

The critical factors for successfully applying lean tools in the Egyptian construction sector

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Received: 28.12.2024; Revised: 06.12.2025; Accepted: 18.12.2025; Available online: 15.12.2024

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Abstract:

Lean construction has gained global recognition for improving efficiency, yet its adoption in Egypt remains hindered by numerous barriers. This study empirically investigates the key factors influencing the successful implementation and adoption of lean construction practices in Egypt. Using a data-driven methodology, the research identifies the five most critical CSFs are: awareness of lean philosophy, elimination of design errors, effective management of the production chain, strong collaborative relationships, and a robust work plan with comprehensive risk planning. An extensive review of previous research was conducted to identify Critical Success Factors (CSFs), resulting in a list of 27 factors included in a survey. A questionnaire was distributed to 162 practitioners involved in construction projects to evaluate the significance of these CSFs in the Egyptian context. Various statistical analyses were performed using IBM SPSS Statistics, including validity and reliability tests, descriptive statistics for ranking the CSFs, and principal component analysis (PCA) to identify the primary drivers of lean construction success. Beyond demonstrating established CSFs, the findings underscore their contextual relevance in a developing economy, offering practical guidance for industry stakeholders and extending theoretical insights into lean implementation across construction environments.

Keywords:

lean construction, critical success factors (CSFS), principal component analysis (PCA), risk management, construction industry, collaborative relationships, production chain management

1. Introduction

The construction industry is a vital economic sector that drives national development and plays a significant role in generating employment opportunities and offering diverse career prospects [52,53,63] and its role in employing labourers and offering a variety of job chances [50,52]. Given its importance, it is crucial to address the challenges faced by this sector, such as time wastage, cost overruns [27], poor management, resistance to change, and inefficient processes [4,28]. To enhance performance and create added value, new methods and management approaches – such as lean techniques – are increasingly required [33,15].

Over the past three decades, considerable efforts have been made to integrate lean methods into construction, following their proven success in the manufacturing sector [22,68]. The core attributes of the lean approach include improved management, higher return rates, avoidance of cost overruns, prevention of delays, enhanced productivity, and increased client satisfaction [36,5].

Lean construction has been adopted in many countries to address issues such as environmental concerns (*Environmental Protection Agency Annual Report and Accounts* [23]), low productivity [29], and waste [49]. Lean construction (LC) is a powerful mechanism for reducing waste and managing projects successfully [11]. As a management philosophy, lean construction (LC) is a powerful mechanism for minimising waste

and ensuring efficient project delivery [51]. Empirical evidence shows that implementing LC can significantly improve the building sector's efficiency, reducing both time and budget overruns [1], shorten project periods by up to 25% [16,25], cut costs by as much as 50% [16], and increase workforce productivity [10].

Despite these benefits, the adoption of lean methods in construction remains limited [13]. The shortage of adaptation to (LC) stems from a failure to understand what "lean" entails. A primary barrier to implementation is the lack of a clear understanding of lean principles, coupled with a shortage of practical methods for their execution [10].

Several studies have sought to identify the characteristics and enablers that ensure successful LC implementation, thereby encouraging its wider adoption in the construction industry [62,60]. Critical Success Factors (CSFs) are those essential elements or conditions that determine the success of lean construction implementation. Identifying and understanding these early success factors is vital, particularly as few studies focus on CSFs that can produce rapid, measurable improvements in LC performance.

In Egypt, the construction industry faces numerous challenges that hinder its ability to achieve strategic goals. These include rework [19], cost overruns, quality deficiencies, safety issues, a shortage of skilled labour, and delays [6,19,57,64]. Given the proven positive impacts of lean thinking in other countries [3,14,15,39,44] there is a strong case for applying it within

Egyptian construction management to address these persistent issues. Investigating the CSFs for lean adoption in Egypt is essential to support stakeholders in implementing it successfully.

Although lean construction has been widely studied globally, research in Egypt remains fragmented, often descriptive, and lacks empirical prioritisation of Lean success factors. Furthermore, existing studies tend to discuss lean construction implementation in general terms without providing a prioritised, data-driven framework tailored to the Egyptian construction sector’s unique context and without providing a systematic, evidence-based ranking of the most critical factors for successful lean adoption. This study addresses this gap by contextualising and prioritising CSFs essential for overcoming ongoing industry challenges, thereby guiding practitioners and policymakers toward effective lean adoption in Egypt. Thus, this study contributes by delivering a data-driven framework that identifies, assesses, and ranks the CSFs most relevant to the Egyptian construction sector, advancing both practice and the international knowledge base on lean construction.

2. Literature review

2.1. Lean construction

Conventional project management methods require improvement to effectively address the challenges faced by modern projects. Lean is a management strategy that seeks to enhance product efficiency and meet customer requirements by eliminating waste in cost, time, operations, and resources [40;69]. The Toyota Production System (TPS) was the first to apply lean principles in production lines, developing a culture-centred framework to promote knowledge sharing and continuous team development [9,20,69,18]. Maintaining high value in product flow, supported by Just-in-Time (JIT) delivery to minimise inventory levels, is a core objective of lean [18,40,69]. Additional goals include improving sustainability documentation and ensuring clarity of information to support effective decision-making. The application of lean principles in the construction industry has been shown to enhance project management processes [30,46,56].

A wide range of lean tools has been developed to support production and construction management by identifying, controlling, and minimising waste [65]. These tools help detect waste, streamline processes, and enable timely corrective actions to improve performance [63,67,74]. Table 1 clarifies the classification of lean tools based on their role in waste detection, processing, or response.

2.2. Lean construction in Egypt

Although lean construction has demonstrated proven benefits internationally, its adoption in Egypt remains uneven and often limited in scope. Numerous studies have examined lean construction (LC) in Egypt, employing various approaches to analyse its adoption and to support construction professionals in deciding whether to apply lean principles in their projects. Early studies highlighted its potential to reduce waste, improve efficiency, and align with sustainability goals, but also noted significant barriers related to limited awareness and inadequate training. A 2014 study investigated the relationship between lean implementation and sustainability, confirming that LC is an effective approach for minimising waste, improving processes, and reducing project durations. However, it also found that the application of lean tools remained limited due to limited awareness and knowledge [54].

Table 1. Lean tools classification based on the waste handling process

The tool name	The definition
Waste Detection	
Histogram	A bar chart to visualise the frequency of causes [32]
Pareto Analysis	A technique to identify the most impactful areas for improvement [12]
5 Whys	Repeatedly asking “why” to identify root causes [63]
Waste Processing	
5S	A waste elimination method consisting of Sorting, Straightening, Shining, Standardizing, and Sustaining [32]
Concurrent Engineering	Performing tasks simultaneously to improve product outcomes [41]
Kanban (Pull System)	A visual workflow management system [63]
Poka-Yoke (Error Proofing)	Preventing and controlling errors [63]
Time and Motion Study	Analysing operational efficiency over time [32]
Muda Walk	Observing processes to identify waste [31]
Value Stream Mapping	A visual representation of process flows [63]
Root Cause Analysis	A systematic approach to problem-solving [31]
Waste Response	
Check Sheet	A structured form for data collection [41]
Construction Analysis	A method for analysing construction workflows [37]
Continuous Flow	Ensuring uninterrupted workflow [32]
First In, First Out	FIFO Line- Managing work demands in sequence [32]
Jidoka/Automation	Designing equipment with built-in error detection [31]
The Last Planner	A system for managing production units [51]
Heijunka	Level Scheduling-Evenly distribute production loads [63]
Visual Management	Using visual cues to improve operational efficiency [63]
Work Structuring	Enhancing functions through supply chain integration [74]
Daily Huddle Meetings	Short, regular coordination meetings [31]
Quality Function Development (QFD)	Using customer feedback to guide design [31]
Six Sigma	A set of tools for quality improvement [63]
Plan, Do, Check, Act	PDCA - An iterative cycle for process improvement [63]
Work Standardization	Documenting best practices [31]
Suggestion Schemes	Encouraging constructive employee input [51]
Just-in-Time (JIT)	Reducing inventory by producing only what is needed [63]
Team Preparation	Developing workforce skills [32]
Kaizen	Kaizen: A philosophy of continuous improvement [63]

In 2018, another study assessed the potential of incorporating lean thinking into the Egyptian construction industry to enhance efficiency and reduce waste. The research linked this effort to Egypt’s Vision 2030 for sustainable development, which aims to improve the country’s economic, social, and environmental

performance [2]. More recent studies examined lean implementation at the project level, for example, in 2021, a study explored the influence of lean tools on construction in Egypt, focusing on awareness, application levels, and perceived benefits. The results indicated that construction professionals use lean tools on-site for various purposes, such as operational monitoring [63]. Notably, the application level of lean techniques was higher than the awareness level, with economic benefits as the most significant advantage. Lean has also been shown to improve project control and reduce project durations [43]. In 2022, research identified the lean tools most critical to project success, highlighting daily follow-ups, systematic work organisation, identification of customer needs, and *Just-in-Time* (JIT) delivery as the most influential. Furthermore, a 2023 analysis of Egypt's Green Pyramid Rating System examined the relationship between lean principles and green building, concluding that lean can significantly enhance the value of sustainable construction practices in Egypt [58].

Taken together, the previous studies indicate a growing awareness of the value of lean in Egypt, but also underscore a lack of empirical, data-driven evaluations of the CSFs that enable effective enactment. This gap underscores the need for research that not only identifies CSFs but also prioritises them for practical application.

2.3. Critical Success Factors for implementing (LC)

Numerous studies worldwide have examined the Critical Success Factors (CSFs) for implementing lean construction, emphasising the importance of various elements in effectively integrating lean principles into construction projects. By identifying and analysing these factors, researchers and practitioners aim to provide insights and recommendations that enable organisations to adopt lean construction practices successfully and achieve improved project outcomes. Researchers also have aimed to identify CSFs that support the successful adoption of lean construction. While specific factors vary by context, common themes include management commitment, workforce training, effective communication, and organisational readiness. For example, Sarhan et al. [59] explored CSFs in the Kingdom of Saudi Arabia (KSA) and found that the most important factors include project management responsibility, education and training for project participants, appropriate selection of lean tools, organizational capacity for transformation, teamwork, adoption of continuous improvement, and a precise definition of customer needs [59]. In a later study [21] identified management commitment as the most influential factor in lean adoption, while supportive government regulations ranked the lowest. He categorised CSFs into six groups: project, policy and strategic, technical, motivational, company, and resources/workforce factors [21].

In Morocco, Arabi et al. [8] found that human factors dominate the CSFs for lean implementation in the construction industry. The study highlighted top management commitment, employee engagement and participation, and effective internal communication as the most critical elements [8]. Similarly, in a study in the UK, Steven's statistical analysis revealed three overarching CSFs that influence all others: management qualifications, client involvement, and the presence of a suitable facilitator [7].

In the UAE, CSFs were grouped into four categories: organisational, structural, managerial, and external factors. Based on the Relative Importance Index (RII) analysis, the most significant factors were management responsibility and

involvement, organisational culture, and employee motivation and focus [73]. More recently, Hyarat et al. [34] conducted a systematic literature review to identify critical factors (CFs) influencing LC adoption, classifying them into six categories: cultural and human, managerial, operational and technical, financial and contractual, educational and knowledge-based, and governmental [34].

Among lean practices, regular team meetings have been identified as one of the most effective for achieving project success [49]. Some studies have examined CSFs supporting the combined adoption of Lean and Building Information Modelling (BIM) in construction projects. For example, in one study focused on megaprojects, thirty CSFs identified from previous research were analysed using the Delphi technique. The results indicated that the most significant factors for Lean-BIM adoption were collaboration during project design, workforce development, data availability, technological capability, and tool management [26].

Several factors influence the successful application of lean construction, and addressing these factors can help overcome common barriers, such as a lack of understanding. Research in this area aims to guide companies in selecting and applying lean tools by examining the CSFs for lean adoption. These studies consistently show that strong commitment and cooperation among all stakeholders are essential for the early and successful implementation of lean in construction projects [10]. For the purposes of this study, all LC CSFs identified from the literature were categorised into four main groups – human, organisational, management, and planning factors – based on their nature, thematic similarities, and functional relevance. This classification follows the approach of previous studies and has been adapted to the Egyptian construction context. Table 2 presents each category along with its associated factors. This approach provides a structured foundation for empirically identifying and prioritising the CSFs most critical to lean adoption in Egypt.

3. Materials and methods

3.1. Aims of the study

The primary aim of this study is to identify the critical factors for the successful implementation of lean construction and to provide insights for project stakeholders, encouraging the adoption of lean practices in Egypt. To achieve this objective, a comprehensive review of previous studies was conducted to determine the relevant Critical Success Factors (CSFs), resulting in a list of 27 factors included in the survey.

3.2. Study methodology

This study begins by defining the research problem and objectives, followed by a review of previous studies to identify the Critical Success Factors (CSFs) for implementing lean construction strategies in Egypt. These CSFs are then categorised into four groups based on their characteristics. The next step involves using a survey method, with a two-section questionnaire designed to collect data. The aim is to evaluate the CSFs for applying lean construction strategies in Egypt. This qualitative methodological approach provides a comprehensive foundation for subsequent statistical analysis.

Table 2. Extracted (CSFs) of applying (LC) from previous studies

Factor code	Factors Group
Human Factors	
F01	Proper training
F02	Institution Support
F03	Coherent team working
F04	Precise description of responsibilities
F05	Awareness of Lean philosophy
F06	Incorporation with experts in (LC)
F07	Encourage the team to adopt new approaches.
Organizational Factors	
F08	Performance of the (LC) tools
F09	Awareness of customer requirements
F10	Reinforce cultural transformation
F11	Communicating information in a satisfactory way
F12	Adequate coordination and collaboration
F13	Proper technique of risk management
F14	Building of a suitable contractual agreement
Management Factors	
F15	Supply Chain
F16	Publicity of the outcomes of the (LC) application
F17	Effective communication
F18	Collaborative connections
F19	Awareness of processes and outcomes.
F20	Appropriate incentive system
F21	Lack of design errors
F22	Minimisation of turnover
Planning Factors	
F23	More profitable management of the production chain
F24	Using effective communication
F25	Utilising effective strategies at work
F26	A transparent management process
F27	A solid work plan with extensive planning for risks

3.3. Study limits and community

Many studies worldwide have examined various aspects of lean construction, including strategies, techniques, tools, barriers, Critical Success Factors (CSFs), and the integration of

lean tools with other systems such as BIM in project management. However, this research focuses specifically on identifying the critical factors that contribute to the successful application of lean tools in construction projects in Egypt. The authors anticipate that these insights will encourage the adoption of lean tools in building projects, thereby enhancing the performance of the construction sector.

The study on lean construction CSFs in Egypt was conducted through a survey targeting construction professionals with diverse specialisations, including architects, civil engineers, project managers, designers, and construction engineers. The questionnaire was distributed electronically via an online form, and the sample was randomly selected from companies involved in building construction projects in the New Administrative Capital City of Egypt. These companies were selected because they utilise advanced systems to manage construction processes and sites. Invitations were sent via email, and participation was voluntary. A total of 162 professionals responded to the survey. Figure 1 illustrates the characteristics of the sample.

The sampling strategy targeted construction professionals in Egypt’s New Administrative Capital City, as these companies actively adopt advanced construction systems and lean tools. Likewise, the selected companies manage multiple construction sites simultaneously, including professionals from all engineering specialisations, and have dedicated management and planning departments that utilise various tools to control project quality, cost, and time. The sample was randomly selected within this population to ensure diverse representation across key roles, including architects, engineers, project managers, and designers. Consequently, the sample size and selection may not be representative of all firms. Additionally, data were collected via self-reported online questionnaires; however, the cross-sectional design does not account for temporal change. Finally, the sample size of 162 respondents was sufficient to support all planned statistical analyses, ensuring reliable and valid results. While the exact total population of construction professionals in the New Administrative Capital City is not publicly available, the study targeted a diverse set of companies that operate across multiple sites and include management and planning sections using various project control tools. The survey included professionals from all relevant specialisations (architects, civil engineers, project managers, designers, and construction engineers) to ensure broad representation.

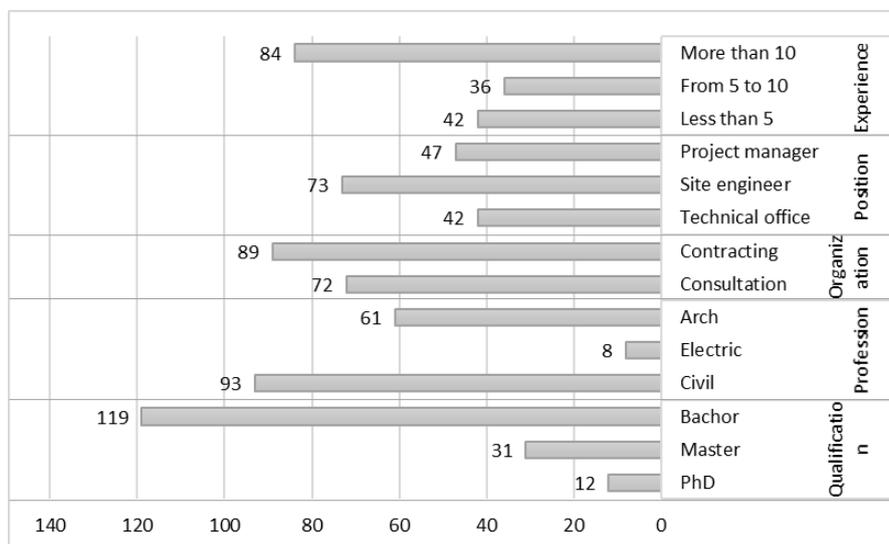


Fig. 1. Respondent’s information

Additionally, the study adopted a quantitative approach that focused on construction professionals within the study area. This area was selected as it represents the technologically advanced construction projects in Egypt, which employ lean management tools. The target population included professionals with diverse specialisations, as appears in Fig. 1, from companies managing multiple construction sites and departments responsible for cost, time, and quality control, with a total of 162 professionals voluntarily participating via questionnaire. The sample was randomly selected to ensure diversity across roles and professional backgrounds. The sample size was statistically sufficient for the intended analyses, for example, Principal Component Analysis [66,48,55]. The current study's sample met this requirement, providing an adequate basis for factor extraction and validation. For correlation and Relative Importance Index analyses, a minimum of 100 observations is considered sufficient to confirm the stability and reliability of the study results. Therefore, the obtained sample of 162 responses exceeds the recommended thresholds for these statistical techniques.

3.4. Preparation of the questionnaire

The questionnaire is a well-established research tool for collecting data on specific phenomena [71]. It was carefully designed, validated, and subsequently used to collect data from construction professionals experienced in lean construction adoption. The collected data were subsequently analysed to identify the Critical Success Factors (CSFs) for lean implementation, which were then categorised into four groups based on their nature.

The questionnaire consisted of two sections. The first section captured respondents' demographic and professional information, including years of experience, academic qualifications, position, organisation type, and area of specialisation. The second section comprised twenty-seven CSFs for lean construction implementation, extracted from a literature review. Respondents evaluated these factors using a five-point Likert scale, ranging from 1 = very low to 5 = very high [35]. Six academics and project management professionals with excellent knowledge of lean construction validated the questionnaire. The collected data were analysed using SPSS software.

To ensure validity and clarity, six academics and project management professionals with extensive knowledge of lean construction reviewed the questionnaire. A pilot test was

conducted with these experts, resulting in refinements to improve clarity and relevance before full distribution. The finalised data were analysed using IBM SPSS Statistics [11,17]:

Several tests were conducted to determine the characteristics of the CSFs and assess their importance:

1. Validity Test: Evaluated the suitability and accuracy of the sample.
2. Reliability Test: Assessed the consistency and stability of the responses using Cronbach's Alpha coefficient, where values close to 1 indicate high reliability and values near 0 indicate poor consistency [15,33].
3. Descriptive Statistics: Ranked the CSFs based on mean scores (MS) [70]. and the Relative Importance Index (RII) [12,38,42,72]. MS provided the average rating of each CSF on the Likert scale, while RII normalised these ratings to allow comparison across factors.
4. Principal Component Analysis (PCA): Compressed the CSFs into seven components to identify the major factors influencing successful lean implementation in Egypt. Any factor with a communality value below 0.5 was excluded, and the PCA was re-run to refine the final factor structure.

4. Results and discussion

The questionnaire examined 27 Critical Success Factors (CSFs) for lean adoption in Egypt's construction sector, compiled from previous research. The survey results were analysed using SPSS, applying multiple tests to identify the key characteristics of these CSFs and determine the most critical factors for successful lean implementation in Egypt.

4.1. Significant SFs groups of adoption (LC) in Egypt

Participants evaluated 27 Critical Success Factors (CSFs) that significantly influence the successful implementation of lean practices in Egypt's construction sector. These factors were categorised into four groups based on their characteristics: organisational, management, planning, and human factors. Figure 2 illustrates the ranking of these CSF groups, based on their Relative Importance Index (RII) calculated from the survey results. The RII values indicate the relative significance of each group, highlighting the factors deemed most critical by the participants.

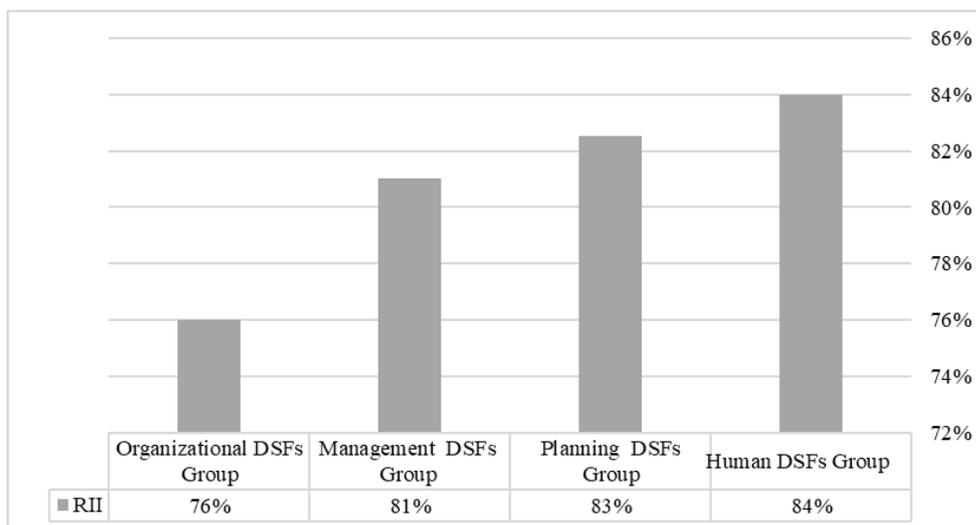


Fig. 2. Groups of (LC) adoption (CSFs) ranking

The analysis of Critical Success Factors (CSFs) for lean construction in Egypt reveals that human resources play the most significant role, with the Human CSFs Group achieving an RII of 84%. This group includes factors related to skills, behaviour, training programs, worker motivation, and attitudes toward lean principles. Close behind, the Planning CSFs Group, with an RII of 83%, encompasses factors associated with effective communication, workflow strategies, and project planning processes. The Management CSFs Group, with an RII of 81%, covers management practices, leadership, and decision-making within construction organisations, including management’s commitment to lean, resource allocation, and internal communication. Finally, the Organisational CSFs Group, with an RII of 76%, comprises factors related to organisational structure,

culture, policies, clear goals, and process flexibility to support lean adoption. Overall, these findings underscore the critical influence of human resources and management practices, while organisational factors also play a supportive role in shaping the successful implementation of lean practices in Egypt’s construction industry.

4.2. Critical SFs of utilising (LC) in Egypt

Practitioners assessed 27 factors that significantly influence the successful implementation of lean practices in Egypt’s construction industry. Table 3 presents the ranking of these factors.

Table 3. Lean construction (CSFs) ranking analysis

CSF#	(CSFs) Group	The CSF	MS	RII	Variance	SD	Rank
F05	Human	Awareness of Lean philosophy	4.44	0.889	0.617	0.785	1
F21	Manag.	Lack of design errors	4.44	0.889	0.543	0.737	2
F23	Planning	More profitable management of the production chain	4.44	0.889	0.395	0.628	3
F18	Manag.	Collaborative connections	4.37	0.874	0.529	0.727	4
F27	Planning	A solid work plan with extensive planning for risks	4.33	0.867	0.741	0.861	5
F06	Human	Incorporation with experts in (LC)	4.26	0.852	0.859	0.927	6
F15	Manag.	Supply Chain	4.26	0.852	0.562	0.750	7
F08	Organiz.	Performance of the (LC) tools	4.22	0.844	0.543	0.737	8
F17	Manag.	Effective communication	4.19	0.837	0.373	0.611	9
F02	Human	Institution Support	4.15	0.830	0.645	0.803	10
F13	Organiz.	Proper technique of risk management	4.15	0.830	0.645	0.803	11
F01	Human	Proper training	4.11	0.822	0.543	0.737	12
F16	Manag.	Publicity of the outcomes of the (LC) application	4.11	0.822	0.691	0.831	13
F19	Manag.	Awareness of processes and outcomes.	4.11	0.822	0.395	0.628	14
F04	Human	Precise description of responsibilities	4.07	0.815	0.661	0.813	15
F10	Organiz.	Reinforce cultural transformation	4.07	0.815	0.513	0.716	16
F26	Planning	A transparent management process	4.04	0.807	0.332	0.576	17
F22	Manag.	Minimization of turnover	4.00	0.800	0.296	0.544	18
F12	Organiz.	Adequate coordination and collaboration	3.96	0.793	0.628	0.792	19
F24	Planning	Using effective communication	3.96	0.793	0.406	0.637	20
F03	Human	Coherent team working	3.93	0.785	0.735	0.857	21
F09	Organiz.	Awareness of customer requirements	3.85	0.770	0.645	0.803	22
F25	Planning	Utilizing effective strategies in work	3.85	0.770	0.422	0.650	23
F20	Manag.	Appropriate incentive system	3.74	0.748	1.007	1.003	24
F07	Human	Encourage the team to adopt new approaches.	3.70	0.741	0.875	0.935	25
F11	Organize.	Communicating information in a satisfactory way	3.67	0.733	0.667	0.817	26
F14	Organize.	Building of a suitable contractual agreement	3.41	0.681	1.130	1.063	27

Based on the analysis presented in Table 3, the factors were evaluated using their Mean Score (MS) and Relative Importance Index (RII), reflecting the perceived influence of each factor as rated by the participants. The results indicate that the top five factors with the highest RII scores are: (1) awareness of lean philosophy (Human), (2) absence of de-sign errors (Management), (3) efficient management of the production chain (Planning), (4) collaborative connections (Management), and (5) a solid work plan with comprehensive risk planning (Planning).

Conversely, the five factors with the lowest RII scores, indicating relatively less influence, are: (1) use of effective work strategies (Planning), (2) appropriate incentive systems (Management), (3) encouraging teams to adopt new approaches

(Human), (4) effective communication of information (Organizational), and (5) establishing suitable contractual agreements (Organizational).

The prioritisation of a deep understanding of lean philosophy highlights its critical role in successful lean implementation. Equally important is the recognition of effective management practices, particularly in minimising design errors, which further supports the successful adoption of lean principles.

Other highly rated factors include collaborative connections, effective communication, and engagement with experts in Lean Construction (LC). Conversely, factors such as establishing suitable contractual agreements and communicating information received lower RII scores, indicating that they are perceived as

less critical to lean success compared to other factors. Overall, the findings underscore the importance of human resource management, planning, and organisational support in promoting successful lean implementation in Egypt's construction industry.

When analysing the previous results. For example, human-related CSFs such as awareness of lean philosophy and incorporation with experts underscore the central role of practitioners' knowledge and attitudes effective implementation of lean construction in Egypt. The local organisational culture, where projects frequently rely on seasoned staff and unofficial knowledge sharing to manage complicated construction processes, is reflected in this emphasis. Human factors may rank higher than some formal organisational or contractual elements because Egyptian construction companies, in contrast to some other regions, prioritise human adaptability and skill development over strict procedural adherence. The importance of planning-related CSFs, for example, effective workflow management and risk planning, stresses the importance of structured project management in the Egyptian context. Many construction companies operate multiple sites simultaneously and maintain dedicated management and planning sections that employ a variety of tools to monitor quality, cost, and time. This operational reality necessitates strong planning practices and explains the high ranking of planning factors, as they directly mitigate risks associated with complex, multi-site operations.

Management factors, such as minimising design errors and fostering collaborative connections, also play a crucial role in lean adoption. The findings suggest that leadership commitment and proactive decision-making are essential to integrating lean practices successfully. Although these results align with international studies, the relative ranking differs due to Egypt's particular management style, which emphasises practical, on-site problem solving and team coordination over formalised incentive systems or rigid contractual frameworks. Finally, organisational factors are rated slightly lower but provide the structural foundation that supports lean adoption. The ranking result of contractual arrangements and organisational culture factors may indicate that while formal structures are important, Egyptian firms often rely more on operational flexibility, adaptive management, and interpersonal collaboration to achieve lean objectives.

The study identified three key factors for successfully implementing Lean Construction in Egypt: awareness of lean

philosophy, avoidance of design errors, and efficient management of the production chain, each with a Relative Importance Index (RII) of 89%. These results are consistent with prior studies conducted in the Gulf Cooperation Council countries and North Africa. Collaboration and comprehensive risk planning were also emphasised, aligning with research from Saudi Arabia and the UAE. While studies from Morocco and Jordan prioritised supply chain management – which our respondents ranked seventh – these results indicate that human factors and planning are more significant in Egypt. Additionally, contractual agreements received a lower importance ranking (RII = 68%), differing from other regional studies that emphasised legal frameworks, suggesting a local preference for operational and human-centric factors. By highlighting the necessity of targeted training, risk management, and enhanced project planning, these findings contribute to the existing literature and provide a context-specific roadmap for implementing Lean Construction in Egypt.

4.3. Principal component analysis (PCA) for the (CSFs)

Principal Component Analysis (PCA) was used to examine the Critical Success Factors (CSFs) and identify the most significant factors within each component based on statistical analysis. The sample size and the number of CSFs were deemed suitable for PCA, as supported by statistical references [48,55]. The PCA employed the Varimax rotation with Kaiser normalisation. After 11 iterations, the rotation converged, producing seven components. These components collectively explain 85.867% of the total variance, and all seven components have eigenvalues greater than one. Figure 3 presents the scree plot of the rotated component variance for the CSFs.

Table 4 presents the PCA results for the Critical Success Factors (CSFs) for implementing lean in construction firms. The rotated component matrix consists of seven components: Component 1 (C1) includes eight CSFs, Component 2 (C2) includes eight CSFs, Component 3 (C3) includes three CSFs, Component 4 (C4) includes four CSFs, Component 5 (C5) includes two CSFs, Component 6 (C6) includes one CSF, and Component 7 (C7) includes one CSF.

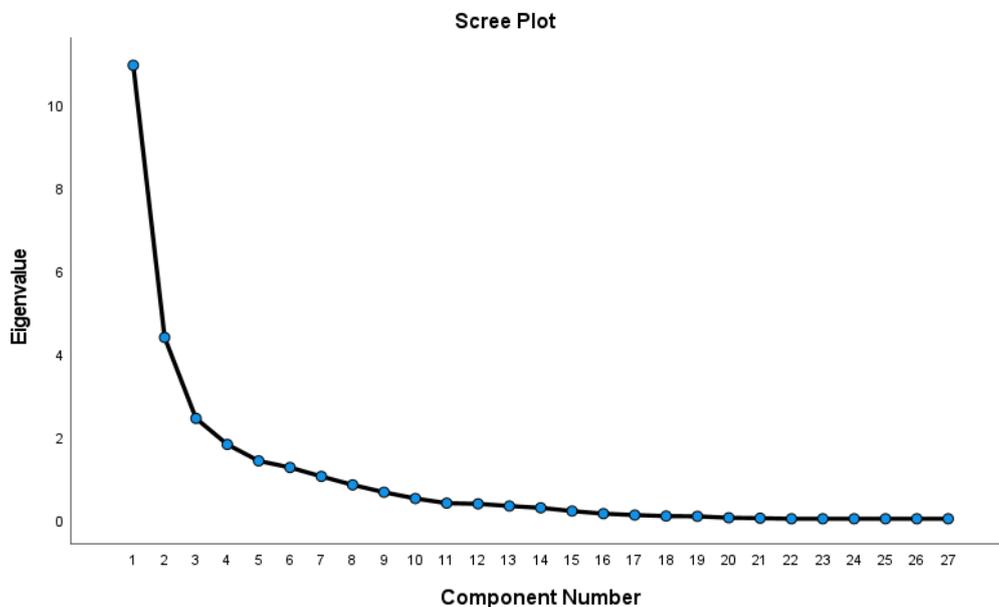


Fig. 3. Scree plot of Rotated Component Variance (CSFs)

Table 4. Rotated Component Matrix of (LC) for CSFs

CSFs	Component						
	1	2	3	4	5	6	7
DSF07	0.882	-0.102	0.064	0.132	0.257	0.127	0.139
DSF11	0.861	0.192	-0.081	0.256	-0.248	-0.049	0.110
DSF03	0.794	-0.162	-0.076	0.325	-0.054	0.213	0.256
DSF20	0.758	-0.001	-0.011	0.073	0.051	0.535	-0.252
DSF02	0.737	-0.009	0.538	-0.045	0.091	-0.005	0.136
DSF04	0.649	0.319	0.221	-0.046	0.231	0.058	0.395
DSF10	0.632	0.196	0.137	0.343	0.206	0.168	-0.115
DSF17	0.570	0.311	0.286	0.229	-0.085	0.403	-0.034
DSF27	0.173	0.885	0.121	-0.037	0.014	0.103	0.099
DSF23	-0.085	0.844	0.012	0.196	0.251	0.020	0.015
DSF25	0.537	0.744	0.086	-0.100	0.179	0.157	-0.008
DSF16	-0.052	0.713	0.351	0.229	0.348	-0.069	0.042
DSF26	0.533	0.699	0.032	0.179	-0.091	-0.177	0.205
DSF15	-0.070	0.654	0.408	0.379	0.300	-0.149	0.203
DSF08	-0.072	0.640	0.285	0.040	0.162	0.303	0.419
DSF24	0.554	0.565	0.078	0.051	0.394	-0.001	-0.320
DSF05	0.055	0.155	0.858	0.139	-0.002	0.292	0.207
DSF06	0.247	0.293	0.788	0.059	0.380	-0.056	0.031
DSF18	-0.116	0.564	0.578	0.235	0.034	0.374	-0.022
DSF12	0.321	0.158	0.221	0.874	0.129	-0.123	0.075
DSF13	0.168	0.105	-0.092	0.869	-0.068	0.333	0.162
DSF09	0.188	-0.021	0.347	0.551	0.033	0.497	0.245
DSF14	0.231	0.381	0.414	0.509	-0.005	0.005	-0.150
DSF21	-0.033	0.462	0.148	-0.005	0.799	0.070	0.079
DSF22	0.534	0.233	0.130	0.067	0.715	0.192	-0.068
DSF19	0.400	0.080	0.184	0.123	0.181	0.794	0.143
DSF01	0.256	0.223	0.161	0.223	-0.016	0.083	0.837

The PCA results indicate the total variance explained by the components of the Critical Success Factors for lean construction, highlighting the contribution of each component to the variability in the collected data. Table 5 and Figure 4 present the total variance for these components.

As shown in Table 5 and Fig. 4, the first component (C1) explains 40.517% of the variance and has an initial eigenvalue of 10.939. C1 accounts for the largest proportion of variability among the factors and is the most influential in explaining the overall success of lean construction adoption, comprising eight CSFs. Component 2 (C2) explains 16.200% of the variance, with an initial eigenvalue of 4.374. Although less impactful than C1, it still contributes significantly to understanding lean construction adoption. Component 3 (C3) accounts for 8.969% of the variance,

with an initial eigenvalue of 2.422, offering additional insights but to a lesser extent than C1 and C2. Component 4 (C4) explains 6.642% of the variance, with an initial eigenvalue of 1.793, indicating a further level of variability with declining influence. Component 5 (C5) explains 5.172% of the variance, with an initial eigenvalue of 1.396, while Components 6 (C6) and 7 (C7) account for the remaining variance with progressively smaller eigenvalues. These results indicate that the first few components capture most of the data's variability, whereas subsequent components explain smaller proportions. Overall, the first three components are the primary factors influencing the success of lean adoption in Egyptian construction firms, with the remaining components contributing to a lesser extent. Table 6 details the CSFs for lean construction utilisation by component.

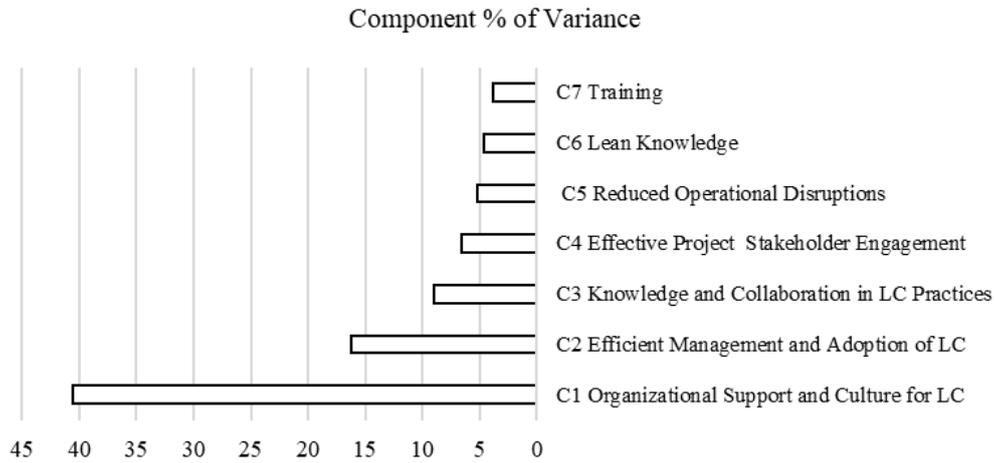


Fig. 4. The five CSFs components% variance

Table 5. Total variance explained of rotated component of (LC) adoption (CSFs)

Component	Initial Eigenvalues		
	Total	% of Variance	Cumulative %
1	10.939	40.517	40.517
2	4.374	16.200	56.717
3	2.422	8.969	65.685
4	1.793	6.642	72.328
5	1.396	5.172	77.499
6	1.237	4.582	82.081
7	1.022	3.785	85.867

Table 6. Lean construction utilising (CSFs) components

F#	Components	Components common features
F07	Encourage the team to adopt new approaches.	
F11	Communicating information in a satisfactory way	
F03	Coherent team working	
F20	Appropriate incentive system	C1
F02	Institution Support	Organisational Support and Culture for (LC)
F04	Precise description of responsibilities	
F10	Reinforce cultural transformation	
F17	Effective communication	
F27	A solid work plan with extensive planning for risks	
F23	More profitable management of the production chain	
F25	Utilising effective strategies at work	
F16	Publicity of the outcomes of the (LC) application	C2
F26	A transparent management process	Efficient Management and Adoption of (LC)
F15	Supply Chain	
F08	Performance of the (LC) tools	
F24	Using effective communication	
F05	Awareness of Lean philosophy	
F06	Incorporation with experts in (LC)	C3
F18	Collaborative connections	Knowledge and Collaboration in (LC) Practices
F12	Adequate coordination and collaboration	
F13	Proper technique of risk management	C4
F09	Awareness of customer requirements	Effective Project Stakeholder Engagement
F14	Building a suitable contractual agreement	
F21	Lack of design errors	C5
F22	Minimisation of turnover	Reduced Operational Disruptions
F19	Awareness of processes and outcomes.	C6 Lean Knowledge
F01	Proper training	C7 Training

Based on the statistical analysis, the component matrix identifies the factors influencing the successful implementation of Lean in Egyptian construction projects and groups them into components. Observing the standard characteristics of the factors within each component, the components can be renamed as follows: (C1) Organizational Support and Culture for Lean Construction (LC), (C2) Efficient Management and Adoption of LC, (C3) Knowledge and Collaboration in LC Practices, (C4) Effective Project Stakeholder Engagement, (C5) Reduced Operational Disruptions, (C6) Lean Knowledge, and (C7) Training for LC.

5. Conclusions

This study provides a comprehensive examination of the critical factors that drive the successful implementation of Lean Construction (LC) principles in Egypt's construction industry. The primary objective is to enhance project stakeholders' understanding of these factors, thereby promoting the widespread adoption of lean methods across construction projects. A thorough review of previous studies was conducted to identify relevant Critical Success Factors (CSFs), resulting in twenty-seven factors categorised into four groups based on their characteristics: human, management, planning, and organisational factors. The collected data were analysed using descriptive statistics and Principal Component Analysis (PCA), providing a structured framework for extracting key insights from the survey responses.

The results rank the four CSF groups as follows: human factors (RII = 84%), planning factors (RII = 83%), management factors (RII = 81%), and organisational factors (RII = 76%). Human factors, including awareness of lean philosophy and collaboration with lean construction experts, were highly influential. Management factors, such as minimising design errors and effective communication, were critical for LC success, while organisational factors, including collaborative connections and process awareness, also contributed significantly.

The top five CSFs, identified as key drivers of lean success, are: (a) awareness of lean philosophy (Human), highlighting the importance of stakeholders' deep understanding and alignment with lean principles; (b) minimizing design errors (Management), as errors lead to budget and schedule inefficiencies; (c) efficient management of the production chain (Planning), optimizing resource use and reducing waste; (d) collaborative connections (Management), fostering strong stakeholder relationships for smoother project execution; and (e) risk management (Planning), emphasizing proactive identification and mitigation of potential project risks.

Conversely, the five least influential factors are: utilising effective work strategies (Planning), implementing appropriate incentive systems (Management), encouraging teams to adopt new approaches (Human), communicating information effectively (Organisational), and establishing suitable contractual agreements (Organisational).

PCA results revealed seven CSF components, collectively explaining 85.867% of the total variance. The most influential components were organisational support and culture for lean construction, followed by efficient management, knowledge and collaboration, effective stakeholder engagement, reduced operational disruptions, lean knowledge, and training.

Overall, the study highlights the critical role of human resource management, planning, and organisational support in promoting successful lean adoption in Egypt's construction industry. The study shows that integrating human, managerial,

planning, and organisational factors is essential for successful lean implementation. It contributes theoretically to lean construction studies by highlighting how local culture, site management, and team engagement shape CSF prioritisation. These findings provide project stakeholders with practical insights to enhance their understanding and implementation of LC practices, offering a roadmap for improving lean utilisation and achieving project success in the local construction context. As well as offering a guide for comparing lean adoption in different countries to bridge the gap between theory and practice worldwide. In practice, it underscores the importance of team training, risk management, and collaborative planning to enhance project outcomes and achieve sustainability.

6. Recommendations

Based on the study's findings regarding the critical factors for successfully applying Lean Construction principles in Egypt's construction industry, several recommendations are proposed. Project owners and policymakers should enhance awareness of lean philosophy through comprehensive training programs on lean principles and methodologies. Design teams and consultants can improve design error management by implementing structured design review processes and stringent quality-control measures to minimise errors and ensure project accuracy throughout the lifecycle. Contractors and project managers should optimise production chain management by applying advanced planning and scheduling techniques to maximise resource utilisation, strengthen collaboration through regular communication, joint problem-solving, and shared decision-making, and enhance risk management practices by developing proactive strategies to identify, assess, and mitigate potential risks. By implementing these recommendations, project stakeholders can optimise practices, improve lean construction performance, and contribute to the long-term sustainability of Egypt's construction sector.

Conflict of Interest

The author declares no conflict of interest.

Acknowledgements

The authors wish to thank all the construction professionals who participated in the survey.

Funding

No funding source available.

Availability of Data and Materials

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Abbreviations

The following abbreviations are used in this manuscript:

CSFs	Critical Success Factors
PCA	principal component analysis
LC	Lean Construction
LD	Linear dichroism
FIFO	First In, First Out
QFD	Quality Function Development
PDCA	Plan, Do, Check, Act
JIT	Just-in-Time

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