

Advancing Sustainable Construction Through Lean and Digital Technologies

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Abstract

Question: Q1: How does integrating lean construction with Building Information Modelling (BIM), Digital Twins, Artificial Intelligence (AI), and Internet of Things (IoT) improve project delivery and sustainability performance across regions? Q2: What barriers most strongly shape adoption, and what strategies help overcome them?

Purpose: This paper examines how lean methods combined with emerging digital technologies can improve construction performance while supporting sustainability objectives and alignment with relevant UN Sustainable Development Goals (SDGs).

Research Method: A mixed-methods design was used, combining a systematic literature review (2000-2025) with a global case study analysis spanning Europe, North America, Asia, and the Middle East.

Findings: Lean-digital integration improves workflow reliability, reduces rework and material waste, and strengthens real-time decision-making. Regional patterns show stronger maturity in parts of Europe, while other regions face barriers tied to skills, organizational culture, and interoperability. The study also links lean-digital practices to SDG-aligned outcomes, particularly responsible resource use and improved infrastructure sustainability, and proposes practical adoption strategies (training, phased implementation, and stakeholder engagement).

Limitations: The case evidence is drawn from documented projects and secondary sources, and the analysis focuses on reported outcomes rather than controlled comparisons. Regional generalizations may not capture variability between sectors, firm sizes, and procurement models.

Implications: Future research should validate standardized performance frameworks that combine lean metrics with sustainability indicators and should examine lifecycle impacts beyond construction, particularly during operations and maintenance using IoT-enabled digital twins and AI-based analytics.

Value for authors: The paper provides decision-ready guidance on how to pair lean tools (e.g., Last Planner System (LPS), Value Stream Mapping (VSM), Just-in-Time (JIT))

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with BIM, AI, IoT, and Digital Twins to reduce waste, improve planning reliability, and track sustainability performance using measurable indicators that support SDG-oriented reporting and delivery.

Keywords: Lean Construction 4.0; BIM; Digital twins; Artificial intelligence; Internet of Things; Sustainability; Sustainable Development Goals (SDGs); Project Management; Industry 4.0

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Introduction

The construction industry is under increasing pressure to improve its efficiency, reduce costs, and meet stringent quality and sustainability standards as productivity growth has significantly lagged behind that of other industries (Barbosa, et al., 2017). Lean construction, an adaptation of lean manufacturing principles, focuses on eliminating waste, optimizing workflows, and improving collaboration among stakeholders (Koskela, 1992; Ballard, 2000). This methodology is grounded in concepts such as Just-in-Time (JIT) delivery, Value Stream Mapping (VSM), and the Last Planner System (LPS), all aimed at enhancing the flow of work, minimizing delays, and ensuring that value is delivered to clients.

While lean construction is a critical tool for improving project outcomes, it is often complemented by frameworks such as ISO 9001:2015 (Quality Management System) and project management methodologies developed by the Project Management Institute (PMI) (ISO, 2015; PMI, 2017). These methodologies provide structure and consistency, ensuring that construction projects adhere to established quality standards, meet deadlines, and stay within budget. Other methodologies, such as Kaplan and Norton's Balance Scorecard and Mark Graham Brown's Scorecard approaches, are also widely used in both the public and private sectors to measure and monitor performance (Alsharqawi et. al., 2017; Alsharqawi et al., 2024).

Additionally, the integration of emerging technologies like Building Information Modelling (BIM), Digital Twins, and Artificial Intelligence (AI) is becoming increasingly important in modern construction. These tools enable real-time project monitoring, enhanced coordination, and predictive analytics, all of which improve decision-making, reduce risks, and increase efficiency (Gao et al., 2020; Eastman et al., 2011). Together, these elements are reshaping the landscape of construction management.

The primary problem addressed in this paper is the construction industry's uneven and often fragmented adoption of lean construction and digital transformation, particularly the integration of lean methods with BIM, Digital Twins, AI, and Internet of Things (IoT) technologies. Although these approaches can improve workflow reliability, enhance real-time decision-making, reduce waste, and strengthen sustainability performance, implementation remains inconsistent across regions due to recurring barriers such as cultural and organizational resistance to change, workforce skill gaps, limited digital literacy, and technical challenges including interoperability and standardization across platforms. Building on these challenges, the objective of this research is to investigate how lean-digital integration can improve project management outcomes and advance sustainability priorities, including alignment with relevant United Nations Sustainable Development Goals (SDGs), by consolidating evidence from a systematic literature review and global case study analysis and translating the findings into practical, context-sensitive recommendations for industry adoption.

Literature Review

Lean Construction Principles

Lean construction is grounded in the philosophy of maximizing value for the client while minimizing waste, drawing from lean manufacturing principles such as the Toyota Production System. Liker's (2004) 14 principles of lean thinking serve as a foundational framework for lean construction. These principles extend beyond efficiency improvements to emphasize a long-term philosophy that prioritizes customer value, continues improvement, and respect for people at all levels. By embedding these core values into construction management, organizations can shift from reactive, short-term strategies to proactive, value-driven approaches that promote quality, sustainability, and innovation across the project lifecycle. In practice, lean construction principles translate into enhanced workflow reliability, collaborative planning, and improved project outcomes through systematic problem-solving and empowerment of teams.

At the core of lean construction is the pursuit of maximizing value while minimizing waste. This philosophy is operationalized through practices such as:

- Value Stream Mapping (VSM), which identifies waste in processes and suggests improvements to enhance flow (Rother and Shook, 1998).
- The Last Planner System (LPS), which engages all project stakeholders in collaborative scheduling to increase reliability and reduce delays (Ballard, 2000).
- Just-in-Time (JIT) Delivery, which minimizes excess inventory by ensuring materials arrive on-site exactly when needed (Koskela, 1992).

These lean principles improve overall efficiency, reduce waste, and ultimately deliver higher value to clients. Contemporary research indicates that lean construction is increasingly being linked with sustainability objectives and digital tools, pointing toward an evolving paradigm often termed "Lean Construction 4.0" (Garcés, et al., 2025). However, despite the proven benefits of lean, many projects still struggle with its implementation due to cultural resistance and organizational inertia. Studies have identified numerous barriers to adopting lean construction including lack of awareness, resistance to change, and management support issues, which underscores the importance of change management in successful lean adoption. For example, a systematic review by Albalkhy and Sweis (2020) identified 29 distinct barriers to lean construction, with the majority related to internal organizational factors such as rigid company culture and lack of lean knowledge (e.g., employees and managers often resist changing established practices even if they recognize industry inefficiencies). Addressing these barriers through training, leadership commitment, and a culture of continuous improvement is critical for realizing the full potential of lean construction in practice (Albalkhy and Sweis, 2020).

Lean Construction 4.0: Integration with Industry 4.0

Lean Construction 4.0 represents a significant evolution of lean principles in the context of modern digital technologies. It refers to the fusion of lean construction methodologies with Industry 4.0 technologies, including the Internet of Things (IoT), Artificial Intelligence (AI), Big Data analytics, and cyber-physical systems to create smarter and more responsive construction processes (Oesterreich and Teuteberg, 2016; Li et al.,

2020). This convergence enables real-time data-driven decision-making and proactive control of construction workflows. For instance, IoT sensors can continuously monitor equipment, materials, and site conditions, providing up-to-the-minute information that helps in reducing variability and preventing delays. AI algorithms contribute to automated process optimization and predictive maintenance, while cyber-physical systems integrate physical construction activities with their digital twins for better coordination. Together, these technologies strengthen the lean focus on waste reduction and flow efficiency by enabling issues to be identified and addressed before they escalate (Villarreal et al., 2021).

Recent studies reinforce the promise of Lean Construction 4.0. Schulze et al. (2025) propose a framework demonstrating how Industry 4.0 tools can mitigate traditional lean implementation barriers, finding that combining lean methods with digital technologies helps overcome challenges in complex, non-repetitive project environments. The integration of real-time data and automation allows teams to respond more quickly to problems, thereby sustaining the continuous improvement cycle central to lean. This synergy is so critical that researchers highlight the “necessity to apply both Lean and Industry 4.0” in tandem for optimum results. In essence, Lean Construction 4.0 is not about replacing lean principles but augmenting them. It leverages advanced technologies to achieve lean objectives more effectively. For example, Hamzeh et al. (2021) discuss how lean tools like pull planning and Kanban can be enhanced by digital platforms, and how real-time analytics support lean decision-making (Hamzeh et al., 2021). Moreover, the human factor remains crucial in Lean 4.0; studies emphasize that successful implementation requires a human-centric approach, leveraging lean’s expertise in change management to ensure that technology adoption is aligned with people and processes. Therefore, Lean Construction 4.0 creates a holistic framework where lean methods and Industry 4.0 technologies jointly drive greater value than either would alone, transforming construction into a more efficient, intelligent, and resilient industry (González et al., 2023).

PMI Methodologies and ISO Standards

Lean construction often operates alongside established project management frameworks and quality standards, which provide complementary strengths. The Project Management Institute (PMI)’s methodologies (e.g. PMBOK Guide) offer comprehensive guidelines for scope, schedule, cost, and risk management that can structure and support lean initiatives. By standardizing practices for planning, monitoring, and risk control, PMI methodologies create a stable project environment in which lean techniques can flourish (Müller and Turner, 2007). For example, clear definition of project scope and robust risk management (per PMI guidelines) help ensure that lean efforts are aligned with client goals and that potential obstacles to workflow are anticipated. These traditional project management tools thus form a reliable foundation for overseeing complex projects, ensuring they stay on schedule and budget while lean methods drive efficiency and waste reduction.

Notably, lean construction’s philosophy has been described as “a new paradigm in construction project management, challenging the traditional PMBOK guide” (Garcés, et al., 2025). Koskela (1992) and other pioneers argued that conventional project management was too rigid and plan-centric, whereas lean offers a more flexible, value-focused philosophy. In practice, rather than contradicting PMI methodology, lean construction augments it: Koskela’s vision was not to discard structured management

processes, but to infuse them with lean thinking creating tools and workflows that generate value at each stage of a project. Recent research by Villanueva et al. (2022) even provides a quantitative framework mapping common lean construction tools to PMI's project management knowledge areas, underscoring how lean techniques (like Last Planner, VSM, etc.) correspond to improved performance in areas such as time management, quality management, and stakeholder communication. This alignment shows that lean and PMI frameworks are not mutually exclusive but in fact complementary integrating lean's waste-cutting and workflow optimization with PMI's thorough planning and control can lead to more effective project delivery.

Similarly, ISO standards like ISO 9001:2015 (Quality Management System) play a complementary role. ISO 9001 provides a structured approach to ensure quality and consistency in processes. When lean construction techniques are applied, ISO 9001 acts as a safeguard that efficiency gains do not compromise quality. For instance, if a project uses lean methods to streamline workflows, ISO 9001 requirements ensures that there are documented procedures and checks so that critical steps are not skipped and outputs meet the required standards (ISO, 2015). In practical terms, lean construction efforts to eliminate waste (e.g. reducing rework, avoiding overproduction of construction components) are reinforced by ISO's insistence on process documentation and continuous improvement of the quality system. Recent case studies have noted that organizations integrating lean practices within ISO-certified quality frameworks achieve better consistency and client satisfaction. Therefore, PMI methodologies and ISO 9001 provide structured frameworks that bolster lean construction: PMI adds rigor in project execution and risk management, while ISO 9001 ensures that quality assurance accompanies the drive for efficiency. This research focuses primarily on lean and technology integration, yet it acknowledges that PMI and ISO frameworks remain valuable scaffolding that supports sustainable process improvement in the construction industry.

Emerging Technologies in Construction

The integration of emerging digital technologies has significantly impacted construction practices in recent years. Key technologies reshaping the industry include BIM, Digital Twins, AI, and IoT. Each of these, when combined with lean construction principles, offers new opportunities to improve efficiency, collaboration, and project outcomes:

- **Building Information Modelling (BIM):** BIM provides a digital representation of a construction project's physical and functional characteristics, serving as a shared knowledge resource for all stakeholders. By centralizing information and enabling 3D/4D visualizations, BIM reduces errors, enhances coordination, and improves decision-making throughout the project lifecycle (Eastman et al., 2011). BIM's collaborative platform aligns naturally with lean principles. Numerous studies have shown that leveraging BIM data through lean principles can significantly improve overall project management and reduce rework. For example, BIM's ability to detect clashes and visualize workflows complements the Last Planner System's focus on reliable scheduling, resulting in fewer delays and change orders. El Mounla et al. (2023) found that a Lean-BIM integrated approach in the design phase helped anticipate and eliminate deviations before construction began, leading to improved quality and time performance (El Mounla et al., 2023). BIM Level 2, which mandates standardized information sharing, has been a catalyst in

places like the UK for both BIM adoption and lean practices, demonstrating how digital models can facilitate lean collaboration across disciplines (Smith, 2014). In essence, BIM acts as an enabler for lean construction by providing real-time, accurate data and a visualization tool that supports the elimination of waste (e.g., unnecessary material usage and design conflicts) and enhances value generation for the client.

- **Digital Twins:** A digital twin is a dynamic, virtual representation of a physical asset, system, or process, continuously updated with real-time data. In construction, digital twin technology allows project teams to monitor and simulate construction activities and building performance in real time. This capability greatly enhances the ability to detect inefficiencies early and optimize performance across the project lifecycle (Kamat and Martinez, 2019). Digital twins strongly complement lean construction practices. They foster greater collaboration and transparency by making the current state of the project visual and accessible to all stakeholders. Research shows that integrating digital twins in lean construction is a “transformative approach to enhance collaboration, efficiency, waste reduction, and decision-making” (Owais et al., 2024). For instance, a digital twin of a construction project can provide instant feedback on the impact of changes or delays, allowing the team to adjust plans proactively (a core lean idea). Digital twins also reinforce continuous improvement: they enable a constant monitoring and feedback loop for key performance metrics such as cycle times, resource utilization, and energy consumption, thus helping to identify waste in real time. Owais et al. (2024) describe how digital twins align with all levels of lean thinking. At the philosophy level, they reinforce principles like value maximization and respect for people by providing transparent data; at the tactical level, they support lean methods (e.g. Target Value Design, VSM, LPS) by visualizing workflows and spotting deviations. Overall, the strategic integration of digital twins with lean construction leads to improved project efficiency and value delivery. As this technology matures, we expect to see digital twins becoming an integral part of lean project delivery systems, enabling real-time adjustments and more robust decision-making on complex projects.
- **Artificial Intelligence (AI):** AI technologies including machine learning algorithms and data analytics are increasingly used in construction to automate tasks, predict risks, and optimize planning and resource allocation. Early applications of AI in construction involved schedule optimization and risk analysis (Tommelein and Ballard, 2003), and recent advances have dramatically expanded AI’s capabilities. For example, AI models can analyse historical project data to forecast potential delays or cost overruns with greater accuracy than traditional methods (Gao et al., 2020). By identifying patterns (such as sequences of activities that typically cause bottlenecks), AI provides project managers with actionable insights to prevent problems before they occur. This predictive power directly supports lean objectives of reducing variability and ensuring reliable workflow. In fact, AI and lean construction have a natural synergy: both strive for continuous improvement and waste reduction through learning and feedback. Recent research posits that combining AI with lean methods can amplify these benefits. The joint implementation yields greater value than using either alone (Cisterna et al., 2022). For instance, AI-driven analytics can rapidly process data from the field

(material deliveries, crew productivity, equipment usage) and suggest adjustments to the plan, which the lean team can evaluate in daily or weekly planning sessions. Cisterna et al. (2022) present a conceptual framework for AI-driven continuous improvement in lean construction, highlighting that human experts (e.g., project managers and last planners) remain crucial as the interface between AI tools and decision-making. They argue that lean's emphasis on change management and respect for people is essential for successfully adopting AI innovations in construction. Practical examples of AI in lean construction include computer vision systems that monitor site progress and quality in real time (reducing defects and rework) and optimization algorithms that adjust sequencing for just-in-time material delivery. As AI becomes more prevalent, guidelines and best practices are emerging to ensure that these tools are used to support - not replace - sound lean processes. Therefore, AI technologies provide powerful new means to analyse and improve construction processes, and when deployed within a lean framework, they can significantly enhance decision-making, productivity, and safety on projects.

- Internet of Things (IoT): IoT refers to networks of sensors and smart devices that collect and exchange data over the internet. In construction, IoT devices can track real-time data on equipment performance, material conditions (e.g. concrete curing temperatures), workforce location, and safety metrics, and much more (Zhao et al., 2019). This continuous stream of information allows project managers to make data-driven decisions promptly, aligning with lean construction's goal of responsive control and waste minimization (Eastman et al., 2011). For instance, IoT-based tracking of equipment usage can prevent idle time and unnecessary fuel consumption by signaling when a machine is underutilized (allowing it to be reallocated or turned off to eliminate waste). Wearable IoT sensors can monitor workers' safety vitals and environmental conditions, helping to preempt accidents or fatigue-related errors, thus improving overall project reliability. A key lean benefit of IoT is enhanced transparency. Real-time updates from the field reduce the information float and enable the Last Planner System to function with up-to-date inputs. Zhao et al. (2019) demonstrated that deploying IoT sensors on a jobsite (for example, to monitor concrete strength gain or track deliveries) resulted in teams making more informed decisions faster, thereby increasing the efficiency of the project lifecycle. In recent work, Saghatforoush et al. (2022) developed a management system that integrates IoT sensors with BIM to improve building operations, exemplifying the power of IoT in a lean context. In their study, environmental IoT sensors (monitoring factors like temperature and humidity in an educational building) fed live data into the BIM model, creating a dynamic digital twin of the facility. This allowed facility managers to identify comfort issues or energy inefficiencies in real time and respond immediately. A clear demonstration of lean principles in operation, as it improved user comfort (value) while reducing energy waste. The system's web-based dashboard provided continuous feedback and even control recommendations, illustrating how IoT can enable a cycle of continuous improvement in facility maintenance (often termed lean maintenance). More broadly, as construction sites become instrumented with IoT (ranging from GPS trackers on trucks to RFID tags on materials and wearables on workers), the data collected can be used for process optimization, preventive maintenance, and enhanced safety. These outcomes align directly with lean goals: minimizing downtime, avoiding material waste (through better logistics and

inventory control), and ensuring smooth workflow. The adoption of IoT in construction has been accelerating, and its benefits in terms of real-time control and integration with lean practices are becoming more evident each year. Researchers forecast that IoT-enabled lean construction will lead to smart construction sites where resources are used just-in-time, processes are monitored continuously, and adjustments are made proactively to maintain flow and value delivery.

These emerging technologies (BIM, digital twins, AI, and IoT) are powerful catalysts for lean construction. When integrated properly, they provide construction teams with real-time insights, predictive analytics, and automation capabilities that greatly augment traditional lean methods. The adoption of such technologies in construction has been steadily increasing across the globe as their benefits for efficiency, cost-effectiveness, and risk management become clear. Importantly, the full value of these tools is realized only when coupled with lean principles. Technology alone cannot solve systemic issues, but technology guided by lean thinking can transform how projects are delivered. This literature review highlights that the convergence of lean and digital technologies holds promise for tackling the industry's longstanding challenges from reducing waste and delays to improving safety and sustainability. The next sections will illustrate the methodology of this paper and explore how these integrated approaches are being implemented in different regions and the outcomes they are achieving.

Methodology

This study employed a mixed-methods research approach to investigate the integration of lean construction principles with emerging technologies across diverse global contexts. The methodology consisted of two interconnected phases: a systematic literature review and a global case study analysis. These phases were embedded within a broader framework that guided problem identification, data collection, analysis, and synthesis, with consideration of Sustainable Development Goals (SDGs) to evaluate alignment with global sustainability priorities. Figure 1 illustrates the methodological approach used in this paper.

In order to achieve the main research objective, the first methodological step involved identifying the key challenges in the construction industry. This included inefficiency, waste, fragmented communication, and environmental impact. Preliminary investigation of academic literature, professional reports, and industry guidelines enabled the identification of these challenges. Based on this, the study formulated its objective to explore how the integration of lean construction methods with emerging digital technologies such as BIM, AI, Digital Twins, and IoT, can improve operational efficiency, reduce waste, enhance decision-making in real time, and support SDG-aligned outcomes such as sustainable infrastructure, responsible resource use, and climate action.

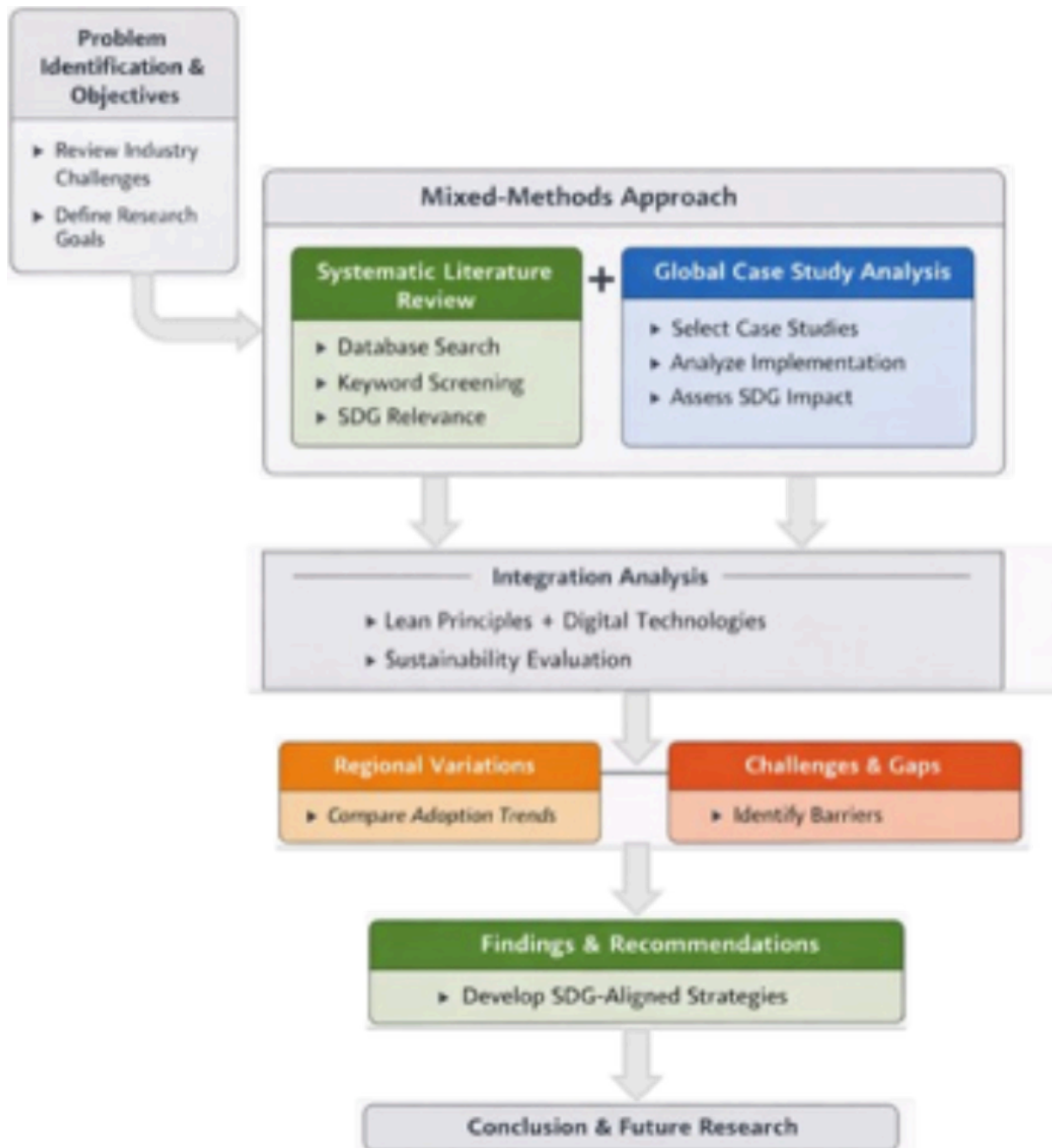


Figure 1. Research Methodology

The systematic literature review was conducted in conjunction with analysis of global case studies as follows:

- **Systematic Literature Review:** A comprehensive review of peer-reviewed academic publications was conducted. Publications were then screened for relevance to in-depth analysis. The detailed steps involved in the selection procedure are: (i) multiple academic and professional databases (e.g., Scopus, ScienceDirect, MDPI,

Google Scholar, conference archives) were utilized to perform a comprehensive search under the “Title, Abstract, Keywords” field; (ii) the search results were limited to papers for the 2000-2025 period; and (iii) a keyword search was carried out, including combinations of “lean construction”, “digital construction”, “BIM”, “AI in construction”, and “IoT construction”. The authors then conducted preliminary screening by reviewing the titles and abstracts of the retrieved papers to determine if they align with the scope of this paper. This review approach is widely adopted across various research fields due to its effectiveness in providing deeper analyses and structured guidance (Alsharqawi, 2025).

- **Global Case Study Analysis:** Case studies were selected from construction projects across Europe, North America, Asia, and the Middle East that had documented implementation of lean construction practices and digital technologies. Selection criteria included: (i) projects completed within the past five years, (ii) clear documentation of lean and digital integration, (iii) availability of quantitative or qualitative outcome measures, and (iv) geographical representation. These cases were analyzed to investigate implementation approaches, challenges encountered, mitigation strategies, and measured benefits.

The integration of these two methodological components allowed to develop findings regarding the current state of lean construction implementation in the digital age, regional adoption patterns, implementation barriers, and effective strategies for advancing the integration of these approaches.

Following this literature review and case study analysis the next step in the methodology was to examine the integration of lean principles with emerging technologies. This involved assessing how lean tools, including value stream mapping, the Last Planner System, and Just-in-Time delivery, are enhanced by BIM, Digital Twins, AI, and IoT. The analysis focused on i) the optimisation of workflows and resource utilisation, ii) real-time decision-making support, and iii) alignment with sustainability objectives. This methodological step enabled the study to evaluate the synergistic effects of lean-digital integration without duplicating outcome-focused sections of the paper.

Regional variations and global trends were investigated by grouping case studies and literature findings according to region. The study explored how economic, regulatory, and cultural factors influence the adoption of lean construction and digital technologies, and how these factors affect SDG-aligned outcomes.

Finally, the methodology included identifying challenges and gaps in adoption. The analysis focused on i) skill gaps and knowledge deficiencies, ii) resistance to organizational and cultural change, and iii) technological barriers such as lack of standardisation and interoperability. These findings informed the synthesis of practical recommendations for overcoming barriers, improving integration, and enhancing sustainable construction performance.

Lean-Digital Integration in Practice: Global Adoption, Case Evidence, and Change Barriers

The integration of lean construction principles, PMI methodologies, and emerging technologies is reshaping construction practices worldwide. Although these frameworks and technologies are broadly applicable, their adoption and effectiveness vary by region,

influenced by local cultural, economic, and regulatory factors. This section presents the analysis and findings derived from the integration of the systematic literature review and case study examination. The analysis reveals patterns in adoption across regions, identifies successful implementation strategies through case examples, and highlights the sustainability benefits achieved through integrated approaches. Each subsection presents distinct findings offering empirical evidence of how lean construction principles and emerging technologies are being implemented in practice across different contexts. The following subsections detail specific aspects of this integration, beginning with an examination of regional variations in adoption patterns.

Global Adoption and Regional Variations

In Europe, countries like the UK, Germany, and the Netherlands have been pioneers in adopting BIM and lean construction principles. In the UK, for example, the government's "BIM Level 2" mandate has accelerated the use of BIM across public sector projects. This mandate emphasizes the importance of using standardized information across all stakeholders, utilizing a centralized digital model shared between all parties involved. Germany has also embraced lean methods in construction, particularly in large infrastructure projects. The integration of BIM and lean construction in these regions has led to improved collaboration, reduced waste, and better alignment with sustainability goals. However, cultural barriers play a significant role in hindering broader adoption, especially in regions with traditional construction practices. For instance, in the UK, the move towards lean construction was initially met with resistance from stakeholders who were accustomed to established processes. The transition to BIM and lean practices was slow because of scepticism regarding the efficacy of these new approaches and a reluctance to change long-standing processes. This resistance was particularly evident among smaller firms, which lacked the resources to implement new technologies and methods. Figure 2 illustrates the global adoption patterns of lean construction and emerging technologies across different countries.

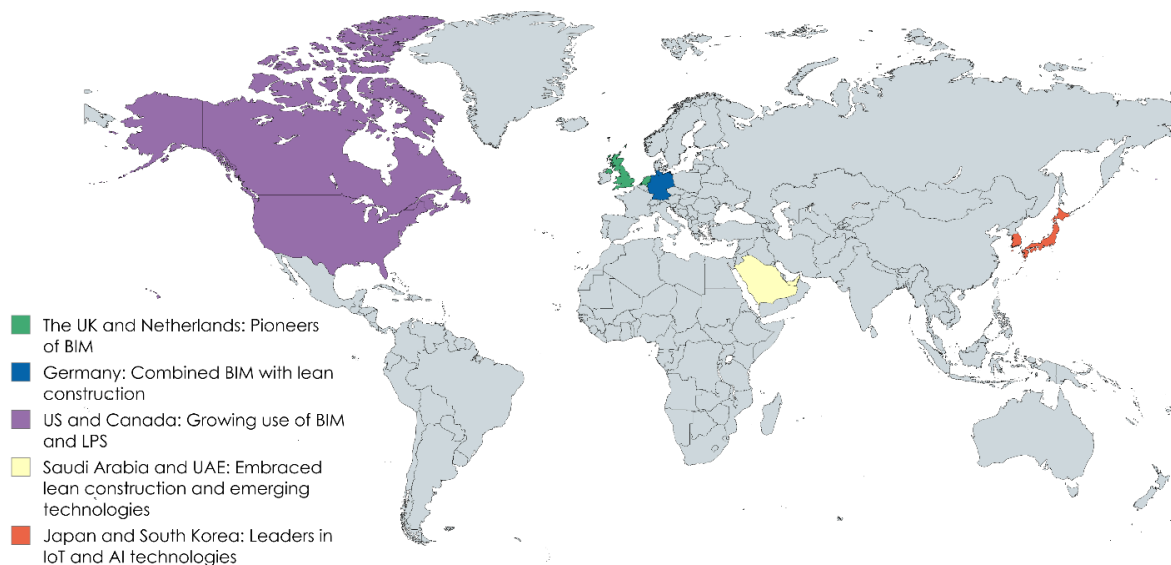


Figure 2. Countries Adopting Lean Construction and Emerging Technologies (Alsharqawi et al., in press)

As shown in the figure, in North America, the adoption of lean construction has been slower but is gaining momentum. In the United States, the use of BIM is growing in both public and private sectors, but the adoption of lean principles has faced resistance, particularly due to the industry's reliance on traditional project management methods. Many organizations remain focused on traditional contracting and project delivery models, which prioritize cost minimization through competitive bidding rather than collaboration and continuous improvement. As a result, the integration of lean construction principles such as the Last Planner System (LPS) has often faced cultural pushback, especially from project managers who have extensive experience with conventional practices.

In the Middle East, particularly in Saudi Arabia and the United Arab Emirates, large-scale projects have embraced lean construction and emerging technologies. However, the region faces both economic and cultural barriers. The rapid pace of development has often led to a preference for fast-tracked schedules over thorough planning and collaboration, limiting the full application of lean practices. Economic factors, such as fluctuating oil prices and shifting market conditions, also impact the funding and prioritization of projects that incorporate these advanced methodologies. There is a clear contrast between large, high-budget projects that adopt digital tools and lean construction and smaller, more cost-conscious ventures where traditional methods still dominate.

In Asia, countries like Japan and South Korea are leading the way in integrating IoT and AI technologies into construction. Japan's use of BIM and smart city technologies is setting a precedent for the region. These technologies enable real-time tracking of construction activities and provide valuable insights for optimization. However, cultural barriers, such as the preference for hierarchy and rigid top-down decision-making, have slowed the full integration of lean principles that emphasize collaboration and decentralized decision-making.

Case Study Examples on Digital Tools Enhancing Real-Time Decision-Making

A key benefit of integrating digital tools into lean construction is their ability to enhance real-time decision-making and reduce waste. For instance, the Crossrail Project in London utilized BIM to provide a collaborative platform where all stakeholders had access to up-to-date project data. This allowed project managers to identify design conflicts early, reducing costly reworks and schedule delays. BIM's ability to centralize data and provide real-time updates enabled teams to make informed decisions promptly, thus enhancing the efficiency of the entire project lifecycle (Eastman et al., 2011; El Mounla et al., 2023).

Similarly, in Germany's Autobahn expansion projects, lean construction practices were integrated with IoT sensors to monitor equipment usage and material delivery in real time. This data was fed into a central system that allowed managers to optimize resource allocation and reduce downtime caused by delays or overstocked materials. The real-time data collection ensured that all materials arrived exactly when needed, avoiding over-ordering, which is a common source of waste in traditional construction practices (Zhao et al., 2019).

The Dubai Expo 2020 project integrated BIM with AI to optimize scheduling and logistics for its massive construction efforts. The AI tools analysed past performance data to predict potential delays and suggest corrective actions. As a result, project managers could adjust plans and schedules proactively, reducing the impact of unforeseen

disruptions and ensuring the timely delivery of the project (Gao et al., 2020; Cisterna et al., 2022).

In the United States, the California High-Speed Rail project integrated BIM with advanced scheduling software and lean principles to manage a complex, multi-phase infrastructure program. Real-time tracking of material deliveries, construction progress, and workforce allocation allowed project managers to identify bottlenecks and reassign resources dynamically. This integration of technology and lean practices reduced idle time, prevented material waste, and improved overall project predictability (Wang et al., 2021).

In Japan, the Tokyo Metropolitan Subway expansion applied digital twins alongside lean construction methodologies to monitor underground construction in real time. Sensors embedded in tunnels and machinery provided continuous feedback on structural integrity, equipment performance, and environmental conditions. By linking this data to a digital twin platform, project managers could simulate scenarios and optimize workflows, reducing delays, enhancing safety, and ensuring precise resource allocation (Tokyo Metropolitan Government, 2025).

Challenges, Skill Gaps and Resistance to Change

The introduction of technologies like BIM, AI, and IoT requires specialized knowledge and skills. To address these challenges, many companies have started to invest in comprehensive training programs that equip workers with the skills necessary to effectively utilize these tools. For example, Skanska in Sweden has partnered with several educational institutions to offer workshops and certification programs focusing on BIM and lean construction practices. These initiatives help workers, from architects to site managers, to effectively integrate digital tools into their daily operations, which is essential for the successful implementation of lean construction methodologies (Zhao et al., 2019). Targeted training programs in Europe have effectively addressed skill gaps, while phased adoption strategies in Asia have mitigated cultural resistance. These examples illustrate how tailored approaches can facilitate the adoption of lean practices and digital tools.

In addition, universities and industry bodies are stepping up their efforts to build expertise in lean construction. The University of Cambridge has developed a range of online courses and certifications aimed at improving competencies in lean construction practices, including the Last Planner System and Lean Project Delivery. These accessible training programs are designed to bridge the skills gap by providing workers with the knowledge and techniques needed to adapt to the evolving digital construction landscape.

Cultural and organizational resistance to change is another significant barrier to the widespread adoption of lean construction practices. Construction companies, especially those with entrenched traditional practices, can find it challenging to shift towards lean methodologies. Overcoming this resistance requires proactive change management strategies that encourage buy-in from all levels of the organization. While previous research has identified barriers, this paper contribution lies in analyzing their relative impact across different regions and proposing context-specific mitigation strategies based on successful case implementations.

One successful approach is involving key stakeholders—including contractors, suppliers, and workers—in the early stages of planning and decision-making. In the UK, for example, large-scale projects have successfully implemented the Last Planner System by engaging workers in collaborative planning sessions. This approach allows workers to voice

concerns, provide input, and have a direct role in shaping the project delivery process. This inclusion helps to reduce resistance and foster a more cooperative and trusting work environment (Ballard, 2000).

Another strategy is implementing pilot projects or small-scale demonstrations of lean methods. These initiatives allow organizations to showcase the benefits of lean practices in a controlled environment, helping to demonstrate their value and viability without overwhelming teams with too many changes at once. For example, small-scale projects in Germany have been used to introduce lean principles before broader implementation in more complex construction projects. This step-by-step approach helps stakeholders see the tangible benefits firsthand, reducing reluctance to adopt lean practices on larger projects. Technological barriers such as interoperability issues can be addressed through standardized protocols, while organizational barriers like resistance to change can be mitigated through stakeholder engagement practices.

This study offers region-specific recommendations tailored to different construction environments. In North America, it is recommended enhancing collaboration through integrated project delivery models, while in the Middle East, it is suggested leveraging economic incentives to promote the adoption of lean practices and digital tools. These recommendations are based on the analysis of regional adoption patterns and the effectiveness of various implementation strategies. By providing these detailed insights and actionable recommendations, this study contributes to the body of knowledge by offering practical solutions for overcoming implementation barriers and advancing the broader adoption of lean construction methods.

Lean-SDG Integration for Sustainability: Strategic Alignment, Project Impacts, and Performance Metrics

Building on the analysis of global adoption patterns and implementation challenges presented in the previous section, this section examines how the integration of lean construction principles and digital technologies contributes directly to sustainability outcomes and alignment with the United Nations Sustainable Development Goals (SDGs). While lean-digital integration has demonstrated clear benefits in improving efficiency and decision-making, its broader value lies in its capacity to systematically reduce environmental impacts, enhance resource efficiency, and support long-term social and economic resilience in the built environment. This section synthesizes evidence from the literature and documented project practices to illustrate how lean methods, when enabled by technologies such as BIM, Digital Twins, AI, and IoT, support SDG-aligned objectives at strategic, project, and operational levels. The discussion highlights mechanisms through which lean-digital integration advances sustainable construction performance, identifies relevant performance metrics, and outlines practical implications for embedding sustainability into construction planning, delivery, and lifecycle management.

Emphasizing Sustainability

Sustainability has become a central strategic imperative in the construction industry, driven by increasing regulatory requirements, client expectations, and global commitments to the United Nations Sustainable Development Goals (SDGs). Early sustainability assessment in the built environment was driven by rating systems such as LEED, BREEAM, and later Envision, which organize performance into categories like energy, water,

materials, site, and social or community impacts, and evaluate projects through checklists or credit-based scoring that roll up into rating levels (e.g., Certified, Silver, Gold, Platinum) (Salama et al. 2025). Construction activities account for a substantial share of global material consumption, energy use, and greenhouse gas emissions, positioning the sector as a critical lever for achieving sustainable development targets (United Nations, 2015; Zhang et al., 2020). The integration of lean construction principles with emerging digital technologies offers a systematic approach to addressing these challenges by reducing waste, improving resource efficiency, and enhancing environmental performance across the project lifecycle (Kamat and Martinez, 2019; Garcés et al., 2025).

Lean construction inherently aligns with sustainability objectives through its emphasis on waste elimination, value maximization, and continuous improvement (Koskela, 1992; Liker, 2004). By minimizing non-value-adding activities such as rework, overproduction, excessive material handling, and idle time, lean practices directly reduce material consumption, energy use, and associated emissions (Albalkhy and Sweis, 2020). When complemented by environmental management systems, lean construction supports the systematic identification, monitoring, and mitigation of environmental impacts within construction operations (ISO, 2015; Zhang et al., 2020).

Strategic Alignment with the United Nations Sustainable Development Goals

The convergence of lean construction and digital technologies demonstrates strong alignment with several SDGs (Figure 3), particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action) (United Nations, 2015). Lean construction contributes to SDG 12 by promoting efficient use of resources and systematic waste reduction, while digital technologies such as BIM and Digital Twins enhance transparency, traceability, and data-driven optimization across construction processes (Eastman et al., 2011; Kamat and Martinez, 2019).



Figure 3. United Nations Sustainable Development Goals (SDGs)

Building Information Modelling (BIM) plays a critical role in sustainable construction by enabling accurate material quantity estimation, clash detection, and early-stage scenario analysis. These capabilities reduce design-related errors, limit over-procurement of materials, and minimize construction waste, reinforcing lean objectives while supporting environmental performance (Eastman et al., 2011; El Mounla et al., 2023). BIM-based 4D and 5D modelling further integrates schedule and cost considerations with sustainability-oriented decision-making, allowing project teams to assess trade-offs between time, cost, and environmental impact (Zhang et al., 2020).

Digital Twins extend sustainability benefits beyond the construction phase into building operation and maintenance. By continuously integrating real-time data from

sensors and monitoring systems, digital twins enable ongoing optimization of energy consumption, indoor environmental quality, and asset performance (Kamat and Martinez, 2019; Owais et al., 2024). This continuous feedback loop strongly aligns with lean principles of continuous improvement and rapid problem resolution, enabling proactive interventions that reduce energy waste and lifecycle environmental impacts (Villarreal et al., 2021).

Project-Level Sustainability Impacts

At the project level, the integration of lean construction methods with digital technologies has demonstrated measurable sustainability benefits. Lean planning approaches such as the Last Planner System, when supported by BIM-based visualization and real-time data from IoT devices, improve workflow reliability and reduce process variability (Ballard, 2000; Zhao et al., 2019). Improved planning reliability leads to fewer delays and reduced rework, which are major contributors to material waste and unnecessary energy consumption in traditional construction projects (Albalkhy and Sweis, 2020).

IoT technologies enhance sustainability outcomes by enabling real-time monitoring of equipment utilization, environmental conditions, and energy use on construction sites. Sensor-based data supports just-in-time logistics and optimized equipment deployment, reducing idle time, fuel consumption, and emissions (Zhao et al., 2019; Saghatforoush et al., 2022). In operational contexts, the integration of IoT data with BIM models creates functional digital twins that enable continuous performance monitoring and preventive maintenance, contributing to long-term reductions in energy use and operational waste (Kamat and Martinez, 2019).

AI further strengthens Lean-SDG integration by enabling predictive analytics and data-driven optimization. AI-based models can analyse historical and real-time project data to identify inefficiencies, forecast energy demand, and support proactive decision-making aimed at reducing environmental impacts (Gao et al., 2020; Cisterna et al., 2022). When embedded within lean continuous improvement cycles, AI enhances the industry's ability to systematically reduce waste and variability while maintaining productivity and cost performance.

Performance Metrics and Measurement Frameworks

Effective Lean-SDG integration depends on robust performance measurement frameworks that capture both operational efficiency and sustainability outcomes. Traditional lean metrics—such as plan reliability, cycle time, and waste reduction—can be expanded to include sustainability indicators such as material waste intensity, energy use per unit of output, carbon emissions, and water consumption (Garcés et al., 2025).

Digital technologies significantly enhance the accuracy and timeliness of sustainability performance measurement. BIM-based quantity tracking enables precise monitoring of material usage and waste, while IoT sensors provide continuous data on energy and resource consumption (Eastman et al., 2011; Zhao et al., 2019). These data streams can be integrated into digital dashboards and performance scorecards, aligning with Balanced Scorecard approaches to link lean operational metrics with environmental and social performance objectives (Alsharqawi et al., 2024).

Implications for Sustainable Construction Practice

The integration of lean construction, digital technologies, and sustainability frameworks represents a shift from reactive environmental management to proactive, data-driven sustainability governance. Rather than addressing environmental impacts after project completion, Lean-SDG integration embeds sustainability considerations throughout planning, execution, and operation phases, enhancing lifecycle performance and long-term asset value (Zhang et al., 2020; González et al., 2023).

While digital tools provide critical technical capabilities, successful Lean-SDG integration remains highly dependent on organizational culture, leadership commitment, and workforce capability. Studies consistently emphasize that training, stakeholder engagement, and change management are essential for translating technological potential into measurable sustainability outcomes (Albalkhy and Sweis, 2020; Hamzeh et al., 2021). As the construction industry advances toward Lean Construction 4.0, aligning lean principles with digital innovation and sustainability objectives will be central to achieving resilient, efficient, and environmentally responsible project delivery.

Conclusion and Future Directions

This paper examined the integration of lean construction principles and digital technologies alongside alignment with the sustainability of the UN SDG goals. By reviewing the literature on lean construction, Building Information Modelling, Digital Twins, Internet of Things, and Artificial Intelligence, this study demonstrates that integration extends beyond operational efficiency and cost control to serve as a strategic enabler, whether this be environmentally or to sustainable construction practices.

The findings highlight that when lean principles are supported by digital tool, construction projects can achieve measurable reductions in waste, energy consumption and emission whilst simultaneously improving planning reliability and lifecycle asset performance.

At a strategic level, Lean SDG integration shows strong alignment with SDG 9, Industry Innovation and Infrastructure, SDG 11, Sustainable Cities and Communities, SDG 12, Responsible Consumption and Production, and SDG 13, Climate Action. Lean's emphasis on waste elimination and value generation directly supports responsible resource use, while digital technologies enhance data availability, traceability, and decision making across the project lifecycle. At the project and operational levels, the combined use of lean planning systems, BIM based visualization, IoT enabled monitoring, and digital twins enables proactive control of material flows, energy use, and process variability, embedding sustainability considerations into everyday construction management practices rather than treating them as post project compliance requirements.

The analysis further underscores the importance of performance measurement frameworks that integrate traditional lean metrics with sustainability indicators. Digital data environments allow organizations to move from fragmented and retrospective reporting toward real time and evidence-based sustainability governance. By linking operational performance metrics with environmental outcomes, such as material waste intensity, energy use, and carbon emissions, Lean Digital systems provide a practical pathway for translating high level SDG commitments into actionable project level controls.

Despite these demonstrated benefits, the literature reveals persistent challenges related to organizational culture, skills gaps, data interoperability, and uneven levels of

digital maturity across the construction industry. Technological capability alone is insufficient to deliver sustainability outcomes without strong leadership commitment, workforce training, and stakeholder alignment. Consequently, Lean SDG integration should be understood as a socio technical transformation rather than a purely technological upgrade.

Future research should focus on developing standardized and empirically validated frameworks for integrating these technologies, particularly BIM and lean construction methods, to improve collaboration and reduce inefficiencies whilst simultaneously supporting SDG targets and indicators. Case studies are needed to assess the lifecycle sustainability impacts of integration beyond the construction phase, particularly during operations and maintenance activities. In addition, further work is required to explore how emerging technologies, such as advanced artificial intelligence, generative design, and carbon aware digital twins, can enhance predictive sustainability performance while remaining consistent with lean principles of simplicity and value focus. From a practical perspective, industry stakeholders should prioritize integrated training, change management strategies, and policy support mechanisms to ensure that Lean Construction 4.0 contributes meaningfully to global sustainability objectives. That being said the potential and challenges of implementing Lean Construction 4.0 should be explored, including interoperability across digital platforms, data security, and workforce transformation through upskilling and digital literacy.

By positioning Lean Digital integration as a core enabler of SDG aligned construction delivery, this paper reinforces the role of the construction sector as a critical driver of sustainable development and highlights pathways for achieving resilient, efficient, and environmentally responsible built environments.

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