

EXPLORING THE POTENTIAL OF LEAN SUSTAINABLE CONSTRUCTION 4.0: A REFLEXIVE ANALYSIS

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ABSTRACT

The construction industry faces a fundamental crisis due to historically low productivity and its significant contribution to carbon emissions and waste. To address these critical issues across environmental, economic, and social dimensions, this research utilizes a reflexive analysis and philosophical synthesis of the intersection of Lean Construction (LC), Construction 4.0, and Sustainable Construction, resulting in the emerging framework “Lean Sustainable Construction 4.0” (LSC4.0). The aim is to clarify the conceptual and philosophical feasibility of this integration. The main contribution demonstrates that Lean Construction and Sustainable Construction are not opposing domains but are instead mutually enhanced by the intelligence of Construction 4.0, which acts as the epistemological tool for quantifying and predicting value and ecological impact. The discussion emphasizes conceptual synergy, the ontological and epistemological implications (redefining the built object as a cyber-physical system), the challenges in establishing LSC4.0, and the future research directions (maturity models and ethical frameworks) to support the comprehensive transformation of the sector.

KEYWORDS

Lean construction, sustainable construction, construction 4.0, construction industry.

INTRODUCTION

Lean Construction (LC) is a management philosophy inspired by Toyota that aims to maximize customer value and minimize waste (time, effort, materials) throughout the construction process, transforming it into a flow and value-creation model (Ballard, 2000; Koskela, 1992). Construction 4.0, on the other hand, represents the digitalization and automation of the industry, based on the Fourth Industrial Revolution (Industry 4.0), enabled by the integration of innovative and cyberphysical technologies such as Building Information Modeling (BIM), the Internet of Things (IoT), Big Data Analytics, robotics, and additive manufacturing (Garcés, García-Alvarado, et al., 2025; Soares et al., 2021). The overlap of both paradigms arises from a functional integration and convergence of purposes; that is, while LC provides the conceptual and philosophical framework (the “what” and “why” of efficiency and value creation), Construction 4.0 contributes the digital tools and technologies (the “how”), working as a fundamental enabler for implementing Lean principles. Thus, Construction 4.0 technologies (such as BIM for visualizing the value stream or IoT for real-time waste monitoring) not only optimize production but also enable continuous improvement and collaborative planning of LC

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with previously unattainable precision and scale, materializing the motivated concept of LC 4.0 (González et al., 2022; Hamzeh et al., 2021).

Sustainable Construction is the comprehensive approach that seeks to meet the needs of the current generation without compromising those of future generations (Kibert, 2016), balancing the three dimensions of development that involve: the environmental aspect, minimizing ecological impact via resource efficiency, renewable materials, and lower life cycle carbon footprint; the economic aspect, ensuring project viability and profitability both initially and through reduced long-term operating costs; and the social aspect, enhancing equity, health, comfort, and well-being for users and surrounding communities (Strezov et al., 2017; Vilaça et al., 2025). The overlap with LC 4.0 is intrinsic and amplified: Lean principles (waste elimination) become the primary driver of the environmental dimension of Sustainable Construction, since all waste eliminated translates directly into a reduction in resource consumption and waste, while Construction 4.0 acts as the instrumental enabler that allows quantifying, monitoring and optimizing sustainability objectives with precision, ensuring the economic viability of sustainable practices and improving the social quality of the built environment through accurate information (Garcés, Forcael, et al., 2025).

The central objective of this research is to conduct a comprehensive philosophical analysis of the triple alignment of LC, Construction 4.0, and Sustainable Construction, resulting in the emerging framework of “Lean Sustainable Construction 4.0” (LSC4.0). Specifically, it seeks to elucidate the conceptual and philosophical viability of this integration, identifying persistent theoretical and practical gaps, the significant value opportunities it offers, the alignment of goals, and the main challenges to implementing it on a larger scale. Finally, the research will explore the ontological (the redefinition of the built object as a sustainable cyberphysical system) and epistemological (the new data-driven knowledge models) implications of LSC4.0, laying the groundwork for a future research agenda to guide the sustainable and digital transformation of the construction sector.

METHODOLOGY

This research uses qualitative, reflexive analysis and philosophical synthesis to develop the LSC4.0 framework. This kind of investigation contends that research involves more than just reporting facts; it is a process of interpretation and reflection (Alvesson & Sköldberg, 2018). Instead of traditional reviews, it critically examines the ontological and epistemological bases of LC, Construction 4.0, and Sustainable Construction to assess their viability as an integrated paradigm. The design evaluates the “what” and “why” of management philosophies like LC versus the “how” of Technology (Construction 4.0), highlighting digitalization as key to multidimensional sustainability.

The framework development involved three steps. First, it evaluated how cyberphysical technologies like BIM, IoT, and AI integrate with LC and Construction 4.0 to translate Lean principles into automated, verifiable processes. Second, it identified synergies, such as waste reduction as an environmental driver, and tensions, like the paradox between Just-in-Time efficiency and supply chain resilience. Finally, it redefined the built object from a static physical structure to a sustainable cyberphysical system with long-term ecological traceability.

LEAN CONSTRUCTION 4.0

LEAN CONSTRUCTION PHILOSOPHY: FROM WASTE TO VALUE

LC is a production management philosophy that aims to maximize customer value by systematically eliminating waste, including errors, overproduction, waiting, and unused talent (Koskela, 1992). Epistemologically, LC operates as a dynamic model that arises from attempting to solve specific industry problems by applying and adapting generic Lean

Manufacturing principles (Koskela, 2020). This approach is based on key principles such as specifying value, ensuring flow, and driving perfection (Forbes & Ahmed, 2020; Pandithawatta et al., 2019), and is structured around the “4Ps” (Philosophy, Process, People, Partners, and Problem Solving) (Nandini et al., 2023). The LC’s success lies in its holistic approach to continuous improvement, recognizing that people, processes, and technology are connected and that the flow of value (Transformation, Flow, and Value) impacts information systems and problem-solving (Forbes & Ahmed, 2020; Garcés & Peña, 2023).

In this sense, LC, which emerged from the adaptation of the Toyota Production System, has evolved from its initial focus on reducing losses and waste (materials, time, overproduction, waiting, etc.) to a comprehensive philosophy that seeks to maximize value for the end customer through continuous improvement and efficiency in project delivery (Forbes & Ahmed, 2020; Koskela, 2020). This evolution prioritizes creating a stable, predictable workflow, minimizing variability, and fostering collaboration among all project participants. The main LC tools for achieving this value and efficiency include: the Last Planner System (LPS), which improves collaborative planning and production control; Value Stream Mapping (VSM), for mapping and identifying non-value-adding activities; and the 5S methodology for organizing and improving the workplace, and the Just-In-Time (JIT) system for inventory and materials management (Gupta & Elhag, 2025; Perez & Ghosh, 2018).

Despite the benefits of the LC philosophy, it needs to proactively respond to the sector’s ongoing changes by incorporating technology and sustainable building practices to meet better the industry’s complex environmental, economic, and social issues. The integration of technologies such as BIM, Artificial Intelligence (AI), robotics, and modular construction not only enhances Lean tools (such as LPS and VSM) but also enables more precise waste reduction and energy and resource optimization from the design phase (Bou Hatoum & Nassereddine, 2022; Hamzeh et al., 2021). This combined effect is crucial for driving decarbonization in construction, promoting the use of low-impact materials, and creating a more resilient and socially just built environment, thus establishing LC as a key factor in delivering higher-value projects and supporting sustainable development (Garcés, Forcael, et al., 2025).

CONSTRUCTION 4.0

Construction 4.0 is an evolutionary framework representing the specific digitalization and industrialization of the construction sector, emerging as a direct extension of Industry 4.0 (Soares et al., 2021). Its evolution focuses on moving from traditional processes to advanced systems, leveraging technological progress to integrate industrial production, cyberphysical systems, and digital technologies (Muñoz-La Rivera et al., 2021). The aim is to revolutionize the industry by focusing on automation, connectivity, and digital transformation (Forcael et al., 2020). Construction 4.0 relies on a variety of core tools and technologies, such as: BIM, drones, virtual and augmented reality, new materials, cloud-based project management, blockchain and cybersecurity, AI, big data, laser scanners, robotics and automation, wearable sensors, the Internet of Things (IoT), additive manufacturing (3D printing), and prefabricated construction (Chen et al., 2022; Muñoz-La Rivera et al., 2021). Additionally, this framework encompasses broader concepts such as LC and digital construction ecosystems (Hamzeh et al., 2021).

Construction 4.0 technologies fall into three categories: (a) *Automation*, integrating digital engineering with robotics and prefabricated construction; (b) *Simulations and Modeling*, using models and simulations like BIM and virtual reality for design and operation; and (c) *Digitization and Virtualization*, focusing on digital and virtual implementation of products and processes (Muñoz-La Rivera et al., 2021). Integrating these categories facilitates effective information exchange between the virtual project (digital model) and the physical construction site. For instance, linking BIM (Modeling) with on-site IoT sensors (Digitization) enables real-time data collection and robotic system control (Automation), supporting the ongoing

development and updating of a digital twin. This real-time data exchange (thanks to cloud computing and Big Data) ensures that the virtual model accurately reflects the physical state and that automation decisions are based on accurate data, maximizing efficiency and quality throughout the construction project lifecycle (Garcés, García-Alvarado, et al., 2025).

LEAN CONSTRUCTION 4.0 FUNDAMENTALS

The LC 4.0 defines the functional integration and convergence of LC philosophy and the technologies of Construction 4.0, transcending the mere sum of its parts (Hamzeh et al., 2021). LC, focusing on value maximization and waste elimination through flow management and continuous improvement, establishes the framework (the “what” and the “why”) (González et al., 2022). Construction 4.0, enabled by technologies such as BIM, IoT, Big Data, and automation, provides the instrumental means (the “how”) to achieve LC principles with unique precision, scale, and speed. According to Hamzeh et al. (2021), LC must leverage the changes driven by Industry 4.0 while retaining its three core pillars (people, processes, and technology), now digitally enhanced. This synergy not only optimizes operational efficiency but also transforms the nature of production, creating a cyberphysical system where decision-making is driven by real-time data, consolidating a continuous, agile, and high-quality value stream.

The practical benefit of the LC 4.0 paradigm lies in achieving radical efficiency and flawless planning, which were earlier only theoretical goals. For example, combining the LPS with AI enables predictive analysis of subcontractor commitments, identifying and mitigating the causes of variability and waste before they impact the Weekly Work Plan (WWP) (Lagos et al., 2024). Another example is Digital Value Stream Mapping (VSM) with IoT sensors, which maps workflow and material locations in real time, eliminating waste from waiting and transportation. It enables JIT delivery and assembly, reducing inventory and site congestion (Albalkhy et al., 2024). Thus, LC 4.0 transforms Lean’s philosophical principles into automated and verifiable processes, elevating continuous improvement to a systemic, data-driven level. Additionally, recent research highlights progress in the construction industry via other technologies such as BIM and AI integration (Valdebenito & Forcael, 2025).

Despite its promise, the implementation of LC 4.0 faces significant challenges that shape the future research agenda. The main obstacle is the skills gap and cultural resistance in an industry slow to adopt digital tech, requiring focus on training and change management (Shang & Sui Pheng, 2014). Still, there are challenges with the interoperability of Construction 4.0 platforms and the security and governance of site-generated data. The future agenda should focus on developing maturity assessment frameworks for integrating Lean and Construction 4.0 and researching models that not only optimize processes through automation but also enhance social conditions and work ethics in advanced environments.

SUSTAINABLE CONSTRUCTION

The construction industry, despite being an economic pillar that contributes 13% to global GDP and employs over 220 million people, faces three critical challenges (Barbosa et al., 2017). Economically, the sector suffers from chronic productivity stagnation, with growth of only 1% over 20 years, compromising its efficiency and competitiveness (Barbosa et al., 2017; United Nations Environment Programme, 2020). On the other hand, the social impact requires better working conditions and stronger communities, highlighting the industry’s need to adopt sustainable construction by integrating environmental, economic, and social pillars to ensure its future viability (Barbosa et al., 2017).

Sustainability in construction is defined by the balance of three interdependent dimensions (Garcés, Forcael, et al., 2025). Environmental sustainability involves reducing resource use (water, energy, virgin materials), managing waste efficiently, and lowering greenhouse gas emissions throughout a building’s life cycle to minimize environmental impact (Kibert, 2016).

Economic sustainability aims for long-term viability and profitability by reducing operating costs through energy efficiency, increasing productivity, and creating added value (Carvajal et al., 2019). Social sustainability, in turn, emphasizes positive impacts on people, such as improved safety, better working conditions, equitable infrastructure, and stronger community engagement. These three dimensions are crucial for construction because their integration turns projects from simple investments into assets that maximize environmental value, reduce economic risk, and enhance quality of life for users and society (Goh et al., 2020).

OVERLAP BETWEEN LEAN CONSTRUCTION 4.0 AND SUSTAINABLE CONSTRUCTION

Despite the remarkable improvements achieved through LC implementation over the past three decades, the construction industry continues to face structural crises that demand a more profound reformulation. The sector is a major contributor to global problems, responsible for a high percentage of carbon emissions, energy consumption, and waste generation worldwide (Tafazzoli et al., 2020). On the economic dimension, historically low productivity, volatile material costs, and persistent inefficiencies, despite Lean practices, demonstrate that waste elimination must evolve to encompass the entire asset lifecycle, rather than just the execution phase (Bou Hatoum & Nassereldine, 2022). Finally, from a social perspective, it calls for better working conditions, safety, and infrastructure that ensure community well-being and equity (Abu Aisheh et al., 2022), beyond just controlling variability and simplifying processes. Figure 1 concisely illustrates the evolution of construction, moving from traditional construction to Lean Sustainable Construction 4.0 by integrating LC principles and Construction 4.0 technologies within a three-dimensional sustainability framework.

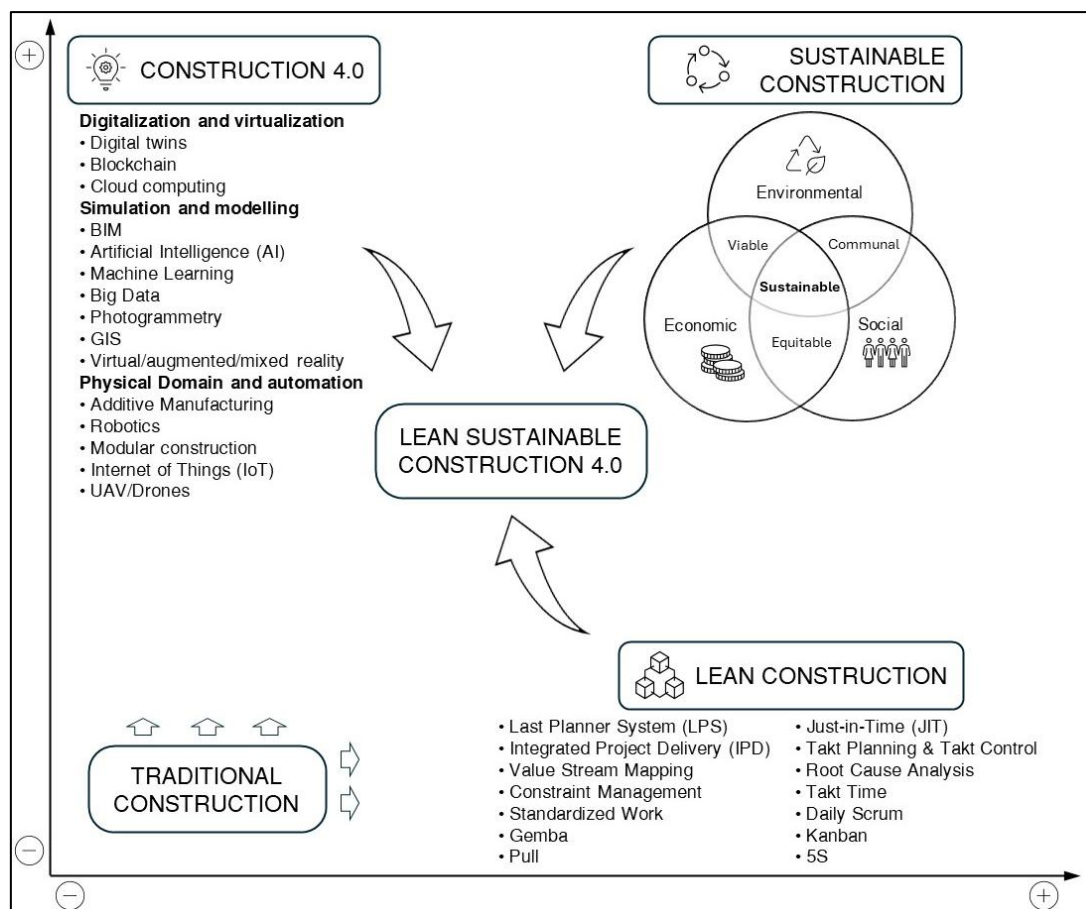


Figure 1: Lean sustainable construction 4.0.

To address the critical challenges faced by traditional construction, which, according to Figure 1, corresponds to such construction with little Lean Construction and little Construction 4.0, Lean philosophy must move beyond its focus on productive efficiency and strategically align with two transformative forces: Sustainable Construction and Construction 4.0. The technological advancements of Construction 4.0 (digitalization and industrialization) are not merely tools but indispensable enablers that empower resource traceability, real-time environmental impact monitoring, and predictive optimization, taking Lean waste reduction to its digital apex. This integration must meet Sustainable Construction's goals, balancing economic, environmental, and social benefits (Vilaça et al., 2025). Only by articulating this LSC4.0 paradigm can the industry meet evolving global demands, transforming its current model into an intelligent solution for the future of global building and infrastructure.

According to Figure 1, an example of implementing LSC4.0 is the robotic prefabrication of modular façade components from recycled materials. In this model, Lean principles such as Just-in-Time (JIT) and Takt Time are used to synchronize production flow, eliminating on-site inventory waste and waiting times. Construction 4.0 technologies, like robotics and BIM, serve as the "how," providing automation and digital traceability needed to manufacture complex modules with precision. This integration directly supports sustainability goals; using recycled materials reduces the environmental footprint, while moving hazardous construction tasks into a controlled factory environment significantly improves workplace safety and social sustainability. Ultimately, this creates a cyber-physical system where real-time data ensures that efficiency (Lean) and digital intelligence (4.0) are focused on achieving a high-value, low-impact built environment.

Thus, the LSC4.0 paradigm emerges from the functional integration and convergence of purposes, aiming to overcome the limitations of each approach in isolation. The fundamental theoretical contribution of LSC4.0 lies in establishing that the radical efficiency of LC and the comprehensive sustainability of Sustainable Construction are not opposing objectives, but instead mutually enabled and amplified by the digitalization and intelligence of Construction 4.0. Within this framework, LC embodies waste elimination, enhancing resource efficiency and reducing environmental impact, which are core to Sustainable Construction. Construction 4.0 (via BIM, IoT, Big Data) serves as the epistemological tool for quantifying, tracing, and optimizing value and sustainability goals throughout the project lifecycle. This overlap creates a cyberphysical system in which continuous improvement (Lean) is managed using real-time data (Construction 4.0), boosting the economic viability of green practices and enhancing social aspects through transparency and quality (Tafazzoli et al., 2020; Vilaça et al., 2025).

Despite LSC4.0's conceptual richness, consolidating this paradigm faces challenges in shaping future research. The primary challenge is the sector's organizational and cultural fragmentation, which hinders the adoption of collaborative methodologies and investment in Construction 4.0 technologies necessary for truly sustainable Lean implementation (Tafazzoli et al., 2020). Epistemological and ontological gaps need to be addressed: how to calibrate the reliability of AI-driven automated decisions in sustainable construction, and how to redefine the "built object" as a cyberphysical system that must operate in accordance with both Lean value metrics and long-term ecological impact? The future agenda should focus on developing integrated maturity models that simultaneously assess all three domains, formulating ethical frameworks for data use and automation within the circular economy, and creating governance mechanisms that align short-term financial incentives with long-term sustainability goals.

Table 1 illustrates the overlap among Construction 4.0, Sustainable Construction principles, and LC principles/tools, which together form the Lean Sustainable Construction 4.0 paradigm.

Table 1: Paradigm overlap: LSC4.0 in practice

Construction 4.0 Technologies	Principles of Sustainable Construction	LC Principles/Tools	Practical example of LSC4.0
BIM (Building Information Modeling)	• Environmental: Resource optimization and passive design. • Economic: Reduction of variability and collisions.	• Value Stream Mapping and visualization • Perfection: interference and error analysis	<i>n</i> D BIM allows early energy simulation and accurate material calculations, reducing waste and enhancing thermal performance.
IoT (Internet of Things), Sensors	• Environmental: Post-occupancy energy and water consumption monitoring. • Social: Monitoring safety and working conditions.	• Waste Reduction: identifying waste caused by waiting or errors. • Visual Control (Gemba). • 5S (Seiri and Seiton): detecting tools/materials out of place.	On-site sensors monitor machinery downtime and energy in real time, reducing waste and optimizing use (Economic/Lean).
Robotics and Prefabrication / Modular Construction	• Environmental: Waste reduction and improved manufacturing quality. • Social: Improved workplace safety (by moving hazardous tasks to a controlled environment).	• Guaranteeing flow: standardization and continuous production flow. • Reducing variability. • Just-in-Time (JIT): delivery of prefabricated components. • Takt Time: synchronization of the modular production flow.	Facade modules are robotically manufactured using recycled materials and assembled on-site. This approach employs JIT delivery, reducing noise (Social) and minimizing waste (Environmental/Lean)
Big Data Analytics, Artificial Intelligence (AI)	• Economic: Supply chain optimization and risk mitigation. • Environmental: Life cycle impact (LCA) prediction.	• Perfection: continuous improvement based on learning. • Pull: planning based on actual demand. • LPS: root cause analysis of failures. • Daily Scrum: a fundamental part of the Agile methodology.	AI analyzes past project data to forecast cost deviations and assess the CO ₂ impact of various design options, supporting informed economic and environmental decisions.
Drones and 3D Laser Scanning	• Social: Remote inspection that improves security and accessibility. • Economic: Speed up capture of status and progress.	• Increased Process Transparency. • Complete process control (check). • LPS: collaborative planning (Pull planning) • Daily Meetings (digital/hybrid).	Drones that compare the current state of the work with the BIM model (visual control) to quickly identify deviations that could generate rework and delays (Economic/Lean).

DISCUSSION

ANALYSIS OF THE CONCEPTUAL AND PHILOSOPHICAL SYNERGY OF THE TRIPLE OVERLAP

The convergence of Lean, Sustainability, and Construction 4.0 is redefining value creation in the AEC sector, shifting from a model focused on efficiency (waste minimization) to a model based on holistic impact management (Vilaça et al., 2025). The waste elimination principles of Lean and the digitalization of Construction 4.0 initially reinforce each other: technologies such as BIM, IoT, and Digital Twins enable the identification, prediction, and mitigation of waste with a precision and scope unattainable in traditional methods, optimizing value streams and physical resources. However, this integration reveals critical conflicts and tensions. The paradox of the digital carbon footprint emerges as a central challenge: while digitalization enables the optimization of physical resources and reduces waste on the construction site

(aligning with Sustainability and Lean), the required technological infrastructure (servers, data centers, devices) has a growing carbon and material footprint, straining the principle of zero systemic impact in Sustainability (Tafazzoli et al., 2020). This contrast requires reinterpreting value and considering the information footprint as a new form of waste to be managed.

The systemic approach to Sustainability acts as a framework that exposes the limitations of purely operational Lean and technological Industry 4.0 approaches, particularly in supply chain management (Shang & Sui Pheng, 2014). Lean's Just-in-Time (JIT) philosophy, while highly efficient in reducing inventory and storage costs, directly conflicts with the imperative of resilience in an environmentally friendly supply chain. A highly efficient JIT system is naturally vulnerable to environmental, social, or geopolitical disruptions, which can threaten the continuity and ecological traceability of materials. Sustainability, which emphasizes a whole life-cycle approach and a circular, regenerative supply chain, necessitates adding strategic redundancy, similar to systemic responsiveness or inventory, to absorb shocks, conflicting with the Lean principle of minimizing stock (Carvajal et al., 2019; Nandini et al., 2023). Therefore, high-impact research must model a sustainable "Just-in-Case" that incorporates digital twins and predictive analytics to balance Lean efficiency with resilience and ecosystem responsibility, laying the foundation for a new LSC4.0 management paradigm.

ONTOLOGICAL AND EPISTEMOLOGICAL IMPLICATIONS OF THE LSC4.0 PARADIGM

It is necessary to address how this new paradigm of LSC4.0 redefines the nature (ontology) of what a construction project is and how the knowledge (epistemology) to manage it is acquired. On the one hand, the integration of Lean, Sustainability, and Construction 4.0 demands a fundamental redefinition of the construction project's ontology; in other words, it is no longer just a completed physical structure but has become a sustainable cyber-physical system (Ghansah & Lu, 2025a). This redefinition suggests that the constructed "object" inherently encompasses its digital twin and operational data streams, rendering long-term functionality and ecological traceability intrinsic to its identity. Lean's zero-waste ethic extends beyond project execution to become a post-occupancy responsibility overseen by a cyberphysical system. The system continuously monitors energy performance and resource usage, generating inefficiency alerts that are interpreted as new forms of waste during the usage phase (Tafazzoli et al., 2020). This approach compels the industry to internalize the costs and value of the entire life cycle from the design stage, elevating sustainability from a supplementary requirement to an intrinsic property of the system.

Furthermore, this new sustainable cyberphysical system objective demands a radical shift in the epistemology of project management, moving towards data-driven decision-making (Ghansah & Lu, 2025a; Tafazzoli et al., 2020). Knowledge of management is no longer based primarily on linear experience and static documentation, but rather on the predictive and prescriptive interpretation of large volumes of real-time data generated by the Digital Twin and the digital supply chain. Nevertheless, this reliance on data raises significant, high-stakes issues: the trustworthiness of the input (sensor performance, compatibility) and, most importantly, potential algorithmic bias. Optimization models (e.g., for JIT or Net-Zero operations) trained on historical data can perpetuate and amplify past inefficiencies or unsustainable externalities (Si et al., 2021). Therefore, high-impact research must develop data ethics frameworks that ensure decision algorithms prioritize ecological resilience and social equity, mitigate bias, and ensure that digitization is a true sustainable enabler rather than a new source of waste and systemic risk.

CHALLENGES AND BARRIERS TO THE CONSOLIDATION AND ADOPTION OF LSC4.0

The main impediment to the large-scale implementation of the LSC4.0 paradigm lies in the triple friction of human, regulatory, and financial factors. On the human level, cultural resistance runs deep: the construction industry, historically tied to fragmented and hierarchical practices, exhibits considerable inertia toward the transparent collaboration and information flow demanded by Lean and Construction 4.0. This resistance increases due to a significant skills gap, in which the workforce may lack the necessary competencies to operate and interpret digital tools such as BIM and IoT, or to apply lifecycle thinking (Shang & Sui Pheng, 2014). This discrepancy between the need for a collaborative, technologically skilled workforce and the current capabilities hinders the transition, limiting companies' ability to capitalize on digital efficiencies and sustainability mandates, and relegating LSC4.0 to pilot projects rather than widespread adoption.

Furthermore, at a structural level, the slow regulatory and governance framework is insufficient to keep pace with the rapid pace of technological change and the urgent demands of sustainability (Garcés, Forcael, et al., 2025). Building codes and construction standards, initially developed under a linear, prescriptive framework, do not align with the flexible, performance-based approaches necessary for Construction 4.0 or with the circular economy goals of sustainability as long as success is measured solely by short-term cost savings, following traditional Lean principles, rather than by comprehensive value, including sustainability and resilience, the LSC4.0 model will be viewed as an extra expense rather than a strategic investment. This perception will continue to limit widespread adoption.

FUTURE RESEARCH AGENDA AND LSC4.0

The theoretical integration of Lean, Sustainability, and Industry 4.0 has revealed a significant knowledge gap that demands the urgent development of integrated maturity models. These frameworks must go beyond the linear evaluation of each paradigm separately and simultaneously measure the functional interdependence among digital maturity (Industry 4.0), operational excellence (Lean), and ecosystem performance (Sustainability), a methodological void. The most promising research direction lies in the predictive role of AI and machine learning (Lagos et al., 2024), particularly in developing predictive models of the environmental impact of waste. These models will utilize Digital Twins to simulate waste propagation, physical, temporal, and data-related, across the entire lifecycle (Ghansah & Lu, 2025a), supporting prescriptive interventions rooted in circularity ethics. Finally, it is essential to establish the necessary ethical and governance frameworks for Modular Construction 4.0 and the Circular Economy, which must address how decisions made in the digital design phase (e.g., the use of BIM or digital twins) directly influence the responsibility for modular components after their useful life.

PRACTICAL IMPLICATIONS

The Lean Sustainable Construction 4.0 (LSC4.0) paradigm translates into transformative practical implications by strategically overlapping the three approaches. The implementation of technologies such as 5D/6D BIM (Construction 4.0) enables economic optimization by pre-calculating and reducing over-purchasing of materials (LC's Just-in-Time approach). This viewpoint, when integrated with energy and thermal simulation calculations, results in reduced post-occupancy (sustainable) environmental consumption. Similarly, the use of IoT and sensors for real-time monitoring of energy consumption or equipment downtime enables immediate identification of waste (Lean's waiting time and energy waste), generating benefits in both economic sustainability (cost savings) and environmental sustainability (reduced footprint).

Furthermore, robotics and modular construction enable the Just-in-Time manufacturing of prefabricated components (Lean), which not only reduces waste (Environmental) but also relocates hazardous tasks to a controlled environment, improving workplace safety and the social dimension of sustainability. This integration of digital tools converts them into cyberphysical systems that support the economic sustainability of green practices and social responsibility, demonstrating that value is maximized only when efficiency (Lean) (Hatoum & Nassereddine, 2023) is intelligently managed (Construction 4.0) (Ghansah & Lu, 2025b) and focused on comprehensive impact (sustainability) (Vilaça et al., 2026).

The LSC4.0 paradigm benefits the entire construction value chain by integrating efficiency, technology, and sustainability. Clients and owners are the primary beneficiaries, gaining access to higher-value assets, reduced lifecycle costs, and better environmental performance. Contractors and subcontractors significantly boost productivity and reduce costs by eliminating waste through cyber-physical optimization methods, such as 5D/6D BIM and robotics/JIT. Society and end users benefit from improved workplace safety (by transferring hazardous tasks to robotics) and a higher-quality built environment with a reduced environmental impact. At the same time, governments and investors find that data traceability reduces project risk and facilitates compliance with the Sustainable Development Goals (SDGs), solidifying LSC4.0 as a driver of economic, environmental, and social value.

CONCLUSIONS

The research establishes that the answer to the important challenges of the construction industry (its low productivity growth and disproportionate environmental impact) lies in articulating a new paradigm: Lean Sustainable Construction 4.0. This framework goes beyond individual methods by suggesting that the radical efficiency of LC and comprehensive sustainability are not conflicting objectives. Instead, they support and enhance each other through digitalization, enabling Construction 4.0 (BIM, IoT, Big Data, and Robotics). LSC4.0 not only takes the Lean philosophy of waste elimination to its cyberphysical enablement and optimization to reduce the environmental footprint, but also, through cyberphysical systems, provides the epistemological tools for the quantification, traceability, and predictive optimization of ecological, economic, and social value and impact throughout the life cycle. While cultural fragmentation and the need to develop integrated maturity models to calibrate the reliability of automated decisions pose significant future challenges, strategic convergence in LSC4.0 is essential. It is the crucial path to transform the industry's current production model into a comprehensive, intelligent, and ethical system that ensures the economic, environmental, and social sustainability of global building.

The theoretical integration of Lean, Sustainability, and Construction 4.0 (LSC4.0) establishes a new and urgent paradigm for the AEC sector, redefining the project ontology as a sustainable cyberphysical system and demanding an epistemological transition toward data-driven decision-making. However, this ideal vision faces systemic obstacles that constitute the most critical knowledge gaps for high-impact research. The central tension arises from the need to harmonize Just-in-Time efficiency with ecological resilience, forcing the industry to reinterpret "value creation" to include non-financial value and manage the paradox of the digital carbon footprint. Future research efforts should focus on developing Integrated Maturity Models that simultaneously assess Lean, Digital, and Sustainable (environmental, economic, and social) performance, leveraging the potential of AI to predict the multidimensional impact of waste and mitigate algorithmic bias in sustainable decision-making across all three dimensions. Bridging the skills gap and aligning the regulatory framework with the speed of circular innovation will be critical for LSC4.0 to move beyond pilot projects and become industry standard practice, laying the foundation for an ethic of circularity and post-occupancy responsibility in the built environment.

ACKNOWLEDGMENTS

This research was supported by the National Research and Development Agency (ANID) of the Government of Chile, Doctoral Scholarship Program Abroad (ANID Scholarship/Foreign Doctorate-2025/72250078), and Fondecyt Regular/Grant number: 1251708. This work was also supported by Vicerrectoría de Investigación y Doctorados de la Universidad San Sebastián-Fund number USS-FIN-26-CNGI-06.

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