digitizing inefficient processes rather than eliminating waste, a concern echoed in previous studies on failed technology implementations in construction (Sackset al., 2010; Tezel &Aziz, 2017). Conversely, aligning technology investment with lean maturity can enhance workflow reliability, transparency, collaboration, and value generation. The phase-based framework developed in this study provides a practical roadmap for selecting appropriate technologies based on organizational capability, project complexity, and production objectives. This is particularly relevant in developing economies, where high implementation costs, workforce skill gaps, and cultural resistance remain significant barriers to large-scale adoption of Lean Construction and advanced digital technologies (Ofori, 2015; Marhani et al., 2013).

The review also identifies several important implications for future research. Despite the growing emphasisonLean4.0, empirical evidence on the long-term performance impacts of intelligent and autonomous systems in construction remains limited. Many studies focus on pilot projects or conceptual frameworks, with few longitudinal investigations assessing sustained improvements in productivity, waste reduction, and value generation (Sacks et al., 2020).

Future research should therefore adopt longitudinal, mixed-method, and multi-project study designs to evaluate the organizational and systemic impacts of advanced technologies. In addition, human and organizational factors such as leadership commitment, workforce capability, trust, and change management remain underexplored in technology-enabled Lean Construction research, despite their critical role in successful implementation (Liker, 2004; Koskelaetal.,2019). Addressing these gaps will be essential for translating technological innovation into durable improvements in construction performance.

6. Conclusion

This study conducted a systematic literature review to examine the evolution of technological integration in Lean Construction and its role in waste elimination and value generation from 1992 to 2025. The review identified four evolutionary phases Stabilization, Collaboration, Flow and Integration, and Lean 4.0 and Intelligence demonstrating that technological advancement progressively strengthens the implementation of lean principles and transforms Lean Construction into a data-driven production system.

The findings reinforce Lean Construction theory by linking technological evolution to the Transformation Flow Value (TFV) framework and by showing how digital technologies systematically address the Eight Wastes (TIMWOODS). From a practical perspective, the results highlight that technology adoption is most effective when aligned with lean maturity, providing practitioners with a structured roadmap for selecting appropriate technologies and avoiding the digitization of inefficient processes. While this review is limited to peer-reviewed literature, future research should focus on empirical validation of Lean 4.0 applications and further investigation of human and organizational factors influencing technology-enabled Lean

Construction. Overall, the study contributes to both theory and practice by clarifying the evolving synergy between lean principles and digital technologies in construction.

Research Limitations

This study is limited by its reliance on peer-reviewed journal literature and a qualitative synthesis approach, which may not fully capture emerging industry practices or context-specific implementation challenges. In addition, the phase-based classification reflects dominant trends in the literature and may overlap due to variations in regional adoption and technological maturity. Future research should empirically validate the proposed framework through longitudinal and mixed-method studies a cross diverse construction context.

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