The Relationship between Lean Construction and Sustainable Construction: The Positive Effects of Lean Methodology on Sustainability in Construction

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Abstract

This study aimed to examine the relationship between lean construction and sustainable construction and identify the lean construction dimensions and implementation factors that significantly enhance economic, social, and environmental sustainability in the Iranian construction industry. This applied quantitative study used a survey-based design involving 136 construction-industry professionals, including employers, contractors, consultants, and managers. A closed-ended questionnaire was developed from the literature and expert opinions to measure five lean construction dimensions—teamwork culture, continuous improvement, customer focus, waste elimination, and standardization—and sustainable construction. Sampling adequacy was confirmed by a Kaiser–Meyer–Olkin coefficient of 0.7039. Partial least squares structural equation modeling was conducted in SmartPLS, with bootstrapping based on 500 resamples. Measurement-model reliability and convergent validity were evaluated using factor loadings, Cronbach's alpha, composite reliability, and average variance extracted. Interpretive structural modeling and MICMAC analysis were subsequently employed to determine the hierarchical relationships, driving power, and dependence power of the statistically significant lean factors. The structural model explained 84.5% of the variance in sustainable construction. Customer focus had a significant positive effect on sustainable construction ($t = 3.224$, $p = 0.001$), as did waste elimination ($t = 2.023$, $p = 0.043$) and standardization ($t = 4.934$, $p < 0.001$). Conversely, teamwork culture ($t = 1.057$, $p = 0.291$) and continuous improvement ($t = 1.192$, $p = 0.234$) did not demonstrate significant effects. MICMAC analysis classified flexible resources, value optimization, and visual management as key driver variables. Reducing cycle time and defined processes were linkage variables, whereas production-system optimization, work-content optimization, and project-workplace organization were dependent variables. Sustainable construction can be substantially strengthened through the systematic implementation of customer-focused practices, waste-elimination mechanisms, and standardized processes. Prioritizing flexible resource allocation, value optimization, and visual management may create the foundational conditions required for broader lean implementation and improved sustainability performance across construction projects.

Keywords: *Lean Construction; Sustainable Construction; Lean Methodology; Structural Equation Modeling; Interpretive Structural Modeling; MICMAC Analysis.*

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1. Introduction

The construction industry plays a central role in economic development, urbanization, infrastructure provision, employment creation, and the formation of the built environment; however, it is also associated with extensive material consumption, energy use, waste generation, occupational hazards, carbon emissions, schedule overruns, cost escalation, and fragmented project delivery. These characteristics have intensified pressure on construction organizations to move beyond conventional performance criteria focused primarily on cost, time, and quality and to

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adopt management approaches capable of simultaneously addressing economic efficiency, environmental responsibility, and social well-being. Sustainable construction has consequently emerged as a comprehensive response to the need for buildings and infrastructure that satisfy present requirements without undermining the capacity of future generations to meet their needs. In this context, sustainability is not limited to environmental protection but encompasses the coordinated management of economic, social, and environmental outcomes throughout the life cycle of construction projects. Recent research has increasingly emphasized that sustainability must be embedded in project planning, procurement, supply chains, workplace practices, risk management, and organizational decision-making rather than being treated as an isolated environmental objective. The transition from traditional risk management to sustainable risk management further demonstrates that construction organizations need integrated systems capable of identifying long-term environmental, social, operational, and governance-related risks alongside conventional project uncertainties [1]. Accordingly, achieving sustainability requires both technical innovations and managerial transformations that improve resource efficiency, stakeholder value, process reliability, safety, adaptability, and long-term organizational performance.

One of the most influential managerial approaches proposed for improving construction performance is lean construction. Lean construction transfers the fundamental logic of lean production to the project-based, temporary, and highly fragmented environment of construction. Its central principles include maximizing value, minimizing waste, improving workflow, reducing variability, supporting continuous improvement, strengthening coordination, and ensuring that resources are used only for activities that contribute to project objectives. Unlike traditional construction management, which often treats individual tasks and organizations as separate units, lean construction views project delivery as an interconnected production system in which delays, rework, waiting, defects, excess inventory, inefficient movement, poor communication, and unreliable planning can generate cumulative losses. Lean practices therefore seek to improve the predictability and continuity of work while aligning production activities with customer-defined value. The relevance of this approach has expanded as construction organizations face increasing demands for higher productivity, shorter delivery times, reduced costs, improved quality, safer workplaces, and lower environmental impacts. Pan and Pan argued for a synergistic reconsideration of lean implementation in practice, emphasizing that construction improvement depends on the coordinated application of lean principles rather than the fragmented adoption of isolated tools [2]. This perspective is particularly important because organizations may formally introduce lean terminology while failing to establish the cultural, procedural, and interorganizational conditions necessary for sustained implementation.

The conceptual relationship between lean construction and sustainable construction is grounded in their shared concern with efficient resource use, waste reduction, value creation, and long-term performance. Lean construction traditionally identifies waste as any activity that consumes resources without creating value for the customer, whereas sustainable construction broadens the concept of waste to include environmental degradation, excessive energy and material consumption, unsafe conditions, social inequity, and life-cycle inefficiency. When these perspectives are integrated, lean methods can support sustainability by reducing rework, defects, overproduction, waiting time, unnecessary transportation, excessive inventory, inefficient movement, and underutilized human capability. These improvements can generate economic benefits through lower costs and higher productivity, environmental benefits through decreased resource consumption and pollution, and social benefits through safer working conditions, clearer responsibilities, improved collaboration, and more reliable project outcomes. Circular economy research in the built environment likewise emphasizes the need to retain the value of materials, products, and building components for as long as possible and to reduce dependence on linear patterns of extraction, consumption, and disposal. Ossio, Salinas, and Hernández conceptualized circular construction as a significant component of the broader transition toward a circular built environment [3]. Similarly, Chen, Feng, and de Soto examined the redesign of construction supply-chain processes through circular economy strategies, highlighting the importance of transforming material flows, procurement practices, and interorganizational relationships [4]. These concerns strongly intersect with lean objectives related to flow improvement, waste elimination, supply-chain coordination, and value optimization.

Construction supply chains are especially important to the lean–sustainability relationship because construction projects depend on extensive networks of clients, designers, consultants, contractors, subcontractors, suppliers, logistics providers, and regulatory institutions. Fragmentation among these actors can lead to delayed information, inconsistent standards, overordering, material shortages, inappropriate inventory, transportation inefficiencies, and poor coordination between design and execution. Lean supply-chain management seeks to improve transparency, synchronize production and delivery, enhance supplier relationships, and reduce non-value-adding activities across organizational boundaries. Sustainable supply-chain management extends these considerations by incorporating environmental performance, ethical practices, labor conditions, resource responsibility, and life-cycle impacts into supplier assessment and selection. Küpeli and Sertyeşilışık developed a preliminary set of supplier-selection criteria based jointly on lean and sustainability considerations, demonstrating the growing need to evaluate suppliers according to operational efficiency as well as environmental and social performance [5]. Information and communication technologies can further strengthen these processes by supporting traceability, information exchange, material recovery, scenario analysis, and data-informed decision-making. Yu and colleagues reviewed technology-based decision-support tools for circular economy implementation in the construction industry and showed the strategic relevance of digital systems to circular and resource-efficient project decisions [6]. Therefore, the integration of lean, circular, and digital practices may provide a stronger basis for improving construction sustainability than the independent application of any single approach.

The social dimension of sustainability is equally significant because construction activities expose workers and project stakeholders to substantial occupational, ergonomic, organizational, and psychological risks. Sustainable construction must therefore protect worker health and safety, improve workplace organization, strengthen participation, promote ethical conduct, and ensure that project value is not achieved at the expense of human well-being. Lean construction can contribute to this dimension by improving workflow visibility, standardizing hazardous procedures, reducing congestion and unnecessary movement, identifying constraints before execution, and encouraging workers to participate in problem-solving. Nevertheless, poorly designed lean systems may also intensify workloads or transfer pressure to employees if productivity goals are pursued without adequate attention to human factors. Research on occupational health and safety in modular integrated construction illustrates the need to assess emerging production systems carefully, particularly in complex activities such as crane operations where process efficiency and worker protection must be managed simultaneously [7]. The construction of sustainable workplace health indicators also reflects a broader movement toward measurable organizational systems that integrate employee health, workplace conditions, and managerial accountability [8]. Ethical leadership is relevant in this regard because the implementation of sustainability and lean practices depends on leaders who can balance performance expectations with fairness, responsibility, transparency, and stakeholder welfare. Although developed in the context of higher education, the construction and validation of a sustainable ethical leadership scale in Iran demonstrates the growing importance of leadership models that connect ethical conduct with long-term institutional sustainability [9].

Organizational culture and professional identity also influence whether lean and sustainable practices become embedded in daily project routines. Lean implementation requires more than technical procedures; it depends on shared assumptions about collaboration, learning, responsibility, problem-solving, and value. Managers must create an environment in which employees can identify inefficiencies, communicate errors, participate in improvement, and coordinate across professional boundaries. The development of leadership identity, especially among individuals newly assuming managerial responsibility, can shape how authority, accountability, and organizational change are interpreted. Blose and colleagues' narrative examination of how novice school principals construct their professional selves, although situated outside construction, illustrates the broader organizational significance of identity formation in leadership practice [10]. Such insights are relevant to construction because project managers and site leaders frequently operate in transitional, high-pressure environments where their interpretation of leadership affects trust, participation, learning, and the acceptance of new methods. Similarly, Six Sigma principles have been applied beyond industrial production to improve complex service systems. Wang and Liu's investigation of factors affecting Six Sigma management in the development of a student mental health service system illustrates the cross-sector transferability of process-improvement principles and the importance of contextual, organizational, and managerial conditions in determining their effectiveness [11]. These studies collectively suggest that the success of lean and sustainability initiatives depends not only on the intrinsic quality of the techniques but also on the human systems through which they are implemented.

Integrated project delivery and collaborative contracting arrangements can provide an institutional setting conducive to lean construction because they promote early stakeholder involvement, shared objectives, coordinated decision-making, transparent information, and collective responsibility for outcomes. In large and complex projects, however, successful integration requires specific competencies in collaboration, systems thinking, digital coordination, planning reliability, conflict management, and continuous improvement. Evans and colleagues proposed a competency framework for integrating lean construction with integrated project delivery in construction megaprojects, linking lean implementation to the evolving future of work in multinational engineering organizations [12]. This competency-oriented approach indicates that lean–sustainability integration cannot be achieved merely by issuing organizational directives; it requires deliberate investment in workforce capabilities, cross-functional learning, and governance structures. Lean methods may also contribute to dispute prevention by improving process transparency, clarifying responsibilities, identifying deviations early, and reducing the operational failures that frequently develop into contractual conflict. Jagannathan and colleagues examined the application of lean principles for the early identification and avoidance of disputes in construction projects, demonstrating that lean management has implications not only for production efficiency but also for relational and contractual performance [13]. Reduced disputes can, in turn, support sustainability by limiting rework, delays, resource losses, adversarial behavior, and the economic and social costs of project conflict.

Despite the theoretical complementarity of lean construction and sustainable construction, implementation remains difficult, particularly in small and medium-sized firms and in developing construction markets. Barriers may arise from limited awareness, insufficient training, resistance to change, fragmented supply chains, conventional contractual structures, short-term cost priorities, inadequate technological infrastructure, weak managerial commitment, and uncertainty regarding the practical benefits of lean methods. Small and medium-sized construction enterprises may face additional constraints because they often possess fewer financial, technical, and human resources for formal process-improvement programs. Silva, Ranadewa, and Rathnasinghe examined the barriers and strategies associated with implementing Lean Six Sigma in construction SMEs through a fuzzy TOPSIS approach, highlighting the need to prioritize context-specific implementation challenges and corrective strategies [14]. In Ethiopia, Maru, Jekale, and Astrey similarly applied integrated fuzzy analytic hierarchy process and fuzzy TOPSIS methods to analyze barriers to lean construction and strategies for overcoming them [15]. These studies demonstrate that implementation barriers are interdependent and should be addressed through structured prioritization rather than isolated interventions. They also show the value of combining expert judgment with analytical methods when reliable archival data are limited or when multiple qualitative and quantitative criteria must be considered simultaneously.

The integration of lean construction and sustainability therefore requires analytical frameworks capable of identifying which lean dimensions exert meaningful effects on sustainable construction and which operational factors should receive priority during implementation. Not all lean practices necessarily have identical sustainability consequences, and their effects may vary according to organizational maturity, market conditions, project type, cultural context, and implementation sequence. For example, teamwork and continuous improvement may be conceptually important, but their influence may remain indirect when organizations lack standardized processes, customer-oriented value definitions, or effective waste-reduction systems. Conversely, practices such as visual management, flexible resource allocation, defined processes, production-system optimization, cycle-time reduction, and supply-chain coordination may directly influence the use of materials, time, labor, and information. Structural equation modeling is useful for evaluating these relationships because it enables researchers to test associations among latent constructs represented by multiple observed indicators. However, statistical significance alone does not clarify the hierarchical dependencies among implementation factors. Interpretive structural modeling and MICMAC analysis can address this limitation by distinguishing foundational drivers from linkage, dependent, and relatively autonomous variables. Such integration is consistent with the increasing use of structured multi-criteria and systems-based techniques in contemporary construction research, including the fuzzy prioritization approaches employed in recent studies of lean implementation barriers [14, 15].

The need for integrated analysis is especially pronounced in developing construction industries, where lean and sustainability concepts may be recognized theoretically but implemented inconsistently in practice. Organizations may adopt individual tools, such as visual boards, short-term planning, site organization, or digital models, without connecting them to a comprehensive strategy for economic, environmental, and social performance. This fragmented adoption can limit the benefits of lean methodology and make it difficult for managers to determine where implementation should begin. Sustainable risk management research emphasizes that construction decision-making must account for interconnected and evolving sources of uncertainty rather than addressing risks in disciplinary isolation [1]. Circular construction research similarly indicates that sustainability requires coordination across life-cycle stages and stakeholder networks [3, 4]. Meanwhile, digital decision-support tools can assist organizations in evaluating alternative resource and circularity strategies, but their effectiveness depends on data quality, organizational readiness, and integration with managerial processes [6]. Consequently, there is a clear need for empirical research that evaluates the statistical relationship between lean construction dimensions and sustainable construction while also determining the driving and dependent relationships among the most influential lean factors.

In Iran, the construction sector has substantial potential to benefit from the coordinated implementation of lean and sustainable construction, given the continuing demand for infrastructure, housing, urban development, resource efficiency, safer workplaces, and improved project performance. Nevertheless, practical implementation remains constrained by conventional management practices, fragmented project structures, limited integration across stakeholders, and insufficient evidence regarding which lean dimensions most strongly contribute to sustainability. The national organizational context further increases the importance of leadership, ethical accountability, and contextually validated management frameworks [9]. At the same time, international evidence on integrated project delivery, dispute avoidance, circular supply chains, workplace health, and lean implementation barriers provides a valuable foundation for developing locally relevant models [5, 8, 12, 13]. A comprehensive assessment should therefore move beyond the assumption that all lean practices automatically produce sustainability benefits and instead identify the dimensions with statistically supported effects, determine the hierarchical relationships among their operational factors, and translate these findings into an implementable sequence for construction organizations.

Accordingly, this study aimed to investigate the relationship between lean construction and sustainable construction, determine the lean construction dimensions that significantly affect economic, social, and environmental sustainability, and prioritize their effective implementation factors through structural equation modeling, interpretive structural modeling, and MICMAC analysis in the Iranian construction industry.

2. Methodology

This study employed an applied, quantitative, cross-sectional research design to investigate the relationship between lean construction and sustainable construction and to determine the positive effects of lean methodology on sustainability performance in the Iranian construction industry. The research framework was developed by integrating survey research, partial least squares structural equation modeling, interpretive structural modeling, and MICMAC analysis. In the initial stage, the principal concepts and variables associated with lean construction and sustainable construction were identified through a review of the relevant literature. These variables were subsequently examined and adapted to the operational conditions of the Iranian construction industry through consultation with construction specialists and practitioners. Lean construction was conceptualized through five major dimensions: teamwork culture, continuous improvement, customer focus, waste elimination, and standardization. Sustainable construction was represented by its three principal dimensions: economic sustainability, social sustainability, and environmental sustainability. The target population consisted of professionals actively involved in the Iranian construction industry who possessed relevant technical, managerial, or practical experience. Participants included employers, contractors, consultants, project managers, and other specialists involved in construction projects. Recruitment was directed toward respondents who had sufficient familiarity with construction processes and, to varying degrees, experience with lean construction and sustainable construction concepts. A total of 136 valid questionnaires were collected and included in the final analysis. Half of the respondents held bachelor's degrees, 35% held master's degrees, and 15% held doctoral degrees. Regarding professional experience, 27% had between five and ten years of construction-industry experience, 52% had between ten and fifteen years, and 21% had more than fifteen years. Contractors constituted 50% of the sample, consultants accounted for 32%, employers represented 14%, and other professionals comprised the remaining 4%. Most participants also reported at least some familiarity with lean and sustainable construction, providing an appropriate expert-oriented basis for evaluating the proposed relationships.

Data were collected using a researcher-developed, closed-ended questionnaire constructed from the variables identified in the literature review and refined through expert consultation. The questionnaire contained two main sections. The first section obtained demographic and professional information, including educational level, years of experience in the construction industry, duration of familiarity or practical experience with lean construction and sustainable construction, and current professional position. The second section assessed the perceived importance, applicability, and interrelationships of the identified lean construction and sustainable construction factors in construction projects. The measurement framework consisted of 19 observed variables. Sixteen variables represented lean construction practices and were classified under five latent dimensions. Teamwork culture included individual participation, organizational commitment, and training. Continuous improvement comprised design standardization, response to defects, error correction, and organizational learning. Customer focus was measured through flexible resources and value optimization. Waste elimination included supply chain management, optimization of the production system, reduction of cycle time, and work-content optimization. Standardization was represented by visual management, project-workplace organization, and defined processes. The remaining three variables measured the economic, social, and environmental dimensions of sustainable construction. Before testing the hypothesized relationships, the adequacy of the dataset for multivariate analysis was assessed using the Kaiser–Meyer–Olkin measure. The KMO coefficient was calculated as 0.7039, exceeding the commonly accepted threshold of 0.60 and confirming that the collected responses were sufficiently suitable for factor-based analysis. The quality of the measurement instrument was further evaluated through indicator loadings, internal-consistency reliability, composite reliability, and convergent validity. All indicator loadings exceeded 0.50 and ranged from 0.852 to 0.931 in the final measurement model. Cronbach's alpha values ranged from 0.817 to 0.901, composite reliability coefficients ranged from 0.910 to 0.936, and average variance extracted values ranged from 0.748 to 0.845. These coefficients demonstrated acceptable indicator reliability, internal consistency, and convergent validity for all study constructs.

The collected questionnaires were coded, screened, and prepared for statistical analysis. Descriptive statistics, including means, standard deviations, minimum and maximum scores, and variances, were initially calculated to summarize participants' evaluations of the main research constructs. Sampling adequacy was examined through the Kaiser–Meyer–Olkin procedure, for which the required calculations were implemented in MATLAB. The relationships between lean construction dimensions and sustainable construction were then assessed using partial least squares structural equation modeling in SmartPLS. This method was selected because it enables the simultaneous evaluation of measurement properties and complex relationships among observed indicators and latent constructs. The analysis was conducted in two principal stages. First, the measurement model was assessed by examining factor loadings, Cronbach's alpha, rho_A, composite reliability, and average variance extracted. Factor loadings above 0.50 were considered acceptable, while Cronbach's alpha and composite reliability coefficients above 0.70 were interpreted as evidence of adequate internal consistency. Average variance extracted values exceeding 0.50 were used to confirm convergent validity. Second, the structural model was evaluated to test the hypothesized effects of teamwork culture, continuous improvement, customer focus, waste elimination, and standardization on sustainable construction. Statistical significance was determined through a bootstrapping procedure using 500 resamples. At the 95% confidence level, relationships with t-values greater than 1.96 and p-values below 0.05 were considered statistically significant. The coefficient of determination was also calculated to assess the explanatory power of the model, with sustainable construction obtaining an R^2 value of 0.845.

Following the structural equation analysis, only lean construction dimensions that showed statistically significant relationships with sustainable construction were retained for interpretive structural modeling. These dimensions were customer focus, waste elimination, and standardization, encompassing nine factors: flexible resources, value optimization, supply chain management, production-system optimization, cycle-time reduction, work-content optimization, visual management, project-workplace organization, and defined processes. Interpretive structural modeling was used to establish the hierarchical and functional relationships among these factors based on expert judgments. The procedure clarified which variables served as foundational drivers and which variables were more dependent on other elements of the lean construction system. MICMAC analysis was subsequently performed to classify the nine factors according to their driving power and dependence power. Four categories were considered: autonomous variables with weak driving and dependence power, dependent variables with weak driving but strong dependence, linkage variables with strong driving and dependence, and driver variables with strong driving but weak dependence. The results of the structural equation model, interpretive structural modeling, and MICMAC analysis were finally integrated to construct a hierarchical analytical framework for explaining how selected lean construction practices can improve the economic, social, and environmental performance of sustainable construction projects.

3. Findings and Results

A total of 136 valid questionnaires were included in the analysis. Regarding educational attainment, 50% of the participants held a bachelor's degree, 35% held a master's degree, and 15% held a doctoral degree. In terms of construction-industry experience, 27% had between 5 and 10 years of experience, 52% had between 10 and 15 years, and 21% had more than 15 years. Regarding familiarity or practical experience with lean construction and sustainable construction, 24% reported approximately one year of experience, 62% reported between one and five years, and 15% reported more than five years. Contractors constituted the largest professional group at 50%, followed by consultants at 32%, employers at 14%, and respondents holding other professional positions at 4%. These characteristics indicated that most participants possessed substantial professional experience and sufficient familiarity with the construction context under investigation. The Kaiser–Meyer–Olkin coefficient was 0.7039, exceeding the minimum acceptable criterion of 0.60 and confirming the adequacy of the dataset for factor-based analysis.

The research framework comprised five lean construction dimensions and three dimensions of sustainable construction. Teamwork culture was represented by individual participation, organizational commitment, and training. Continuous improvement included design standardization, response to defects, error correction, and organizational learning. Customer focus was measured through flexible resources and value optimization. Waste elimination comprised supply chain management, production-system optimization, cycle-time reduction, and work-content optimization. Standardization was represented by visual management, project-workplace organization, and defined processes. Sustainable construction was measured through economic, social, and environmental sustainability. Thus, the complete measurement framework contained 19 observed variables.

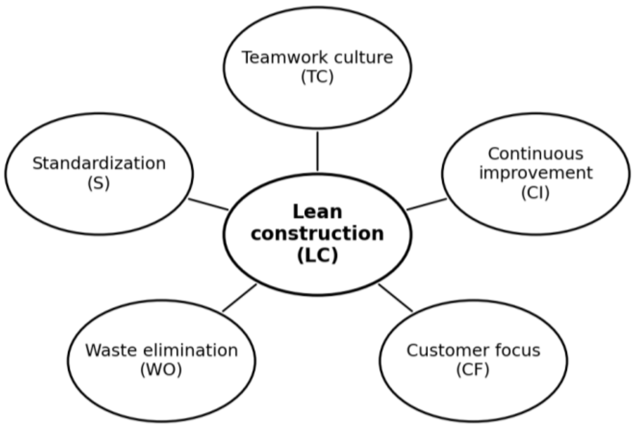

Figure 1. Main Elements of Lean Construction

The indicator-level results demonstrated that all multiple correlation coefficients exceeded the criterion of 0.50. The coefficients ranged from 0.741 for flexible resources to 0.829 for individual participation and value optimization. The factor loading coefficients were also consistently high, ranging from 0.852 for optimization of the production system to 0.931 for value optimization. Therefore, none of the indicators was removed from the measurement model. The complete indicator-level findings are presented in Table 1.

Table 1. Indicator-Level Explanatory Power and Factor Loading Coefficients

Construct	Code	Indicator	R^2	Factor loading
Teamwork culture	F1	Individual participation	0.829	0.918
Teamwork culture	F2	Organizational commitment	0.791	0.920
Teamwork culture	F3	Training	0.778	0.893
Continuous improvement	F4	Design standardization	0.764	0.868
Continuous improvement	F5	Response to defects	0.801	0.900
Continuous improvement	F6	Error correction	0.776	0.874
Continuous improvement	F7	Organizational learning	0.782	0.870
Customer focus	F8	Flexible resources	0.741	0.907
Customer focus	F9	Value optimization	0.829	0.931
Waste elimination	F10	Supply chain management	0.791	0.877
Waste elimination	F11	Optimization of the production system	0.757	0.852
Waste elimination	F12	Reducing cycle time	0.755	0.856
Waste elimination	F13	Work-content optimization	0.785	0.875
Standardization	F14	Visual management	0.759	0.865
Standardization	F15	Project workplace	0.788	0.900
Standardization	F16	Defined processes	0.778	0.901
Sustainable construction	F17	Economic sustainability	0.754	0.888
Sustainable construction	F18	Social sustainability	0.771	0.869
Sustainable construction	F19	Environmental sustainability	0.779	0.876

The descriptive findings showed that all study constructs obtained mean scores above the midpoint of the measurement scale. Waste elimination received the highest mean score among the lean construction dimensions, with a mean of 3.7525 and a standard deviation of 0.7065. It was followed by customer focus, continuous improvement, standardization, and teamwork culture. Sustainable construction had a mean score of 3.4258 and a standard deviation of 0.7147. These results indicated that respondents generally evaluated the application and importance of the identified lean and sustainable construction dimensions positively. The descriptive statistics are reported in Table 2.

Table 2. Descriptive Statistics of the Main Research Constructs

No.	Construct	N	Minimum	Maximum	Mean	Standard deviation	Variance
1	Teamwork culture	136	1	6	3.4925	0.7125	0.4187
2	Continuous improvement	136	2	5	3.5330	0.5697	0.3112
3	Customer focus	136	2	5	3.6125	0.6287	0.5312
4	Waste elimination	136	2	5	3.7525	0.7065	0.6814
5	Standardization	136	2	5	3.5212	0.7925	0.6712
6	Sustainable construction	136	2	4	3.4258	0.7147	0.5127

The internal-consistency findings supported the reliability of all latent constructs. Cronbach's alpha coefficients ranged from 0.817 for customer focus to 0.901 for continuous improvement, and all coefficients exceeded the recommended threshold of 0.70. The rho_A coefficients ranged from 0.828 to 0.902, while composite reliability coefficients ranged from 0.910 to 0.936. These results indicated strong internal consistency among the indicators assigned to each construct. Convergent validity was also confirmed because all average variance extracted values exceeded 0.50. The AVE coefficients ranged from 0.748 for waste elimination to 0.845 for customer focus, demonstrating that each latent construct explained more than half of the variance in its observed indicators. The combined reliability and convergent-validity results are provided in Table 3.

Table 3. Reliability and Convergent Validity of the Measurement Model

Construct	Cronbach's alpha	rho_A	Composite reliability	Average variance extracted
Teamwork culture	0.897	0.902	0.936	0.829
Continuous improvement	0.901	0.901	0.931	0.771

Customer focus	0.817	0.828	0.916	0.845
Waste elimination	0.888	0.889	0.922	0.748
Standardization	0.867	0.869	0.919	0.790
Sustainable construction	0.851	0.851	0.910	0.770

Following confirmation of the measurement model, the hypothesized structural relationships were evaluated through the bootstrapping procedure with 500 resamples. At the 95% confidence level, relationships with t-values greater than 1.96 and p-values below 0.05 were considered statistically significant. The findings showed that three of the five lean construction dimensions had significant relationships with sustainable construction. Customer focus had a significant positive relationship with sustainable construction, with a t-value of 3.224 and a p-value of 0.001. Waste elimination also had a significant positive relationship with sustainable construction, although the magnitude of its statistical evidence was comparatively weaker, with a t-value of 2.023 and a p-value of 0.043. Standardization produced the strongest statistically significant relationship with sustainable construction, with a t-value of 4.934 and a p-value below 0.001.

In contrast, teamwork culture did not have a statistically significant relationship with sustainable construction, as its t-value of 1.057 was below the critical value of 1.96 and its p-value was 0.291. Continuous improvement also failed to demonstrate a statistically significant effect, with a t-value of 1.192 and a p-value of 0.234. Consequently, the hypotheses concerning customer focus, waste elimination, and standardization were supported, whereas the hypotheses concerning teamwork culture and continuous improvement were not supported. The coefficient of determination for sustainable construction was 0.845, indicating that the lean construction dimensions included in the model collectively explained 84.5% of the variance in sustainable construction. This value demonstrated the strong explanatory power of the proposed structural model.

Table 4. Testing of the Structural Relationships between Lean Construction and Sustainable Construction

Hypothesis	Structural relationship	t-value	p-value	Decision
H1	Teamwork culture → Sustainable construction	1.057	0.291	Not supported
H2	Continuous improvement → Sustainable construction	1.192	0.234	Not supported
H3	Customer focus → Sustainable construction	3.224	0.001	Supported
H4	Waste elimination → Sustainable construction	2.023	0.043	Supported
H5	Standardization → Sustainable construction	4.934	<0.001	Supported

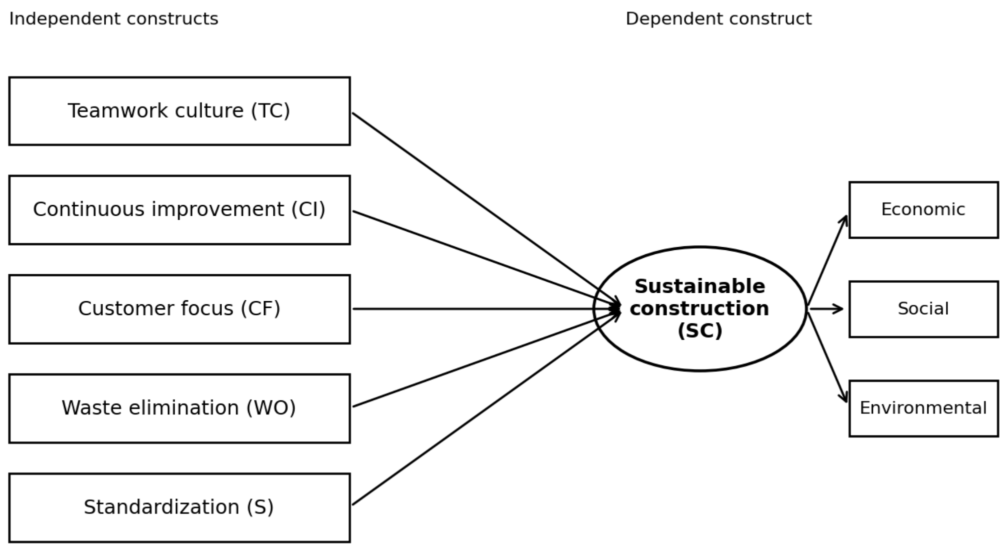

Figure 2. Structural Model between Lean Construction and Sustainable Construction

Based on the structural equation modeling findings, only the lean construction dimensions with statistically significant relationships with sustainable construction were retained for the interpretive structural modeling stage. These dimensions were customer focus, waste elimination, and standardization. Together, they comprised nine factors: flexible resources, value optimization, supply chain management, optimization of the production system, reducing cycle time, work-content optimization, visual management, project workplace, and defined processes.

The initial prioritization results showed that optimization of the production system obtained the highest average score at 3.88. Reducing cycle time ranked second with a mean score of 3.75, followed by flexible resources with a mean of 3.68. Value optimization obtained a mean of 3.46, defined processes obtained 3.28, work-content optimization obtained 3.21, supply chain management obtained 3.15, and project workplace obtained 3.015. Visual management received the lowest average score at 2.89. However, the importance of the factors was not determined solely by their mean scores; their driving and dependence powers were also considered through MICMAC analysis.

The MICMAC results classified flexible resources, value optimization, and visual management as driver variables. These factors possessed strong driving power and comparatively weak dependence and therefore represented the foundational elements of lean construction implementation. Reducing cycle time and defined processes were categorized as linkage variables because they exhibited both strong driving power and strong dependence. These variables were therefore highly interactive and potentially sensitive to changes elsewhere in the system. Optimization of the production system, work-content optimization, and project workplace were classified as dependent variables, indicating that their successful implementation relied substantially on the development of more influential factors. Supply chain management was classified as an autonomous variable because it exhibited comparatively weak driving and dependence powers. The initial scores and MICMAC classifications are presented together in Table 5.

Table 5. Initial Prioritization and MICMAC Classification of Effective Lean Construction Factors

Code	Effective lean construction factor	Dimension	Average score	MICMAC classification	Interpretation
F8	Flexible resources	Customer focus	3.68	Driver variable	Strong driving power and weak dependence
F9	Value optimization	Customer focus	3.46	Driver variable	Strong driving power and weak dependence
F10	Supply chain management	Waste elimination	3.15	Autonomous variable	Weak driving power and weak dependence
F11	Optimization of the production system	Waste elimination	3.88	Dependent variable	Weak driving power and strong dependence
F12	Reducing cycle time	Waste elimination	3.75	Linkage variable	Strong driving power and strong dependence
F13	Work-content optimization	Waste elimination	3.21	Dependent variable	Weak driving power and strong dependence
F14	Visual management	Standardization	2.89	Driver variable	Strong driving power and weak dependence
F15	Project workplace	Standardization	3.015	Dependent variable	Weak driving power and strong dependence
F16	Defined processes	Standardization	3.28	Linkage variable	Strong driving power and strong dependence

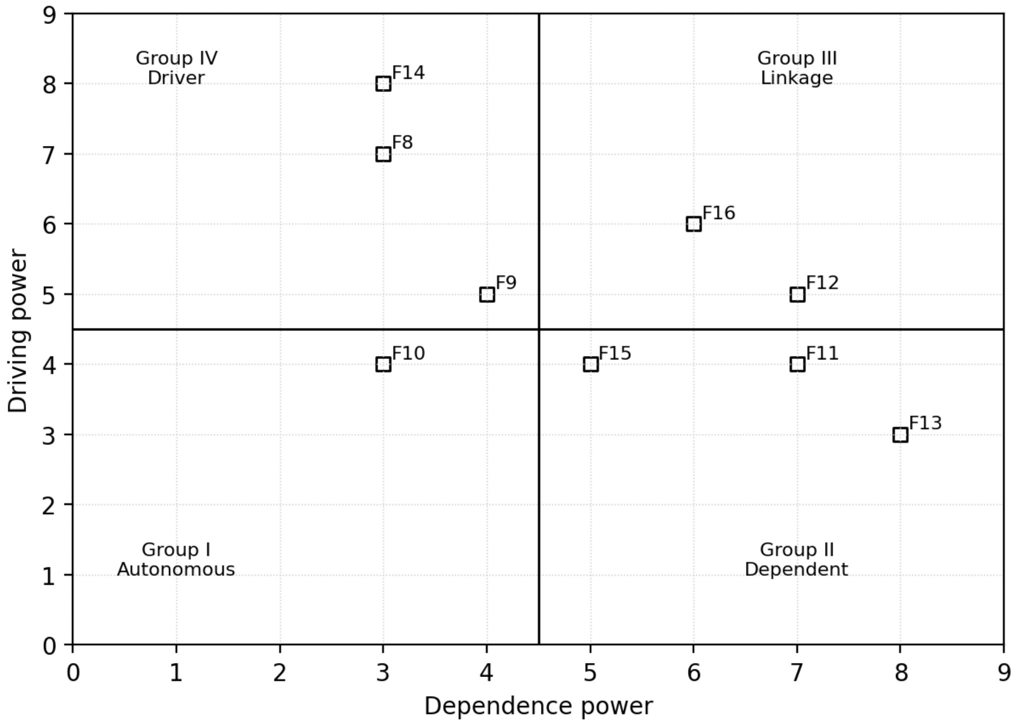

Figure 3. MICMAC Analysis of Lean Construction Parameters

Interpretive structural modeling organized the nine significant lean construction factors into five functional levels. Flexible resources and visual management were positioned at the fifth and deepest functional level, indicating that they served as primary driving factors in the implementation hierarchy. Value optimization and defined processes were located at the fourth level. Supply chain management and project-workplace organization were placed at the third level. Optimization of the production system and reducing cycle time were positioned at the second level, while work-content optimization was located at the first and most dependent level. This hierarchy indicated that sustainable lean implementation should begin with the higher-level driving conditions rather than with isolated operational outcomes.

At the fifth level, flexible resources required organizations to identify user needs before the design phase, allocate human, technical, and material resources flexibly, and strengthen coordination between design and implementation teams. Visual management required the use of visual controls for project progress, quality, safety, and site performance, thereby improving communication transparency and decision-making. At the fourth level, value optimization required project value to be defined from the perspectives of clients and users while aligning cost, quality, time, and sustainability objectives. Defined processes required clear procedures for design, procurement, construction, quality control, documentation, responsibilities, and workflow.

At the third level, supply chain management required stronger supplier coordination, fewer material-delivery delays, and improved communication among designers, contractors, and suppliers. Project-workplace organization required the systematic arrangement of site layouts, material-storage areas, safety zones, and workflow paths to reduce waiting, waste, and unnecessary movement. At the second level, production-system optimization involved applying contemporary project-management instruments, including building information modeling, look-ahead planning, workflow control, and progress monitoring. Cycle-time reduction required improved planning, coordination, rapid decision-making, and timely elimination of workflow constraints. At the first level, work-content optimization required work packages to be defined according to project needs, project modifications to be updated rapidly, and qualified project managers, trained contractors, and specialist consultants to be employed. The complete functional hierarchy and associated implementation strategies are presented in Table 6.

Table 6. Functional Levels and Implementation Strategies for Effective Lean Construction Factors

Functional level	Dimension	Code and factor	MICMAC cluster	Implementation strategy
Fifth level (V)	Customer focus	F8: Flexible resources	Driver variable	Identify user needs before the design phase; allocate human, technical, and material resources flexibly; and improve coordination between design and execution teams.
Fifth level (V)	Standardization	F14: Visual management	Driver variable	Apply visual controls to monitor project progress, quality, safety, and site performance and to improve transparency in communication and decision-making.
Fourth level (IV)	Customer focus	F9: Value optimization	Driver variable	Define value from the perspectives of clients and users, strengthen stakeholder interaction, and align cost, quality, time, and sustainability objectives.
Fourth level (IV)	Standardization	F16: Defined processes	Linkage variable	Establish clear procedures for design, procurement, construction, quality control, documentation, responsibilities, and workflow.
Third level (III)	Waste elimination	F10: Supply chain management	Autonomous variable	Improve supplier coordination, reduce delays in material delivery, and strengthen communication among designers, contractors, and suppliers.
Third level (III)	Standardization	F15: Project workplace	Dependent variable	Organize site layout, material storage, safety zones, and workflow paths to reduce waste, waiting time, and unnecessary movement.
Second level (II)	Waste elimination	F11: Optimization of the production system	Dependent variable	Apply building information modeling, look-ahead planning, workflow control, progress monitoring, and other contemporary project-management tools.
Second level (II)	Waste elimination	F12: Reducing cycle time	Linkage variable	Shorten process duration through improved planning, coordination, rapid decision-making, and timely removal of workflow constraints.
First level (I)	Waste elimination	F13: Work-content optimization	Dependent variable	Define work packages according to project needs, update project changes promptly, and employ qualified managers, trained contractors, and expert consultants.

Overall, the integrated findings indicated that customer focus, waste elimination, and standardization constituted the statistically effective dimensions of lean construction for enhancing sustainable construction. Among these dimensions, standardization demonstrated the strongest structural relationship with sustainability. The ISM and MICMAC findings further showed that implementation should begin with flexible resources, visual management, and value optimization because these factors possessed the strongest driving roles. Improvements in these foundational factors were expected to facilitate the development of defined processes, supply chain coordination, workplace organization, production-system optimization, cycle-time reduction, and, ultimately, work-content optimization.

4. Discussion and Conclusion

The present study examined the relationship between lean construction and sustainable construction in the Iranian construction industry and identified the lean factors that most strongly contribute to economic, social, and environmental sustainability. The structural equation modeling results showed that customer focus, waste elimination, and standardization had statistically significant positive relationships with sustainable construction, whereas teamwork culture and continuous improvement did not produce significant direct effects. Standardization demonstrated the strongest relationship with sustainable construction, followed by customer focus and waste elimination. Moreover, the structural model explained 84.5% of the variance in sustainable construction, indicating that the proposed lean construction dimensions possessed substantial explanatory power. The subsequent interpretive structural modeling and MICMAC analyses showed that flexible resources, value optimization, and visual management were the principal driver variables. Reducing cycle time and defined processes were classified as linkage variables, while optimization of the production system, work-content optimization, and project-workplace organization were dependent variables. Supply chain management was categorized as an autonomous factor. These findings suggest that the influence of lean construction on sustainability is neither uniform nor generated through the isolated use of lean tools; rather, it depends on the configuration, sequencing, and interaction of managerial and operational practices.

The significant positive effect of customer focus on sustainable construction indicates that sustainability performance improves when project decisions are based on the needs, expectations, and long-term value perceptions of clients and users. Customer focus in the present model was represented by flexible resources and value optimization, both of which can help organizations align project design, execution, and operation with economic, environmental, and social objectives. Value optimization encourages project participants to distinguish between activities that create meaningful stakeholder value and those that consume time, labor, materials, or capital without producing corresponding benefits. This result is consistent with the synergistic interpretation of lean practice proposed by Pan and Pan, who argued that construction improvement requires the coordination of value, workflow, and production decisions rather than the fragmented use of isolated techniques [2]. It also aligns with Evans and colleagues' competency framework for integrating lean construction and integrated project delivery, in which collaborative value definition, early stakeholder engagement, and coordinated resource allocation were central to improving complex project performance [12]. From a sustainability perspective, customer focus may prevent overdesign, unnecessary specifications, inefficient resource allocation, and operational outcomes that fail to satisfy users. Thus, customer-oriented lean practices can contribute simultaneously to cost control, user satisfaction, accessibility, efficient operation, and reduced life-cycle resource consumption.

The classification of flexible resources and value optimization as driver variables provides further evidence that customer focus functions as a foundational rather than merely outcome-oriented dimension. Flexible resources had strong driving power because the capacity to reallocate human, technical, financial, and material resources allows project organizations to respond to changes in user requirements, workflow constraints, supply disruptions, and sustainability priorities. In construction projects, rigid allocation systems often create waiting, idle capacity, duplicated work, and delayed responses to design or execution changes. Flexibility enables organizations to prevent these losses while maintaining project value. Value optimization similarly guides decisions about what should be produced, how it should be delivered, and which requirements should receive priority. Jagannathan and colleagues showed that lean methods can support the early identification and avoidance of construction disputes by improving process clarity, communication, and the alignment of expectations [13]. This evidence supports the present conclusion that defining value from the perspectives of clients and users can reduce misunderstandings and prevent decisions that later generate redesign, claims, or conflict. The finding is also compatible with sustainable risk management research, which emphasizes that project value must be evaluated against long-term economic, environmental, social, and governance risks rather than short-term delivery targets alone [1].

Waste elimination also had a significant positive relationship with sustainable construction. Although its statistical effect was weaker than those of standardization and customer focus, it remained significant and conceptually important. Lean waste elimination directly addresses unnecessary material use, waiting, rework, excessive transportation, inefficient movement, defects, overprocessing, and poor coordination. Reducing these forms of waste can improve economic sustainability through lower costs and higher productivity, environmental sustainability through reduced resource consumption and emissions, and social sustainability through safer and more orderly working conditions. The result is consistent with the circular economy perspective, which seeks to reduce the loss of material value and replace linear systems of extraction, use, and disposal with regenerative and closed-loop practices. Ossio and colleagues' definition of circular construction emphasizes the restructuring of built-environment processes to maintain the value of products, components, and materials across their life cycles [3]. Similarly, Chen, Feng, and de Soto showed that circular economy strategies require major changes in construction supply-chain processes, including procurement, logistics, reuse, recovery, and stakeholder coordination [4]. These principles correspond closely with the waste-elimination components examined in the present study.

The ISM findings clarified that the operational effects of waste elimination develop through a hierarchy. Reducing cycle time was identified as a linkage variable, whereas production-system optimization and work-content optimization were dependent variables. This indicates that cycle-time reduction can both influence and be influenced by other lean factors, while production and work-content improvements depend substantially on the establishment of higher-level managerial conditions. Reduced cycle time should therefore not be interpreted simply as accelerated construction. Instead, it should result from the elimination of waiting, improved coordination, faster information flow, timely constraint removal, and more reliable planning. Poorly managed attempts to shorten project duration may create unsafe work pressure, quality defects, and additional rework, thereby undermining sustainability. The occupational health and safety evidence presented by Mohandes and colleagues in modular integrated construction demonstrates that advanced production methods must be coordinated with careful hazard management, particularly in complex and high-risk operations [7]. The present results consequently suggest that time efficiency contributes to sustainability only when it is supported by defined processes, visual control, competent management, and safe production planning.

Standardization had the strongest positive effect on sustainable construction. This finding suggests that sustainable outcomes are particularly dependent on clear, repeatable, transparent, and controllable project procedures. Standardization in the present research included visual management, project-workplace organization, and defined processes. These practices reduce ambiguity, stabilize workflow, clarify responsibilities, make deviations visible, and support consistent performance across design, procurement, construction, quality control, documentation, and safety management. Defined processes can reduce errors and variation, while visual management enables project teams to monitor progress, constraints, quality problems, safety risks, and sustainability indicators in an accessible form. Project-workplace organization can decrease unnecessary movement, congestion, waiting, material damage, and exposure to hazards. The finding is compatible with research on sustainable workplace health indicators, which emphasizes the importance of measurable, institutionalized, and systematically monitored workplace conditions [8]. Standardization may therefore operate as an enabling structure through which environmental, social, and economic goals are translated into observable routines.

The designation of visual management as a driver variable is especially noteworthy. Although it obtained the lowest average importance score among the nine factors entered into the ISM analysis, its high driving power indicated that its systemic influence was greater than its descriptive ranking suggested. This distinction confirms the value of combining statistical and structural techniques, because factors with modest average ratings may nevertheless occupy influential positions in an implementation system. Visual management improves information transparency, supports rapid problem identification, and enables project participants to coordinate activities around shared performance indicators. It can also make sustainability visible by displaying material consumption, waste volumes, safety performance, energy use, delays, and corrective actions. In this respect, digital technologies and information systems can strengthen visual management by providing real-time data, traceability, and decision support. Yu and colleagues highlighted the importance of information and communication technologies in supporting circular economy decisions in construction, particularly where organizations must evaluate material flows and complex life-cycle alternatives [6]. The present findings imply that visual management may act as an interface connecting lean operations, digital information, and sustainability monitoring.

The significant role of defined processes as a linkage variable also helps explain why standardization exerted the strongest structural effect. Defined processes possess both substantial driving power and substantial dependence, meaning that they influence many operational outcomes while simultaneously relying on higher-level drivers such as visual management, resource flexibility, and value optimization. When procedures are explicitly defined, organizations can assign responsibility, establish performance criteria, identify deviations, document lessons, and improve coordination among stakeholders. However, procedures that are defined without reference to customer value or actual project conditions may become bureaucratic and inflexible. The present hierarchy therefore suggests that process standardization should be preceded or supported by value clarification and flexible resource systems. This interpretation agrees with lean implementation studies showing that successful improvement requires coherent organizational systems rather than the mechanical replication of tools. Silva and colleagues found that construction SMEs face interrelated barriers to Lean Six Sigma implementation and therefore require prioritized, context-sensitive strategies rather than generic prescriptions [14]. Maru and colleagues reached a similar conclusion in their investigation of barriers and overcoming strategies for lean construction in Ethiopia, demonstrating that organizational, technical, cultural, and resource constraints must be managed as an interconnected system [15].

In contrast to the three supported relationships, teamwork culture did not have a statistically significant direct effect on sustainable construction. This does not necessarily mean that teamwork is unimportant. Rather, its influence may be indirect, conditional, or insufficiently institutionalized in the studied context. Teamwork culture was represented by individual participation, organizational commitment, and training, all of which may contribute to sustainability through their effects on process implementation rather than through a direct path. For example, trained and committed employees may improve visual management, standardization, and waste identification, but these outcomes depend on whether the organization provides formal procedures, decision authority, resources, and leadership support. Construction projects are also characterized by temporary teams, contractual fragmentation, and changing stakeholder networks, which may weaken the consistency of teamwork practices. The findings of Evans and colleagues indicate that collaborative project delivery requires specific competencies and institutional arrangements; collaboration alone does not automatically produce integrated performance [12]. The narrative analysis of novice leadership by Blose and colleagues, although conducted in an educational setting, similarly shows that professional identity, authority, and role interpretation shape how leaders construct participation and organizational relationships [10]. Accordingly, teamwork may support sustainability only when it is embedded in stable governance and operational systems.

Continuous improvement likewise failed to show a statistically significant direct relationship with sustainable construction. This result may reflect a gap between the formal endorsement of improvement and its practical implementation. Continuous improvement requires repeated learning cycles, systematic analysis of errors, rapid responses to defects, feedback mechanisms, and the organizational capacity to translate lessons into revised practice. In project-based construction settings, lessons may not be transferred effectively from one temporary project team to another. Organizations may correct immediate problems without changing the systems that produced them, or they may lack reliable data for evaluating improvement. The cross-sector application of Six Sigma examined by Wang and Liu demonstrates that improvement systems depend on multiple organizational and contextual factors and cannot be expected to succeed through technical methods alone [11]. Furthermore, sustainable improvement requires ethical and long-term leadership commitment. Mohammadi and Karimi's development of a sustainable ethical leadership scale in Iran emphasizes that sustainability-oriented leadership combines responsibility, fairness, accountability, and a long-term institutional perspective [9]. Thus, continuous improvement may become statistically influential only when it is supported by leadership continuity, systematic data collection, knowledge transfer, and standardized procedures.

The classification of supply chain management as an autonomous variable also warrants careful interpretation. Supply chain management is commonly regarded as central to both lean and sustainable construction, yet in the present MICMAC model it exhibited relatively weak driving and dependence powers. This result may indicate that supply-chain practices were insufficiently integrated with internal project systems or that respondents perceived them as relatively external to site-level decision-making. The finding should not be interpreted as evidence that supply chains are unimportant. Küpeli and Sertyeşilışık demonstrated that supplier selection should incorporate both lean and sustainability criteria, including operational, environmental, and social considerations [5]. Circular construction research also identifies supply-chain redesign as essential to material recovery and resource efficiency [4]. Therefore, the autonomous classification may reveal a contextual weakness in the current Iranian construction environment: supply-chain sustainability may remain disconnected from project planning, value definition, and operational control. Strengthening this integration could alter its structural position in future models.

Overall, the findings demonstrate that lean construction contributes to sustainable construction most effectively through a structured sequence beginning with foundational drivers. Flexible resource allocation, visual management, and value optimization create the conditions necessary for the development of defined processes, improved supply-chain coordination, organized workplaces, optimized production systems, shorter reliable cycles, and better work-content design. The high explanatory power of the model confirms that lean methodology offers a strong management basis for sustainability, but the unsupported paths also caution against assuming that every lean principle produces an immediate direct effect. Sustainable lean implementation requires alignment among leadership, stakeholder value, process transparency, resource systems, workplace health, circularity, risk management, and operational control. This integrated interpretation is consistent with recent research that treats construction sustainability as a systemic transformation rather than a collection of independent environmental practices [1, 3].

This study had several limitations. The cross-sectional design captured respondents' perceptions at a single point in time and therefore did not permit causal conclusions regarding the long-term effects of lean construction practices. The data were collected through a self-report questionnaire and may have been influenced by social desirability, recall error, or differences in respondents' interpretations of lean and sustainable construction. Although the sample included experienced professionals, it was limited to 136 participants within the Iranian construction industry, which may restrict the generalizability of the findings to other countries, regulatory systems, organizational sizes, and project types. The model examined five broad lean construction dimensions and may not have captured all technological, contractual, cultural, financial, and institutional determinants of sustainability. In addition, the ISM and MICMAC stages depended on expert judgments, and the resulting hierarchy may vary with the composition and experience of the expert group.

Future studies should employ longitudinal designs to evaluate how lean construction implementation affects sustainability outcomes across multiple project phases and after project completion. Larger samples should be recruited from different regions, organizational sizes, and construction sectors, including residential, commercial, infrastructure, industrial, and modular projects. Comparative international research could determine whether the insignificant effects of teamwork culture and continuous improvement are specific to the Iranian context or reflect broader implementation challenges. Future models should incorporate digital technologies, building information modeling, circular procurement, leadership, organizational readiness, contractual integration, safety climate, and sustainable risk management. Researchers could also combine structural equation modeling with artificial neural networks, machine learning, system dynamics, fuzzy multi-criteria methods, or longitudinal network analysis. Objective project data, such as waste volumes, rework rates, energy consumption, accident frequency, cost deviation, and schedule performance, should be used alongside perceptual measures.

Construction organizations should begin lean–sustainability programs by strengthening the factors with the greatest driving power: flexible resources, value optimization, and visual management. Client and user requirements should be identified early and translated into measurable economic, social, and environmental value criteria. Project dashboards and visual control systems should display workflow constraints, material consumption, waste, quality, safety, and sustainability indicators. Managers should establish clear and adaptable procedures for design, procurement, construction, documentation, and quality control while avoiding rigid bureaucracy. Cycle-time reduction should be pursued through reliable planning and constraint removal rather than work intensification. Organizations should also integrate suppliers into project planning, apply sustainability criteria in supplier selection, and create mechanisms for transferring lessons across projects. Training, employee participation, and continuous improvement should be linked to formal responsibilities, decision authority, performance measurement, and leadership accountability so that these practices generate observable sustainability outcomes.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

The authors report no conflict of interest.

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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