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Bridging barriers to lean construction adoption in megaprojects: a data-driven contribution to sustainable development using SEM

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Abstract
Megaprojects frequently face cost overruns, delays, and inefficiencies due to their complexity and multi-stakeholder dynamics. As large-scale infrastructure projects with significant economic and social impacts, they demand innovative solutions to enhance performance and sustainability. Lean Construction (LC) offers a promising approach to achieving these goals, yet its adoption remains limited by various barriers. While prior studies have identified Critical Success Factors (CSFs), there is a lack of robust statistical validation on how these factors mitigate LC adoption challenges. To address this gap, this study employs a sequential mixed-methods approach integrating a systematic literature review to identify preliminary factors, followed by semi-structured interviews with industry experts to refine and validate these factors. A structured questionnaire was then administered to 379 construction professionals involved in megaprojects in China to gather quantitative data. Finally, Partial Least Squares Structural Equation Modeling (PLS-SEM) was used to examine the causal relationships between CSFs and LC Barriers (LCBs). Results show that CSFs significantly reduce LCBs, with Strategic Leadership ($\beta = 0.243$), Resource and Knowledge Availability ($\beta = 0.193$), and Process Improvement ($\beta = 0.188$) being most influential. The model demonstrates acceptable explanatory power ($R^2 = 0.263$), predictive relevance ($Q^2 = 0.252$), and effect size ($F^2 = 0.356$). This study provides the first empirically validated framework linking success factors with LC adoption barriers, offering actionable strategies for more effective implementation in complex project environments.

Keywords Lean Construction · Megaprojects · Structural Equation Modelling · Critical Success Factors · Adoption Barriers · Sustainable Development

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1 Introduction

Megaprojects are large-scale developments with investment costs exceeding US$1 billion, playing a crucial role in the global economy. Annual megaproject expenditures are estimated to range between USD 6–9 trillion, contributing approximately 8% to the global GDP (Flyvbjerg, 2014). Megaprojects typically involve multiple stakeholders from both public and private sectors and are characterized by their high complexity, extended development timelines, and significant socio-economic and environmental impacts (Platoni & Timpano, 2020). Despite their strategic importance, megaprojects face escalating challenges in an era of climate urgency, rapid urbanization, and heightened stakeholder expectations, making their efficient delivery critical to sustainable development goals (SDGs).

Yet, realizing this potential is far from straightforward. Although megaprojects are lauded for driving economic growth and infrastructure development, they are plagued by systemic issues such as cost overruns, schedule delays, and significant safety risks. The performance issues in construction megaprojects are well-documented. Global infrastructure studies highlight alarming inefficiencies: for instance, rail projects outside North America experience cost overruns of up to 65% (Cantarelli & Flyvbjerg, 2015). Even in highly developed regions such as Europe, transportation infrastructure projects frequently suffer from budget inflation and schedule delays (Locatelli et al., 2017). These inefficiencies stem from deep-seated systemic issues, often originating from unrealistic budgeting, flawed project designs, and strategic misrepresentation by stakeholders (Flyvbjerg, 2014). Compounding these challenges, the increasing complexity of modern megaprojects, such as smart cities and renewable energy initiatives, demands advanced technologies, innovative methods, and operational frameworks to align with global sustainability targets.

Advanced technologies are emerging as transformative enablers of sustainable megaproject delivery. Innovations such as renewable energy systems, energy-efficient materials, and digitalization tools are reshaping the industry (Deng et al., 2024; Sudarsan & Chithra, 2024). For instance, self-healing concrete, recycled composites, and smart sensing technologies enhance infrastructure durability and resource efficiency (Liu & Zhao, 2024). Complementing these material innovations, digital technologies like Building Information Modeling (BIM), artificial intelligence (AI), and the Internet of Things (IoT) optimize energy use and operational performance, according to Asif et al. (2024), integrating these tools could reduce energy intensity in construction by 30%–50% by 2040.

Beyond technology, green construction practices and collaborative frameworks are essential for scaling sustainability. Passive design strategies and sustainable material sourcing improve building performance and occupant comfort (Kuttimarks et al., 2024; Peng et al., 2025). To maximize their impact, the establishment of innovation ecosystems is critical. These ecosystems foster collaboration among stakeholders, including governments, industry leaders, and researchers, amplifying the effectiveness of sustainable technologies in mitigating climate change and promoting eco-friendly urban design (Chatti et al., 2024; Husainy et al., 2024). Collectively, these strategies address pressing environmental challenges in construction, as emphasized by (Hussein El Gamaly, 2024), ensuring a pathway toward resilient and sustainable infrastructure.

While technological and green innovations offer solutions, systemic inefficiencies in megaprojects also demand process-oriented methodologies (Flyvbjerg et al., 2013). Lean Construction (LC), as a continuous improvement approach, minimizes waste, boosts productivity, and enhances safety while aligning with sustainability goals (Marhani et al., 2012). LC also focus on value maximization and waste reduction, directly addressing

megaprojects'triple constraint of scope, time, and cost. Despite its proven benefits in smaller projects, its adoption in large-scale initiatives remains fragmented.

Many countries have experienced significant benefits from implementing LC practices. In the USA, lean tools such as the Last Planner System (LPS) and Kaizen activities have led to projects being completed ahead of schedule, within budget, and with fewer defects and lower costs (Leonard, 2006; Salem et al., 2006). For instance, a housing developer achieved a 50% cost reduction (Leonard, 2006), while lean techniques helped decrease accident rates by 58%, demonstrating how improved worksite organization can revolutionize safety outcomes (Nahmens & Ikuma, 2009). Sweden's construction sector echoes this success, where prioritizing value-added activities trimmed project costs by 1.25% (Arleroth & Kristensson, 2011). Beyond efficiency, the synergy between lean and green construction principles has unlocked environmental gains, with waste minimization and optimized resource use driving sustainability forward (Carneiro et al., 2012; Nahmens & Ikuma, 2012). However, the scalability of these successes to megaprojects that involve multilayered governance and geographically dispersed teams remains underexplored.

1.1 Research gap

While LC has emerged as a promising strategy for addressing common construction failures in megaprojects (El-Sabek & McCabe, 2017; Evans et al., 2021), existing studies focus narrowly on isolated case studies or tool-specific applications, lacking a holistic, validated framework to address systemic barriers in megaprojects. Numerous studies have explored opportunities and practices for LC adoption in megaprojects (Belayutham et al., 2022; El-Sabek & McCabe, 2018; Gil, 2022; Ma & Fu, 2020; Phelps, 2012; Rodrigues & Lindhard, 2023; Schöttle & Böker, 2023). For instance, Evans et al. (2021) investigated the critical success factors for integrating BIM with LC in megaprojects, while Evans et al. (2022) developed a competency framework to facilitate the integration of LC and Integrated Project Delivery (IPD). However, no study has statistically modelled how enhancing CSFs can mitigate barriers to LC adoption in megaprojects, creating a crucial gap in both theory and practice. This gap aligns with the findings of Ibrahim et al. (2025), who emphasized the need for empirical validation of LC's scalability in construction megaprojects. Addressing this gap is urgent, as megaprojects are pivotal to global infrastructure resilience and decarbonization.

Additionally, a key limitation of existing literature is its reliance on descriptive or basic inferential methods, such as mean scores, principal component analysis, and fuzzy AHP, to prioritize CSFs or barriers (Adhi & Muslim, 2023; Hyarat et al., 2024; Lam et al., 2024). These approaches fail to establish causal relationships between CSFs (e.g., stakeholder collaboration, leadership commitment) and barriers (e.g., resistance to change, resource constraints). Although interpretive structural Modeling (ISM) has been applied to map hierarchical relationships within CSFs or barriers (Prabaharan & Shanmugapriya, 2023; Sarhan et al., 2020), no study has statistically tested the direct interplay between CSFs and barriers.

1.2 Novelty and contribution

Consequently, this research addresses this gap by being the first study to empirically validate how enhancing CSFs can systematically mitigate barriers, offering actionable insights for optimizing LC adoption by: (1) identifying the barriers that hinder LC adoption in

construction megaprojects, (2) exploring the CSFs that enhance LC adoption in construction megaprojects, (3) testing the hypothesis that CSFs can help mitigate these barriers, and (4) determining the most influential success factors in promoting LC adoption and overcoming obstacles. The central research question guiding this study is: To what extent do critical success factors (CSFs) statistically mitigate barriers to LC adoption and improve the performance of construction megaprojects, and which CSFs hold the most significant influence?

To meet the research objectives, this study utilizes Structural Equation Modelling (SEM), a powerful statistical technique suited for examining intricate relationships among multiple variables. SEM enables a more nuanced understanding of how critical success factors contribute to overcoming barriers, providing richer insights compared to conventional analytical methods. A survey instrument was developed based on key variables identified from existing literature. This initial draft underwent pre-testing and feedback through semi-structured interviews to enhance its validity and relevance. The final dataset was collected from 379 experts working on megaprojects in China, ensuring high reliability. These experts, with extensive experience in construction project management, provided valuable insights that strengthen the study's findings. Without a unified approach, organizations struggle to fully maximize the potential of LC, making it crucial to develop an empirically tested model that can guide future implementation efforts. By achieving these objectives, this study contributes to academia by providing a statistically validated model linking CSFs to barrier mitigation and industry by offering actionable strategies for scalable LC implementation.

The rest of this paper is organized into several key sections. Section 2 presents the theoretical framework and reviews relevant literature on Lean Construction Enablers (LCEs) and their effectiveness in addressing Lean Construction Barriers (LCBs). Section 3 details the research methodology, including the procedures used for data collection and analysis. Section 4 reports the main findings of the study, followed by an in-depth discussion of these results in Sect. 5. Section 6 outlines both practical and theoretical implications, along with actionable recommendations derived from the study's outcomes. Finally, Sect. 7 provides a conclusion and suggests potential areas for future research.

2 Literature review

2.1 Theoretical background

Lean principles began to take shape in the 1970 s when a team of researchers at MIT's International Motor Vehicle Program, headed by James Womack, worked to formalize and advocate for the Lean Production System (LPS). This framework was largely influenced by the Toyota Production System (TPS), developed earlier in the twentieth century by Japanese industrial engineer Taiichi Ohno. Ohno developed TPS in response to the intense post-World War II competitive pressures faced by Toyota, particularly from American automakers, who dominated the market with high productivity and customer-centric approaches (Aburumman et al., 2024; Sheykhizadeh et al., 2024). Lean methodologies prioritize maximizing customer value while minimizing waste to enhance efficiency and quality (Ballard & Koskela, 1998; Ballard & Howell, 2003; Singh et al., 2025). Core principles include just-in-time production, continuous flow, and waste reduction, supported by tools like value stream mapping. Human and cultural factors, leadership, employee engagement,

and organizational learning are vital to sustaining Lean practices, as demonstrated by Toyota's emphasis on people-driven processes (Liker & Morgan, 2006; Tommelein, 2015).

In construction, Lean adoption has grown, yet its definition remains contested. Researchers highlight its variability: Ansah et al. (2016) describe Lean as *"the effective integration of people, materials, and resources to minimize costs, remove inefficiencies, and ensure timely project completion without excessive cost reduction,"* while Saieg et al. (2018) frame it as *"applying lean manufacturing principles to construction to boost productivity, quality, and practical adoption."* This conceptual ambiguity, alongside fragmented workflows and stakeholder resistance, complicates implementation (Green & May, 2005; Igwe et al., 2022). Though tools like Integrated Project Delivery (IPD) aim to enhance collaboration and efficiency, global adoption faces barriers such as logistical hurdles, poor information flow, and cultural reluctance (Xing et al., 2021). Successful Lean integration requires aligning processes, nurturing adaptive cultures, and committing to long-term learning (Saieg et al., 2018).

While LC principles are universal, their application diverges significantly between small-scale and megaprojects due to differences in complexity, resource dynamics, and stakeholder engagement. Small projects, characterized by limited scope and fewer stakeholders, often prioritize localized waste reduction, such as just-in-time material delivery, and agile decision-making. As Koskela (2000) emphasizes that lean's adaptability thrives in these simpler contexts. Conversely, megaprojects, defined by Flyvbjerg (2014), large-scale, capital-intensive endeavours with extended timelines, require scalable lean strategies to address multifaceted challenges. These projects demand advanced stakeholder coordination (Toor & Ogunlana 2010), given the involvement of governments, multinational contractors, and communities, small projects benefit from direct communication channels. Additionally, lean tools like the Last Planner System (Howell & Ballard, 1998) and BIM (Azhar, 2011) are critical for managing megaproject complexity but may be overly cumbersome for smaller initiatives. Risk mitigation further highlights this divide: megaprojects rely on lean-driven adaptive planning (Geraldi et al., 2011), while small projects focus on incremental process improvements. Collectively, these distinctions underscore the need for tailored lean enablers, such as policy alignment and digital integration, to address megaprojects' unique scale-driven challenges, a gap this study seeks to address.

The global application of LC methodologies in megaprojects has demonstrated their effectiveness in improving outcomes through region-specific adaptations. For example, Koseoglu et al. (2018) illustrated how integrating BIM with LC in the Istanbul Grand Airport project (Turkey) expedited design iterations and improved documentation coordination, yielding higher-quality results. Similarly, Idrissi Gartoumi et al. (2024) showcased LC's role in mitigating quality defects and enhancing stakeholder satisfaction in Morocco's Mohamed VI Tower project. Flores and Ollero (2013) highlighted LC's ability to optimize workflows and minimize waste, boosting productivity in Peru. In the United States, Lostuvali et al. (2014) linked LC adoption in the Cathedral Hill Hospital project to reduced rework and enhanced collaboration. Meanwhile, Li et al. (2021) developed a framework integrating BIM and LC for owner-dominated megaprojects in China, improving stakeholder alignment. These examples collectively emphasize LC's adaptability to diverse regional and operational contexts.

Research methods investigating LC integration have also evolved to address barriers and enhance implementation. For instance, Evans & Farrell (2021) conducted a Delphi survey in Qatar to prioritize barriers to BIM-LC integration, while their later work (Evans et al., 2023) utilized interviews and focus groups across the MENA region to explore challenges aligning LC with Integrated Project Delivery (IPD). Building on this, Evans et al.

(2023) developed a competency framework via a middle eastern questionnaire survey, offering guidelines for integrating LC with Global Integrated Delivery (GID) and sustainability goals. Such studies underscore the value of mixed method approaches in identifying region-specific challenges and fostering LC's global applicability.

Despite these advancements, significant gaps persist in testing that CSFs can help mitigate these barriers. Crucially, no study has statistically modelled how enhancing CSFs can reduce obstacles to LC adoption in megaprojects, creating a gap in both theory and practice. Addressing this gap is urgent, as megaprojects are pivotal to global infrastructure resilience and decarbonization, necessitating a systematic framework to address their scale-driven complexities.

2.2 Critical success factors for LC adoption

The successful adoption of LC practices relies on various CSFs encompassing organizational and technical aspects. First and foremost, the financial capability of a company is a significant enabler, as organizations with more substantial financial resources are better positioned to invest in training, technology, and the necessary equipment for lean practices (Shurrab & Hussain, 2018; Watfa & Sawalha, 2021). In addition, enhancing awareness about the compatibility of lean principles with existing construction processes helps overcome resistance and ensure smoother integration (Demirkesen & Bayhan, 2020). Furthermore, government and organizational support in the form of clear regulations, policies, and top management commitment play a pivotal role in creating an environment conducive to lean adoption (Idrissi Gartoumi et al., 2024). A clear early strategic vision is equally important, as it aligns all stakeholders towards a common objective and ensures that lean principles are integrated into the project's overarching goals (Sarhan et al., 2020). Additionally, incentive mechanisms, such as tax exemptions or reward systems, motivate stakeholders to adopt lean practices and support long-term commitment (Sadikoglu et al., 2024). Moreover, the commitment from both top and middle management is vital for driving lean adoption across all levels of the organization, as their active participation helps overcome potential barriers (Aslam et al., 2020).

The leadership capabilities of clients and contractors also play a critical role, as strong leadership encourages the sharing and implementation of lean practices among all project participants (Saini et al., 2018). Effective stakeholder management, including the development of trusting relationships, is another crucial factor that ensures all parties are aligned with the lean objectives (Sadikoglu et al., 2024; Ying et al., 2022). A customer-centric value definition, which focuses on understanding customer needs, preferences, and expectations, ensures that lean efforts align with the ultimate goal of delivering value to the customer (Sweis et al., 2016). Satisfying customer demands through lean practices is closely tied to this, as organizations that meet or exceed customer expectations enhance their competitive edge (Sarhan et al., 2020). The early involvement of key stakeholders ensures that their insights are incorporated from the outset, making it easier to address potential issues and ensuring smoother implementation of lean practices (Abusalem, 2020). Building strong relationships with stakeholders further enhances collaboration and ensures that all parties remain committed to the lean goals throughout the project lifecycle (Watfa & Sawalha, 2021). The availability of qualified lean leaders and managers is another key enabler, as these individuals possess the expertise to guide teams and navigate the challenges of lean adoption effectively (Demirkesen & Bayhan, 2020). Furthermore, providing training for

all employees is essential to ensure that everyone within the organization understands lean principles and can contribute to their successful implementation (Sadikoglu et al., 2024).

Managing resistance to change is another critical factor for successful lean adoption. Establishing lean research groups and initiatives dedicated to managing resistance ensures smooth transition to lean practices and that the organizational culture supports continuous improvement (Alsehaimi et al., 2014). Adequate resource availability and familiarity with lean techniques, such as the Last Planner System or Just-in-Time (JIT), further enhance the likelihood of successful implementation (Idrissi Gartoumi et al., 2024). Moreover, using flexible resources and adaptive planning allows for better handling unforeseen changes, thereby minimizing disruptions and enhancing project efficiency (Diekmann et al., 2003). Effective logistics and procurement systems focusing on value creation also contribute to lean success by ensuring timely delivery of materials and reducing waste (Ying et al., 2022). Finally, applying appropriate lean tools and techniques, such as the Last Planner System, 5S, and Value Stream Mapping, is essential for improving processes and eliminating waste (Bajjou & Chafi, 2018a, b). Visual management tools, such as dashboards and performance indicators, further enhance transparency and accountability, ensuring that lean goals are met and progress is continuously monitored (Sweis et al., 2016). Integrating technology and innovation plays a pivotal role in implementing LC successfully. One of the key success factors is the adoption of new construction technologies and innovative methods, such as BIM, which enhances collaboration, reduces waste, and improves project efficiency (Mellado & Lou, 2020; Meshref & Ibrahim, 2024; Sarhan et al., 2020). Additionally, modular integrated construction (MIC) has emerged as a transformative approach that aligns with LC principles by streamlining processes, minimizing material waste, and accelerating project timelines (Lam et al., 2024; Sweis et al., 2016). As digital transformation continues to reshape the construction industry, leveraging these advanced methodologies is essential for maximizing the benefits of LC and ensuring its sustainable adoption in megaprojects. Table 1 provides a comprehensive overview of prior research on CSFs, highlighting the methodologies, geographical contexts, and analytical approaches used in these studies.

2.3 Barriers for LC adoption

Adopting LC in construction megaprojects faces numerous barriers that hinder its complete integration and effectiveness. These multifaceted barriers range from organizational resistance to financial constraints, stakeholder limitations, and technological challenges. Understanding these obstacles is crucial to formulating strategies promoting LC adoption and improving megaproject efficiency.

One of the primary barriers to LC adoption is the construction industry's resistance to shifting away from traditional working practices (Balkhy et al., 2021). Many companies remain hesitant to embrace lean methodologies due to the fragmented nature of the industry, particularly in large-scale projects where different contractors and subcontractors operate independently (Evans et al., 2023). Additionally, the lack of long-term commitment to innovation and change within organizations further slows the transition to lean practices (Hyarat et al., 2024). Complex organizational hierarchies also contribute to slow decision-making, making it challenging to implement lean strategies efficiently (Singh et al., 2024). Furthermore, insufficient training and education programs for workers limit their understanding and ability to apply LC principles effectively (Moradi & Sormunen, 2023).

Table 1 Overview of CSFs for LC implementation studies in prior literature

Ref	Year	Num of CSFs	Data Collection	Analysis Method	Country	Domain
Lam et al. (2024)	2024	20	Interview	Mean Score, Standard Deviation, Principal Component Analysis, Mann–Whitney U Test	Hong Kong	CSFs & Barriers
Marhani et al. (2023)	2023	12	Survey	Mean Score, Standard Deviation	Malaysia	CSFs
Adhi & Muslim (2023)	2023	30	Survey	Certainty Index, Rii, Fuzzy Ahp, Fuzzy-Topsis	Indonesia	CSFs, Barriers, Strategies
Noorzai (2023)	2023	11	Survey	Ahp, Sensitivity Analysis	Iran	CSFs & LC Tools
Demirkesen & Bayhan (2022)	2022	27	Survey	Mean Score, Standard Deviation, Exploratory Factor Analysis (EFA), Kruskal-Walli's Test	USA	CSFs & LC Tools
Arabi et al.(2022)	2022	16	Survey	Mean Score, Standard Deviation	Morocco	CSFs
Meshref et al. (2022)	2022	18	Interview	Simos', WSM	Egypt	CSFs
Kariyawasam & Siriwardana (2021)	2021	15	Survey	Mean, RII, SD	Sri Lanka	CSFs & Barriers
Watfa & Sawalha (2021)	2021	22	Survey	Mean, Relative Importance Index (Rii)	UAE	CSFs
Bhawani et al. (2021)	2021	27	Interviews	Content Analysis Approach	USA	CSFs & Barriers
Evans et al. (2021)	2021	30	Two-round Delphi survey	Mean Score Ranking, Inter-Rater Agreement (IRA), Spearman's Rank Correlation, Mann–Whitney U Test	12 Country	CSFs & BIM
Sarhan et al. (2020)	2020	12	Survey	Interpretive Structural Modelling (Ism)	Saudi Arabia	CSFs
Bayhan et al. (2019)	2019	27	Survey	Mean Score	Turkey	CSFs & Barriers

The role of stakeholders in LC adoption is significant, yet poor communication and collaboration among project stakeholders often hinder progress (Moradi & Sormunen, 2023). Many projects suffer from a lack of early stakeholder involvement, which leads to misaligned goals and delays in implementation (Lam et al., 2024). Moreover, the low level of awareness regarding LC techniques and the perception that LC methodologies are overly complex discourage labor participation (Bajjou & Chafi, 2018a, b). The high turnover of the workforce in construction projects further exacerbates the challenge, making it difficult to maintain continuity in LC adoption efforts (Pedrosa et al., 2023).

From a procedural standpoint, the limited use of off-site construction techniques and prefabrication remains a significant constraint to lean implementation (Pedrosa et al., 2023). Prefabrication and modular construction, which align with LC principles, are underutilized in megaprojects, leading to inefficiencies and waste. Additionally, uncertainties in the supply chain contribute to delays and resource mismanagement, making it difficult to maintain lean workflows (Silva et al., 2023). Another major challenge is the lack of an adequate performance measurement system to track LC adoption and assess its impact effectively (Moyo & Chigara, 2023).

Financial constraints pose another significant challenge in the adoption of LC methodologies. Many organizations lack funding to initiate LC implementation, particularly in developing economies (Musa et al., 2023). The absence of incentives and motivation for employees to engage in LC training and development further discourages the adoption of lean practices (Zhan et al., 2022). Additionally, the high costs associated with lean adoption and inflationary pressures make it difficult for construction firms to invest in the necessary resources and training required for successful implementation (Bashir et al., 2015).

The lack of technological advancement and research in LC presents a significant obstacle to its widespread adoption. There is a low level of research in industry and academia, which limits the development of new tools and frameworks for lean implementation (Evans et al., 2023). Additionally, the absence of advanced software solutions tailored to LC principles restricts efficient project management and decision-making (Ahmed & Sobuz, 2020). The lack of legal frameworks and contract guidelines adapted to modern construction technologies, such as BIM and LC integration, further complicates implementation efforts (Evans & Farrell, 2021; Evans et al., 2023). Moreover, many industry professionals still lack knowledge and experience in utilizing BIM to facilitate LC adoption (Evans & Farrell, 2023; Musharavati, 2023). Table 2 provides a comprehensive overview of prior research on LCBs, highlighting the methodologies, geographical contexts, and analytical approaches used in these studies.

The literature review highlights several studies investigating CSFs and LCBs in LC implementation, revealing valuable insights and notable limitations. Most studies employ basic statistical techniques like mean scores, standard deviation, and relative importance indices (RII), which, while useful for descriptive analysis, fail to explore complex relationships between variables. Although some studies use advanced methods such as AHP, Fuzzy AHP, and ISM, these approaches are often limited to ranking factors and lack the ability to test causal relationships. Exploratory Factor Analysis (EFA) and Principal Component Analysis (PCA) are occasionally used, but these methods primarily focus on data reduction rather than hypothesis testing. Furthermore, the focus on specific domains, such as CSFs, barriers, or tools, varies across studies, making it challenging to draw comprehensive conclusions. These gaps motivate the use of more robust methodologies like SEM, which can examine complex, multivariate relationships, test hypotheses, and model latent variables such as leadership commitment and organizational culture. SEM also allows integrating multiple constructs, enabling a more comprehensive analysis of LC implementation. By

Table 2 Overview of LCBs for LC implementation studies in prior literature

Ref	Year	Number of LCBs	Data Collection	Analysis Method	Country
Hyarat et al. (2024)	2024	27	Survey	Mann–Whitney U, Principal Component Analysis (PCA), Linear Regression	Jordan
Lam et al. (2024)	2024	22	Survey	Mean Score, Standard Deviation, PCA, Mann–Whitney U Test	Hong Kong
Singh et al. (2024)	2024	37	Survey	Fuzzy AHP (fAHP)	India
Evans et al. (2023)	2023	28	Interview, Survey	Mean Score, Standard Deviation, PCA, Eigenvalues	Middle East & North Africa
Silva et al. (2023)	2023	22	Survey	Weighted Average (MIS), Kruskal–Wallis Test	Brazil
Mano et al. (2023)	2023	18	Survey	Exploratory Factor Analysis (EFA)	Brazil
Huaman-Orosco et al. (2022)	2022	27	Survey	Exploratory Factor Analysis, RII	Peru
Prabaharan & Shanmugapriya (2023)	2023	12	Survey	Interpretive Structural Modeling (ISM)	India
Mano et al. (2021)	2021	83	Interview	Content Validity Ratio (CVR)	Brazil
Moyo & Chigara (2023)	2023	32	Survey	RII, Mann–Whitney U Test, Kruskal–Wallis Test	Zimbabwe
Balkhy et al. (2021)	2021	30	Survey	Exploratory Factor Analysis, Mean Score	Jordan
Evans & Farrell (2021)	2021	28	Interview	Two-Round Delphi Survey	Qatar
Hussain et al. (2019)	2019	24	Interview	Interpretive Structural Modeling (ISM)	Pakistan
Bajjou and Chafi (2018a, b)	2018	9	Survey	Mean Score Analysis	Morocco
Sarhan et al. (2018)	2018	22	Survey	Mean Item Score (MIS), Mann–Whitney U Test, PCA	Saudi Arabia (KSA)
Khaba & Bhar (2017)	2017	13	Interview	Interpretive Structural Modeling (ISM)	India
Shang & Sui Pheng (2014)	2014	22	Survey	Mean Score, Standard Deviation, PCA	China
Alinaitwe (2009)	2009	31	Survey	Mean Score, Variance Analysis	Uganda

adopting SEM, future research can address the limitations of prior studies, improve the generalizability of findings, and provide deeper insights into the causal mechanisms driving LC adoption. Integrating qualitative and quantitative data within an SEM framework can further enhance the understanding of LC implementation challenges and success factors, paving the way for more effective megaproject strategies. Consequently, based on the rationale outlined earlier in this study and illustrated in Fig. 1, we formulated the following hypothesis (H1):

3 Methods

This section outlines the methodological framework of the study, encompassing the research context, research design, data collection procedures, questionnaire survey development, and the data analysis procedures, including the development of the Partial Least Squares Structural Equation Modeling (PLS-SEM) model.

3.1 Research context

This study focuses on construction megaprojects in Mainland China and Hong Kong; regions were chosen based on their extensive megaprojects and shared regulatory frameworks. Following Wang et al. (2021), the study targeted megaprojects with investments exceeding 0.5 billion CNY. Respondents, comprising senior and middle managers, focused on their most recently completed megaprojects to minimize hindsight bias (Eriksson et al., 2017). The research aims to identify CSFs and LCBs to facilitate LC implementation, addressing a gap in large-scale project management literature.

3.2 Research design

The study adopts a mixed-methods sequential design (Fig. 2), structured into four interconnected stages to ensure methodological rigor and triangulation of insights. First, a systematic literature review was conducted using the Scopus database and PRISMA methodology to identify preliminary CSFs and LCBs. Next, semi-structured interviews with ten industry experts specializing in Chinese megaprojects were employed to refine and validate these factors, incorporating contextual nuances and practical insights. This qualitative phase informed the third stage, where a structured questionnaire survey was administered to 379 professionals to collect quantitative data on CSFs and LCBs, ensuring broad representativeness through random sampling. Finally, partial least squares structural equation modelling (PLS-SEM) was applied to test hypothesized relationships between constructs, leveraging its predictive power and robustness for complex models. This sequential integration

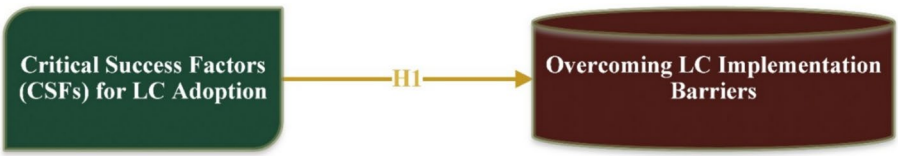

Fig. 1 Research Hypothesis

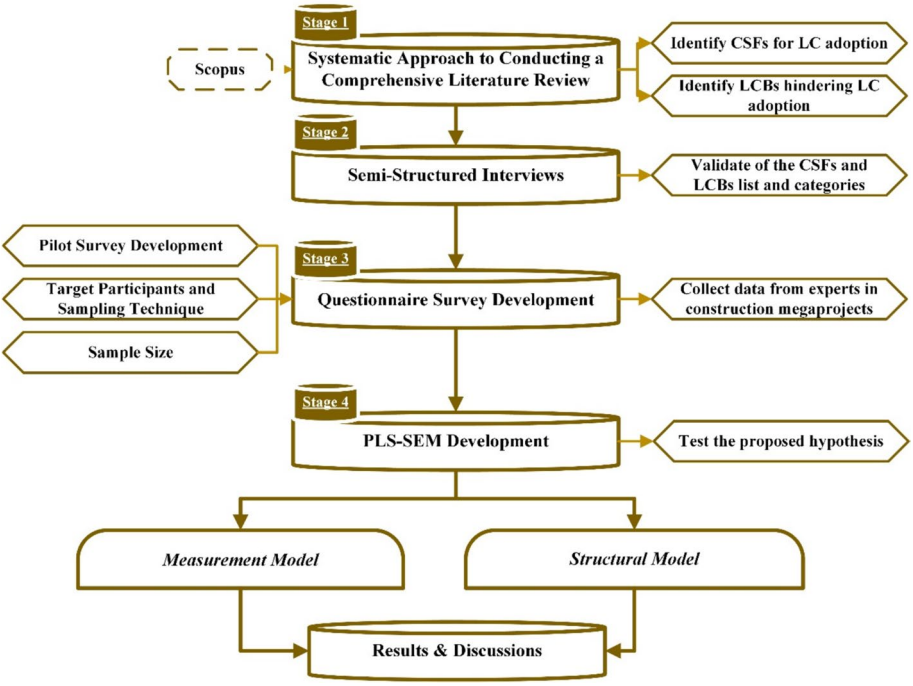

Fig. 2 Research Methodology

of qualitative and quantitative approaches enhances the validity of findings by systematically bridging theoretical frameworks with empirical validation, while addressing both exploratory and confirmatory research objectives.

3.3 Data collection

3.3.1 Systematic approach to conducting a comprehensive literature review

The Scopus database was utilized for literature retrieval due to its extensive coverage. Recognized as one of the leading academic search engines, Scopus is frequently used alongside platforms such as Google Scholar and Web of Science (Ibrahim et al., 2024b). The study employed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology to ensure a structured and unbiased selection of scholarly sources (Ibrahim et al., 2024a). This approach facilitates a rigorous process of identifying, screening, selecting, and extracting relevant data while enhancing reliability and minimizing bias (Ibrahim et al., 2024c).

3.3.2 Semi-structured interviews

A comprehensive understanding of the CSFs for lean adoption and LCBs is essential for enhancing efficiency in the construction industry. To gain deeper insights, semi-structured interviews were conducted with ten experts specializing in Chinese construction megaprojects, all with extensive knowledge of lean tools and practices. These professionals, with 11

to 25 years of experience and predominantly holding advanced degrees (master's or Ph.D.), assessed the previously identified CSFs and LCBs, evaluating their influence on LC implementation. The interview transcripts were analyzed using thematic analysis with a hybrid approach, blending deductive (theory-driven) and inductive (data-driven) coding. Initial codes were derived from the literature-based CSFs and LCBs, while emergent codes captured novel insights. Findings from interviews were triangulated with the literature review and interview results. For instance, interview-derived TI3 and TI4 were added to the Technology and Innovation (TI) category in the CSFs table. The interviews contributed to the validation of the CSF and LCB lists, leading to modifications in certain variables, as outlined in Table 3 for CSFs and in Table 4 for LCBs. Furthermore, originally derived from previous studies, the initial categorization of CSFs and LCBs was refined and reorganized for improved clarity and applicability.

3.4 Questionnaire survey development

The questionnaire survey was chosen as the main method for collecting data due to its effectiveness in generating numerical data that supports in-depth statistical evaluation. It also allows for rapid data collection from a wide pool of participants (Ali et al., 2025; Young, 2015). The survey instrument was organized into four main parts. The initial section collected demographic details of the respondents. The second part listed the Critical Success Factors (CSFs) identified through prior literature. The third section presented the Lean Construction Barriers (LCBs) drawn from existing research. The final section included an open-response item, enabling participants to propose any additional CSFs or LCBs not covered in the earlier sections.

After identifying the CSFs and LCBs, a pilot study was conducted to assess the reliability of these variables, as recommended by Gouda Mohamed and Hathout (2025). This phase is essential for validating the selected factors, identifying potential issues, refining wording, and gathering participant feedback. A pilot questionnaire survey was administered to five participants, and based on their input, necessary modifications were made to enhance clarity and accuracy.

To ensure a representative sample, this study employed a random sampling technique, a widely accepted method in social science research (Bhardwaj, 2019; Rahman et al., 2022). The effectiveness of this approach has been demonstrated in previous studies that have successfully applied it in similar research contexts (Alnaser et al., 2024; Elmousalami et al., 2023).

Ensuring that the sample size aligns with the study objectives is essential when PLS-SEM (Ali & Kineber, 2024). PLS-SEM is particularly beneficial for studies with relatively small sample sizes (J. Hair et al., 2019a, b). Previous research, such as Attia et al. (2023), has demonstrated its successful implementation with sample sizes below 100. with 70 responses, and Abdulai et al. (2024) with 63 responses. In this study, data were collected between March and September 2024, yielding 379 valid responses (effective response rate: 80.46%) out of 471 received.

3.5 Data analysis procedures (PLS-SEM Model Development)

SEM is widely used to examine and validate theoretical frameworks by analyzing the relationships among latent constructs and their associated indicators. Compared to other modelling approaches, SEM offers the advantage of simultaneously evaluating both direct and indirect effects within proposed causal pathways (Fan et al., 2016). The validation

Table 3 Critical Success Factors (CSFs) to adopting LC in construction megaprojects

Category	ID	CSFs	Ref
Strategic and Leadership (SL)	SL1	Financial Capability of the company	(Shurrab & Hussain, 2018; Watfa & Sawalha, 2021)
	SL2	Enhancing awareness that is compatible with construction processes	(Aslam et al., 2020; Demirkesen & Bayhan, 2020)
	SL3	Government and Top organisational management support (i.e., regulations or policies)	(Evans et al., 2021; Idrissi Gartoumi et al., 2024)
	SL4	Clear Early Strategic Vision	(Lam et al., 2024; Sarhan et al., 2020)
	SL5	Incentive mechanisms (i.e., tax exemptions, reward mechanisms)	(Lam et al., 2024; Sadikoglu et al., 2024)
	SL6	Commitment by top and middle management in lean practices	(Aslam et al., 2020; Demirkesen & Bayhan, 2020)
	SL7	Leadership capabilities of clients and main contractors to encourage the sharing of lean practices	(Saini et al., 2018; Watfa & Sawalha, 2021)
Stakeholder and Relationship Management (SRM)	SRM1	Effective stakeholder management and fostering trusting relationships	(Sadikoglu et al., 2024; Ying et al., 2022)
	SRM2	Customer-centric value definition (i.e., needs, preferences, and expectations)	(Bajjou & Chafi, 2018a, b; Sweis et al., 2016)
	SRM3	Satisfying customer demands	(Bajjou & Chafi, 2018a, b; Sarhan et al., 2020)
	SRM4	Early involvement of key stakeholders	(Abusalem, 2020; Watfa & Sawalha, 2021)
	SRM5	Building Relationships with stakeholders	(Abusalem, 2020; Watfa & Sawalha, 2021)
Resource and Knowledge Availability (RKA)	RKA1	Availability of Qualified Lean Leaders and Managers for Effective Implementation	(Demirkesen & Bayhan, 2020; Watfa & Sawalha, 2021)
	RKA2	Training for all employees ensures successful implementation	(Lam et al., 2024; Sadikoglu et al., 2024)
	RKA3	Existence of lean research groups and initiatives to manage the resistance to change	(Alsehaimi et al., 2014; Demirkesen & Bayhan, 2020)
	RKA4	Adequate Resource Availability and familiarity with Lean techniques	(Demirkesen & Bayhan, 2020; Idrissi Gartoumi et al., 2024)
	RKA5	Using flexible resources and adaptive planning	(Bajjou & Chafi, 2018a, b; Diekmann et al., 2003)

Table 3 (continued)

Category	ID	CSFs	Ref
Planning and Operational Efficiency (POE)	POE1	Establish logistics, procurement systems and material movement plans that focuses on value creation and innovative organizational processes	(Sarhan et al., 2020; Ying et al., 2022)
	POE2	Applying appropriate LC tools/techniques (e.g., Last Planner System, 5S, Value Stream Mapping, JIT, Pull flow etc.)	(Bajjou & Chafi, 2018a, b; Sarhan et al., 2020)
	POE3	Visual management tools and techniques	(Bajjou & Chafi, 2018a, b; Sweis et al., 2016)
	POE4	Comprehensive Coordination and Adaptation to Complexity	(Idrissi Gartoumi et al., 2024; Zegarra & Alarcón, 2019)
Process Improvement and Waste Elimination (PIW)	PIW1	Eliminate waste like (e.g., double handling, material constraints, scrap, changeover)	(Diekmann et al., 2003; Sweis et al., 2016)
	PIW2	Reduce variability and cycle time	(Bajjou & Chafi, 2018a, b; Sweis et al., 2016)
	PIW3	Standardized metrics and strategies that align with continuous improvement (e.g., PPC metrics, quality and productivity metrics)	(Sadikoglu et al., 2024; Sarhan et al., 2020)
	PIW4	Benchmarking with Top leading companies	(Aslam et al., 2024; Watfa & Sawalha, 2021)
	PIW5	Adopting standardized methods and tools (e.g. root cause analysis, defect response plan, error proofing devices (poke yoke))	(Aslam et al., 2020; Sadikoglu et al., 2024)
Technology and Innovation (TI)	TI1	Adopting new construction technologies/innovation methods (e.g., BIM)	(Mellado & Lou, 2020; Sarhan et al., 2020)
	TI2	Enhance Modular Integrated Construction	(Lam et al., 2024; Sweis et al., 2016)
	TI3	Improved circular economy to reduce waste (i.e., carbon emission)	Interview
	TI4	Integrating with the new methods (i.e., Digital Twin, Blockchain)	Interview

Table 4 LCBs for LC adoption in construction megaprojects

Category	ID	LCBs	Ref
Organizational and Attitudinal Barriers (OAB)	OAB1	Resistance of the industry to change from traditional working practices	(Balkhy et al., 2021; Evans et al., 2023)
	OAB2	The fragmented nature of construction industry, especially in construction megaprojects	(Evans et al., 2023; Hyarat et al., 2024)
	OAB3	The organization lacks consistent dedication to innovation and long-term transformation	(Evans et al., 2023; Hyarat et al., 2024)
	OAB4	Decision-making is slowed down by a complicated hierarchical structure	(Hyarat et al., 2024; Singh et al., 2024)
	OAB5	Lack of training and education programs	(Moradi & Sormunen, 2023; Musharavati, 2023)
	OAB6	Organisational challenges, project strategies, and policies	(Hyarat et al., 2024; Silva et al., 2023)
	OAB7	Lack of involvement and support of governments	(Singh et al., 2024)
Stakeholder Barriers (SB)	SB1	Poor understanding of customer needs and poor customer focus	(Moradi & Sormunen, 2023; Singh et al., 2024)
	SB2	Poor communication and a lack of spirit of collaboration between project stakeholders	(Moradi & Sormunen, 2023; Sarhan et al., 2018)
	SB3	Lack of early involvement of project stakeholders	(Lam et al., 2024; Singh et al., 2024)
	SB4	Unskilled labour and a low level of education of the site foreman	(Musa et al., 2023; Pedrosa et al., 2023)
	SB5	Low awareness about LC techniques & concepts	(Lam et al., 2024; Singh et al., 2024)
	SB6	Labor considers LC too complex	(Bajjou & Chafi, 2018a, b; Prabaharan & Shanmugapriya, 2023)
	SB7	High turnover of the workforce	(Pedrosa et al., 2023; Shang & Sui Pheng, 2014)
Process Barriers (PB)	PB1	Off-site construction and prefabrication are rarely used	(Hyarat et al., 2024; Pedrosa et al., 2023)
	PB2	Uncertainty in the supply chain	(Silva et al., 2023; Singh et al., 2024)
	PB3	Inadequate performance measurement system	(Hyarat et al., 2024; Moyo & Chigara, 2023)
Financial Barriers (FB)	FB1	Lack of incentives and motivation for the employees to learn about LC	(Hyarat et al., 2024; Zhan et al., 2022)
	FB2	Financial constraints hinder the launch of Lean Construction initiatives	(Huaman-Orosco et al., 2022; Musa et al., 2023)
	FB3	Additional cost and high inflation rates	(Bashir et al., 2015; Sarhan et al., 2018)

Table 4 (continued)

Category	ID	LCBs	Ref
Technological and Knowledge Barriers (TKB)	TKB1	Low level of research in industry and academia	(Evans & Farrell, 2021; Evans et al., 2023)
	TKB2	Lack of software advancement that helps in implementing LC	(Ahmed & Sobuz, 2020; Moyo & Chigara, 2023)
	TKB3	Lack of legal frameworks (guidelines) and contracts tailored to the uncertainties of BIM and LC	(Evans & Farrell, 2021; Evans et al., 2023)
	TKB4	Inadequate knowledge and real-world experience in using BIM appropriately	(Evans & Farrell, 2023; Musharavati, 2023)

procedure in SEM typically involves a two-stage process: initially, the measurement model is evaluated using Confirmatory Factor Analysis (CFA) to confirm that the observed variables appropriately reflect the underlying constructs. In the subsequent stage, the structural model is developed, and hypotheses are tested through path analysis (Xiong et al., 2015).

SEM serves as a comprehensive statistical technique for validating theoretical frameworks and systematically evaluating causal interconnections among variables. Its application spans diverse fields such as management studies, organizational sciences, and construction project analysis (Oyewobi et al., 2016). SEM encompasses two primary methodologies: Partial Least Squares Structural Equation Modelling (PLS-SEM) and covariance-based SEM (CB-SEM). PLS-SEM is frequently adopted over CB-SEM due to three key advantages: (1) superior predictive accuracy, (2) greater adaptability for analyzing complex multi-construct models, and (3) enhanced capacity to accommodate measurement error and variability (Hair et al., 2019a, b).

This research focuses on validating a theoretical framework by evaluating its predictive strength and investigating interconnections among variables. As such, PLS-SEM was selected as the methodological preference. This approach facilitates the examination of relationships between critical success factors (CSFs) for lean construction (LC) adoption and lean construction barriers (LCBs), thereby supporting LC implementation in large-scale infrastructure projects. Figure 3 illustrates the model components and associated validation procedures employed in the PLS-SEM analysis.

3.5.1 Measurement model

In PLS-SEM, the measurement model is evaluated using convergent and discriminant validity tests to ensure the reliability and validity of the constructs (Tham et al., 2019).

Convergent validity is assessed using four key criteria: (1) Outer Loadings, (2) Composite Reliability, (3) Cronbach's Alpha, and (4) Average Variance Extracted (AVE) (Leguina, 2015).

Outer loadings These indicate the correlations in reflective measurement models, demonstrating how well each item represents its associated construct (Leguina, 2015). Although outer loadings are typically used in reflective models, they can also be applied to formative models. A loading of 0.4 is acceptable, while 0.5 is satisfactory, and values above 0.7 are highly desirable (Hair et al., 2021).

Composite reliability (ρc) This metric is often favored over Cronbach's Alpha because it considers the varying factor loadings of all indicators, rather than assuming uniform weights across items, as noted by Hock et al. (Hock et al., 2010). In exploratory research, a composite reliability value exceeding 0.6 is generally considered acceptable, whereas a threshold of 0.7 or higher is recommended for confirmatory studies. Reliability is regarded as strong when values fall between 0.8 and 0.9. The calculation of composite reliability follows the formula presented in Eq. (1) (Ali et al., 2023b):

$$c = \frac{\left(\sum_{i=1}^{p} \lambda_i\right)^2}{\left(\sum_{i=1}^{p} \lambda_i\right)^2 + \sum var\left(\varepsilon_i\right)} \tag{1}$$

where: λ_i represents the factor loadings of the observed variables, $var(\varepsilon_i)$ represents the error variances of the observed variables. It can be determined using the following equation: $var\left(\varepsilon_i\right) = 1 - \lambda_i^2$ and p is the number of practices for the latent construct.

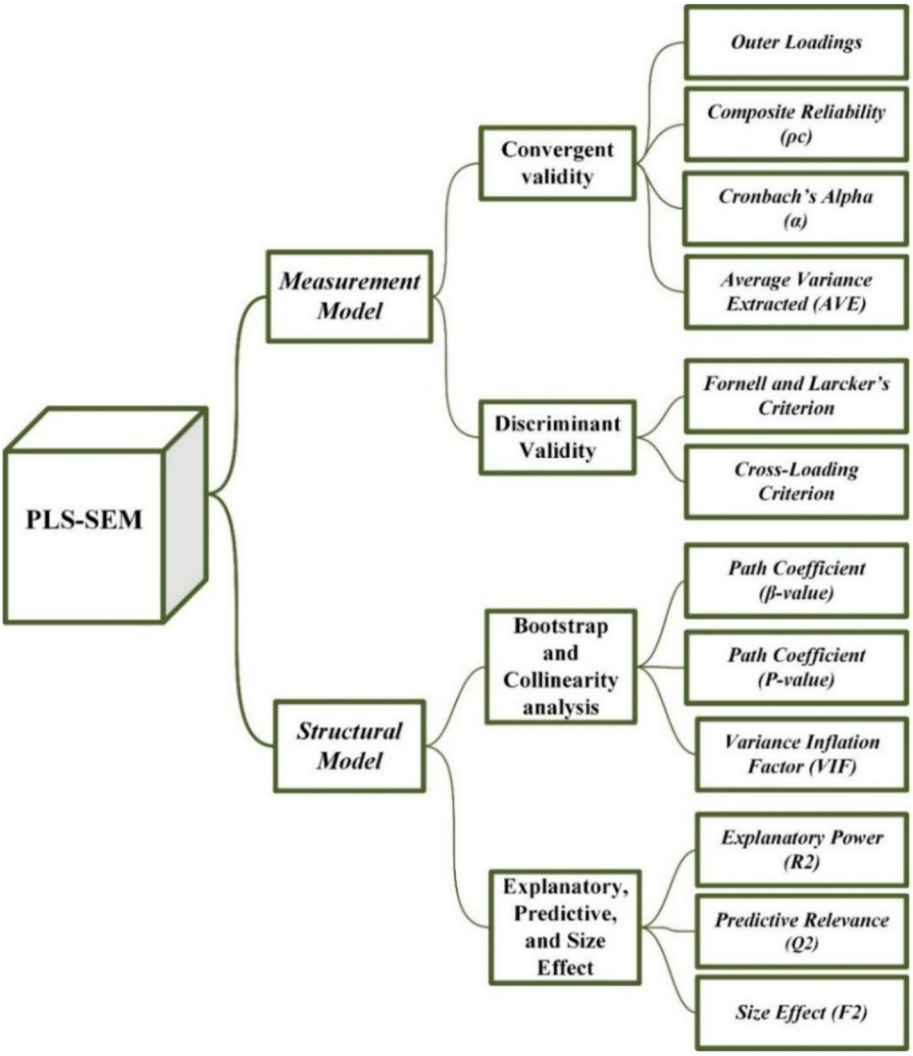

Fig. 3 Key Components and Validation Tests for PLS-SEM Analysis

Cronbach's alpha (α) Despite its limitations, it is widely used to measure internal consistency. A score above 0.6 is acceptable and aligns with composite reliability thresholds (Hock et al., 2010). It is computed using the Eq. (2) (Elrifaee et al., 2025):

$$\alpha = \frac{k}{k-1}\left(1 - \frac{\sum var\left(x_i\right)}{var\left(x_{total}\right)}\right) \tag{2}$$

where k is the number of items, $var\left(x_i\right)$ is the variance of each item, $var\left(x_{total}\right)$ is the total variance of all items combined.

Average variance extracted (AVE) AVE measures convergent validity by assessing the shared variance among items within a construct. A value above 0.5 is required for validity (Memon & Rahman, 2014). AVE is calculated using Eq. (3) (Ali et al., 2024):

$$AVE = \frac{\sum_{i=1}^{p} \lambda_i^2}{\sum_{i=1}^{p} \lambda_i^2 + \sum var(\varepsilon_i)} \tag{3}$$

where: λ_i denotes the factor loadings of the observed indicators, p is the total number of indicators associated with the latent variable, $var(\varepsilon_i)$ refers to the error variances corresponding to each indicator. The error variance for each item can be derived using the following expression: $var(\varepsilon_i) = 1 - \lambda_i^2$

For this study, SmartPLS software was utilized to conduct these calculations, ensuring precision and efficiency while generating visual representations of the results.

Discriminant validity confirms that each construct is distinct and represents a unique concept, avoiding substantial overlap with other constructs (Hair et al., 2013). This property is evaluated through two approaches: (1) the Fornell–Larcker Criterion and (2) the Cross-Loading Criterion.

Fornell and larcker's criterion Discriminant validity is established when the square root of the average variance extracted (AVE) for each construct is greater than its correlations with all other constructs in the measurement model (Memon et al., 2017). This approach confirms that constructs account for more variance in their own indicators compared to other constructs within the model.

Cross-loading criterion Each measurement item must demonstrate stronger association with its designated construct than with alternative constructs in the model (Yu et al., 2021). If an indicator loads more strongly on a different construct than its intended one, it suggests poor discriminant validity.

These tests collectively confirm that the measurement model differentiates well between constructs, ensuring robust validity in PLS-SEM analysis.

3.5.2 Structural model

The structural model was evaluated using bootstrap analysis, a statistical resampling method that estimates the sampling distribution of a statistic (Hair et al., 2014). This approach is particularly useful for determining the significance of relationships between variables, as it provides precise estimates of standard errors and confidence intervals (Elrifaee et al., 2025). By implementing bootstrap resampling, this study identifies the most influential first-order constructs and ensures the robustness of the findings (Leguina, 2015). This method allows for a thorough examination of variable relationships, ensuring the reliability and validity of the results.

Bootstrap analysis includes two key components for assessing the significance of path coefficients:

Path coefficient (β-value) This measure evaluates the magnitude of the relationship between constructs, reflecting how a predictor variable impacts an outcome variable (Haas et al., 2014). A greater β-value indicates a stronger influence of a predictor latent variable on a criterion latent variable (Hussain et al., 2018). Generally, a β-value exceeding 0.09 is interpreted as indicating a meaningful relationship."

Path coefficient (*P*-value) This value indicates the likelihood that the detected associations arose randomly. It serves as a tool to assess whether the connections between variables are statistically meaningful (Hair et al., 2013). A threshold of ≤ 0.05 is commonly accepted to indicate significance (Leguina, 2015).

Collinearity assessment (Variance Inflation Factor (VIF)) To verify the stability of formative constructs, multicollinearity was evaluated using VIF values. All VIF results were below the conservative threshold of 5, confirming the absence of significant collinearity (Hair et al., 2014).

The structural model was constructed to examine the hypothesis that implementing critical success factors (CSFs) for lean construction (LC) adoption in large-scale construction projects could reduce challenges impeding its implementation. This hypothesis was assessed using three primary metrics: the coefficient of determination (R^2), effect size (f^2), and predictive relevance (Q^2).

Explanatory power (R^2) The R^2 value quantifies the predictive capability of the model's constructs. A determination coefficient (R^2) ranging from 0.02 to 0.13 indicates minimal explanatory power, whereas values between 0.13 and 0.26 suggest moderate predictive strength. An R^2 exceeding 0.26 demonstrates substantial explanatory capacity (Olanrewaju et al., 2021; Ringle et al., 2014).

Predictive relevance (Q^2) For the hypothesis to be valid, the Q^2 value must be greater than 0 (Hair et al., 2014; Hair et al., 2019a, b).

Effect size (f^2) The f^2 value measures the impact of excluding a specific predictor on the endogenous construct. An f^2 between 0.02 and 0.15 represents a small effect, while values between 0.15 and 0.35 indicate a medium impact. An f^2 greater than 0.35 shows a significant effect (Hair et al., 2019a, b).

The thresholds for these tests are summarized in Table 5. These metrics collectively provide a comprehensive evaluation of the structural model's robustness in explaining the hypothesized relationships.

4 Results

This Results section presents a comprehensive overview of the study's findings, beginning with the demographic profile of the respondents, followed by the Structural Equation Modeling (SEM) outcomes, and concluding with the translation of statistical insights into practical and actionable strategies.

4.1 Respondents' profile

As illustrated in Table 6, the 379 respondents represent a diverse and experienced cohort within the construction industry, primarily based in Mainland China (63.85%) and Hong Kong (36.15%). Their professional roles span multiple disciplines, with site engineers (34.04%) constituting the largest group, followed by architects/designers (22.43%), project managers (12.14%), and researchers (7.39%), among others. While the distribution across roles is

Table 5 Evaluation criteria for PLS-SEM

Model Component	Test	Measurement Aspect	Threshold	Indicator	References
First Order Model	Convergent Validity	Composite Reliability	From 0.6 to 0.8	Accepted	(Ali et al., 2023b; Hock et al., 2010)
			From 0.8 to 0.9	Good	
			Greater than 0.9	High reliability	
		Cronbach's Alpha	Greater than 0.6	Accepted	(Memon & Rahman, 2014)
		Outer loadings	Less than 0.4	Rejected	(Ali et al., 2023a; Hair et al., 2016)
			From 0.4 to 0.7	Accepted	
			Higher than 0.7	Highly satisfactory	
		Average Variance Extracted (AVE)	Greater than 0.5	Accepted	(Memon & Rahman, 2014)
	Discriminant Validity	Cross Loading Criterion	Each construct exhibits the strongest factor loading in comparison to all other constructs within the same row, confirming discriminant validity	Relationship is valid	(Yu et al., 2021)
		Fornell-Larcker	For each construct, the square root of its average variance extracted (AVE) must exceed its highest correlation with any other construct in the same column, further supporting discriminant validity	Relationship is valid	(Memon et al., 2017)
Second Order Construct	Bootstrap Analysis	β-value	Greater than or equal to 0.09	Accepted	(Hair et al., 2016)
		P-Value	Less than or equal to 0.05	Accepted	(Hair et al., 2016)
		VIF	Less than or equal to 5	Accepted	(Hair et al., 2014)

Table 5 (continued)

Model Component	Test	Measurement Aspect	Threshold	Indicator	References
Path Model	Explanatory Power	R^2	From 0.02 to 0.13	Weak	(Olanrewaju et al., 2021; Ringle et al., 2014)
			From 0.13 to 0.26	Moderate	
			Greater than 0.26	High	
	Predictive relevance	Q^2	Greater than 0	Accepted	(Hair et al., 2014; Hair et al., 2019a, b)
	Effect size analysis	F^2	From 0.02 to 0.15	Small	(Hair et al., 2019a, b)
			From 0.15 to 0.35	Medium	
			Greater than 0.35	Large	

uneven, the sample reflects a mix of technical, managerial, and academic perspectives. Most respondents (55.15%) reported 11–15 years of industry experience, and a significant majority (85.49%) had participated in at least two megaprojects (costing over 0.5 billion CNY), underscoring their practical familiarity with large-scale projects. Although the sampling method was not explicitly stated, the regional diversity and targeted inclusion of experienced professionals suggest a purposive or convenience-based approach, prioritizing accessibility and relevance to megaproject expertise. This profile strengthens the validity of the findings, as respondents possess substantial hands-on knowledge of complex construction initiatives.

4.2 SEM results

The following section presents the outcomes of the SEM analysis, beginning with the measurement model assessment, which evaluates the reliability and validity of the constructs, followed by the structural model results, which examine the hypothesized relationships among the variables.

4.2.1 Measurement model results

(i) Convergent validity

As illustrated in Fig. 4, the outer loading values for all constructs in the measurement model exceed the threshold of 0.7, with some constructs reaching as high as 0.867. These

Table 6 Demographic profile of construction industry respondents

Characteristic	Categories	Frequency ($N = 379$)	Percentage ($N = 100\%$)
Region	Mainland China	242	63.85%
	Hong Kong	137	36.15%
Project Type	Institutional (schools, hospitals, etc.)	40	10.55%
	Infrastructure/Transportation	110	29.02%
	Commercial	64	16.89%
	Residential	165	43.54%
Years of Experience	1–5 years	33	8.71%
	6–10 years	100	26.39%
	11–15 years	209	55.15%
	16 years or more	37	9.76%
Number of Career Megaprojects (Cost > 0.5 billion CNY)	1	55	14.51%
	2	104	27.44%
	3	111	29.29%
	More than 3	109	28.76%
Project position	Architect/Designer	85	22.43%
	Construction Manager	36	9.50%
	Project Manager	46	12.14%
	Researcher	28	7.39%
	Site Engineer (Civil, Structural, Mechanical, etc.)	129	34.04%
	Surveyor	34	8.97%
	Others	21	5.54%

high values demonstrate strong reliability and convergent validity, indicating that the constructs significantly influence their respective latent variables.

Table 7 further confirms that all constructs meet the required thresholds for Composite Reliability (ρc), with values exceeding 0.7, validating their acceptability. Constructs such as SRM, POE, PIW, and PB exhibit Composite Reliability scores above 0.8, signalling strong reliability. Additionally, constructs like SL, OAB, FB, and TKB achieve scores of 0.9 or higher, reflecting excellent reliability.

Similarly, all constructs surpass the required thresholds for Cronbach's Alpha (α), with values exceeding 0.6, further affirming their internal consistency and reliability. This strengthens the confidence in the constructs'reliability and supports the measurement model's consistency.

Moreover, Table 7 reveals that all constructs meet the required thresholds for Average Variance Extracted (AVE), with AVE values exceeding 0.5. This confirms that the constructs achieve acceptable levels of convergent validity and are suitable for inclusion in the study.

The findings collectively confirm that the analytical model is both coherent and stable, indicating that the variables incorporated effectively and accurately capture the underlying constructs they are intended to measure. Additionally, a comprehensive analysis of the interrelationships between these constructs has been conducted, offering solid support for the theoretical connections proposed in the study. This further establishes the model's strength and validity.

(ii) Discriminant validity

Table 8 presents the results of the cross-loading analysis. The values highlighted in bold indicate the highest loading for each construct relative to other constructs in the same row, confirming that each construct shares a stronger relationship with its own indicators than with those of any other construct. This confirms that the constructs in the model are distinct and not overly correlated, supporting the discriminant validity of the measurement model.

Table 7 The results of reliability and convergent validity tests

Construct	Cronbach's alpha	Composite reliability (ρc)	Average variance extracted (AVE)
CSFs for Lean Construction:			
Strategic and Leadership (SL)	0.884	0.909	0.589
Stakeholder and Relationship Management (SRM)	0.836	0.884	0.604
Resource and Knowledge Availability (RKA)	0.865	0.903	0.650
Planning and Operational Efficiency (POE)	0.827	0.885	0.659
Process Improvement and Waste Elimination (PIW)	0.855	0.897	0.635
Technology and Innovation (TI)	0.845	0.896	0.684
LC Barriers:			
Organizational and Attitudinal Barriers (OAB)	0.899	0.920	0.622
Stakeholder Barriers (SB)	0.919	0.935	0.673
Process Barriers (PB)	0.831	0.899	0.748
Financial Barriers (FB)	0.840	0.904	0.758
Technological and Knowledge Barriers (TKB)	0.869	0.911	0.718

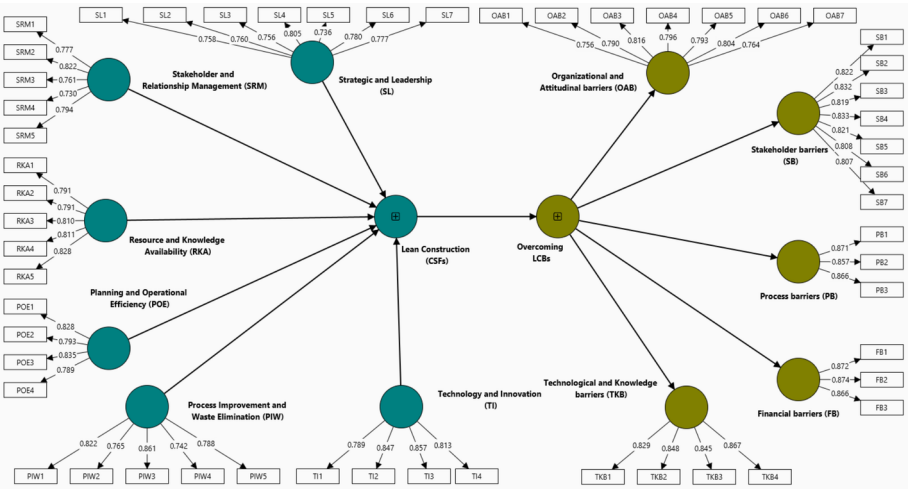

Fig. 4 Measurement model- outer loading values

Table 9 presents the results of Fornell and Larcker's (1981) criterion. The bolded values indicate that each construct exhibits the strongest relationship with itself, as reflected by the highest value in its respective column. This result confirms that the constructs are sufficiently distinct, further supporting the discriminant validity of the measurement model.

4.2.2 Structural model results

Table 10 and Fig. 5 present the outcomes of the bootstrapping analysis, which rigorously tests the statistical significance, strength, and validity of the hypothesized relationships in the structural model. Below, we unpack these findings and their implications:

(i) **Path coefficients (β-values):**

- The β-values quantify the strength and direction of relationships between variables. All paths show positive β-values, confirming that the predictors (e.g., SL, RKA, POE) contribute to enhancing CSFs, which in turn significantly mitigate LCBs in megaprojects.
- SL (β = 0.243) and RKA (β = 0.193) emerge as the strongest predictors of CSFs, suggesting that *"Strategic Leadership"* and *"Resource Knowledge Allocation"* are pivotal drivers of successful CSF implementation.
- The exceptionally strong β-values for OAB → CSFs (0.941) and SB → LCBs (0.958) indicate near-perfect predictive relationships. While statistically significant, such high values may reflect the dominance of these constructs in the model or measurement scale effects, warranting further validation in future studies.
- The CSFs → LCBs path (β = 0.512) underscores that effective CSF adoption directly reduces LCBs by over 51%, highlighting its practical importance in megaproject management.

Table 8 Cross-loadings of measured items

	FB	OAB	POE	PIW	PB	RKA	SRM	SB	SL	TKB	TI
FB1	**0.872**	0.714	0.432	0.390	0.705	0.374	0.369	0.722	0.411	0.720	0.405
FB2	**0.874**	0.706	0.420	0.425	0.666	0.407	0.374	0.718	0.382	0.705	0.428
FB3	**0.866**	0.679	0.388	0.379	0.671	0.328	0.323	0.669	0.380	0.696	0.375
OAB1	0.591	**0.756**	0.329	0.360	0.566	0.315	0.311	0.647	0.359	0.591	0.324
OAB2	0.638	**0.790**	0.344	0.372	0.606	0.313	0.302	0.681	0.317	0.635	0.396
OAB3	0.664	**0.816**	0.399	0.393	0.639	0.358	0.340	0.713	0.390	0.723	0.417
OAB4	0.700	**0.796**	0.376	0.334	0.616	0.331	0.348	0.694	0.362	0.655	0.383
OAB5	0.602	**0.793**	0.328	0.309	0.613	0.307	0.315	0.688	0.323	0.641	0.308
OAB6	0.629	**0.804**	0.349	0.356	0.655	0.342	0.313	0.695	0.368	0.644	0.350
OAB7	0.610	**0.764**	0.323	0.335	0.596	0.331	0.328	0.672	0.376	0.644	0.366
POE1	0.432	0.451	**0.828**	0.680	0.359	0.711	0.670	0.411	0.660	0.438	0.681
POE2	0.326	0.281	**0.793**	0.619	0.259	0.683	0.607	0.310	0.562	0.310	0.577
POE3	0.392	0.354	**0.835**	0.678	0.314	0.638	0.592	0.327	0.577	0.365	0.652
POE4	0.387	0.348	**0.789**	0.635	0.325	0.634	0.583	0.337	0.597	0.360	0.588
PIW1	0.386	0.395	0.673	**0.822**	0.372	0.689	0.583	0.414	0.611	0.441	0.621
PIW2	0.314	0.309	0.604	**0.765**	0.299	0.630	0.622	0.313	0.598	0.336	0.579
PIW3	0.412	0.408	0.724	**0.861**	0.327	0.743	0.635	0.390	0.650	0.431	0.674
PIW4	0.335	0.294	0.593	**0.742**	0.282	0.552	0.547	0.290	0.547	0.309	0.622
PIW5	0.371	0.358	0.606	**0.788**	0.286	0.628	0.605	0.344	0.574	0.351	0.654
PB1	0.661	0.652	0.286	0.287	**0.871**	0.282	0.272	0.707	0.284	0.647	0.277
PB2	0.667	0.685	0.369	0.391	**0.857**	0.338	0.380	0.749	0.383	0.699	0.361
PB3	0.700	0.679	0.350	0.341	**0.866**	0.314	0.315	0.730	0.337	0.703	0.364
RKA1	0.373	0.373	0.657	0.624	0.288	**0.791**	0.642	0.345	0.646	0.317	0.614
RKA2	0.313	0.319	0.640	0.653	0.272	**0.791**	0.650	0.327	0.604	0.353	0.620
RKA3	0.329	0.301	0.642	0.658	0.267	**0.810**	0.620	0.299	0.615	0.338	0.605
RKA4	0.298	0.309	0.672	0.639	0.255	**0.811**	0.647	0.290	0.626	0.309	0.602
RKA5	0.398	0.373	0.702	0.717	0.367	**0.828**	0.663	0.380	0.678	0.390	0.661
SRM1	0.339	0.358	0.618	0.638	0.311	0.688	**0.777**	0.362	0.688	0.332	0.628
SRM2	0.318	0.329	0.618	0.616	0.315	0.643	**0.822**	0.352	0.660	0.342	0.595
SRM3	0.251	0.284	0.555	0.552	0.247	0.554	**0.761**	0.284	0.553	0.296	0.533
SRM4	0.319	0.298	0.528	0.496	0.282	0.563	**0.730**	0.301	0.507	0.337	0.522
SRM5	0.356	0.315	0.615	0.605	0.292	0.646	**0.794**	0.285	0.617	0.306	0.575
SB1	0.645	0.716	0.333	0.358	0.701	0.339	0.316	**0.822**	0.315	0.687	0.359
SB2	0.666	0.729	0.367	0.355	0.710	0.343	0.347	**0.832**	0.349	0.671	0.352
SB3	0.696	0.744	0.378	0.371	0.660	0.326	0.362	**0.819**	0.345	0.748	0.386
SB4	0.632	0.696	0.330	0.355	0.702	0.297	0.291	**0.833**	0.315	0.674	0.298
SB5	0.649	0.696	0.316	0.355	0.683	0.317	0.328	**0.821**	0.345	0.698	0.334
SB6	0.716	0.705	0.360	0.357	0.708	0.359	0.358	**0.808**	0.374	0.681	0.371
SB7	0.635	0.696	0.375	0.384	0.678	0.361	0.346	**0.807**	0.390	0.654	0.314
SL1	0.359	0.379	0.520	0.533	0.334	0.589	0.581	0.341	**0.758**	0.391	0.538
SL2	0.355	0.328	0.578	0.582	0.279	0.602	0.546	0.321	**0.760**	0.362	0.546
SL3	0.309	0.348	0.536	0.573	0.286	0.583	0.584	0.291	**0.756**	0.330	0.547
SL4	0.309	0.324	0.586	0.610	0.265	0.653	0.653	0.327	**0.805**	0.289	0.553
SL5	0.364	0.355	0.610	0.583	0.324	0.593	0.556	0.333	**0.736**	0.339	0.575

Table 8 (continued)

	FB	OAB	POE	PIW	PB	RKA	SRM	SB	SL	TKB	TI
SL6	0.378	0.374	0.586	0.593	0.327	0.612	0.659	0.334	**0.780**	0.362	0.598
SL7	0.342	0.325	0.557	0.551	0.271	0.590	0.625	0.328	**0.777**	0.348	0.552
TKB1	0.680	0.716	0.371	0.384	0.691	0.360	0.333	0.710	0.387	**0.829**	0.382
TKB2	0.668	0.687	0.368	0.401	0.627	0.333	0.328	0.703	0.370	**0.848**	0.393
TKB3	0.666	0.665	0.412	0.429	0.661	0.399	0.379	0.673	0.390	**0.845**	0.396
TKB4	0.736	0.717	0.396	0.387	0.698	0.347	0.366	0.753	0.378	**0.867**	0.401
TI1	0.401	0.397	0.597	0.624	0.303	0.593	0.543	0.348	0.549	0.399	**0.789**
TI2	0.391	0.371	0.648	0.666	0.332	0.662	0.626	0.356	0.611	0.374	**0.847**
TI3	0.417	0.420	0.673	0.697	0.349	0.673	0.648	0.375	0.679	0.439	**0.857**
TI4	0.321	0.338	0.629	0.625	0.293	0.614	0.613	0.312	0.560	0.320	**0.813**

Table 9 Correlation of constructs (Fornell-Larcker)

	FB	OAB	POE	PIW	PB	RKA	SRM	SB	SL	TKB	TI
FB	**0.871**										
OAB	0.804	**0.789**									
POE	0.475	0.444	**0.812**								
PIW	0.458	0.445	0.805	**0.797**							
PB	0.782	0.778	0.388	0.394	**0.865**						
RKA	0.425	0.416	0.802	0.717	0.361	**0.806**					
SRM	0.408	0.409	0.757	0.751	0.373	0.799	**0.777**				
SB	0.808	0.768	0.428	0.442	0.843	0.408	0.409	**0.820**			
SL	0.449	0.452	0.740	0.749	0.388	0.787	0.683	0.423	**0.768**		
TKB	0.812	0.722	0.456	0.472	0.790	0.424	0.415	0.739	0.450	**0.847**	
TI	0.463	0.461	0.771	0.691	0.387	0.770	0.736	0.421	0.728	0.464	**0.827**

Table 10 Bootstrap analysis results

	B-value (> 0.09)	*P*-value (< 0.05)	VIF (< 5)	Significance
SL → CSFs	0.243	0.000	3.401	Supported
SRM → CSFs	0.173	0.000	3.614	Supported
RKA → CSFs	0.193	0.000	4.850	Supported
POE → CSFs	0.154	0.000	4.058	Supported
PIW → CSFs	0.188	0.000	4.188	Supported
TI → CSFs	0.158	0.000	3.400	Supported
OAB → CSFs	0.941	0.000	1.000	Supported
SB → LCBs	0.958	0.000	1.000	Supported
PB → LCBs	0.892	0.000	1.000	Supported
FB → LCBs	0.894	0.000	1.000	Supported
TKB → LCBs	0.918	0.000	1.000	Supported
CSFs → LCBs	0.512	0.000	1.000	Supported

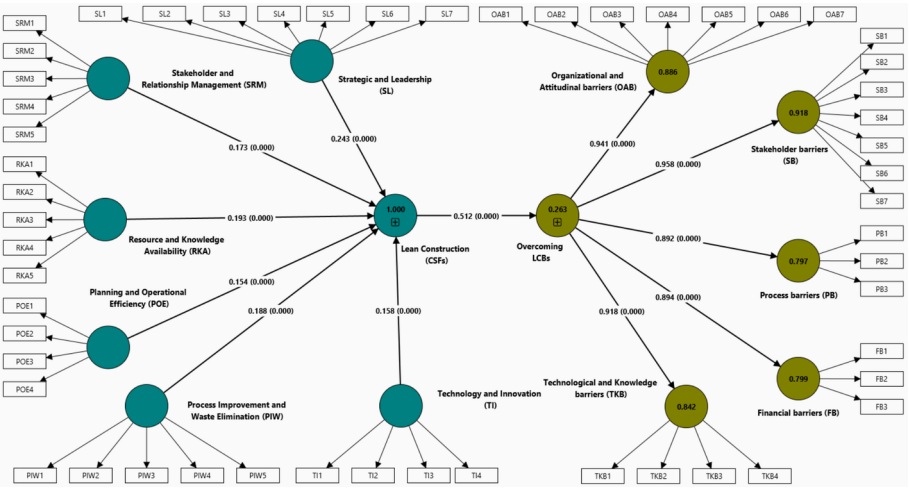

Fig. 5 Structural model- Path coefficient

(ii) **Statistical significance (*P*-values):**

- All relationships exhibit p-values $=0.000$, which are *highly statistically significant* ($p < 0.001$). This confirms that the observed effects are unlikely to be due to random chance, reinforcing the reliability of the model's hypothesized paths.

(iii) **Multicollinearity assessment (VIF):**

- Variance Inflation Factor (VIF) values for predictors of CSFs range between 3.401 (SL) and 4.850 (RKA), all below the conservative threshold of 5.0. This indicates acceptable multicollinearity, ensuring that predictor variables are distinct and independently contribute to explaining CSF variance.
- The VIF values for LCBs' predictors (SB, PB, FB, TKB) are all 1.0, confirming no multicollinearity in the LCBs' relationships.

(iv) **Hypothesis support:**

The label *"Supported"* for all paths validates the theoretical framework, confirming that the data robustly align with the hypothesized relationships between predictors, CSFs, and LCBs.

The analysis reveals a hierarchical influence of predictors on CSFs in LC adoption, with Strategic Leadership (SL) emerging as the strongest driver ($\beta = 0.243$), underscoring the pivotal role of visionary leadership in shaping CSFs. This is followed by Resource and Knowledge Availability (RKA) ($\beta = 0.193$), highlighting the importance of accessible resources and expertise in supporting Lean practices. Process Improvement and Waste Elimination (PIW) ranks third ($\beta = 0.188$), reflecting the value of operational efficiency in driving CSFs. Stakeholder and Relationship Management (SRM) ($\beta = 0.173$) and Technology and Innovation (TI) ($\beta = 0.158$) subsequently demonstrate moderate yet significant impacts, emphasizing collaboration and technological integration as key contributors. Finally, Planning and Operational Efficiency (POE) ($\beta = 0.154$)

exhibits the least but meaningful influence, completing the hierarchy. The model's statistical robustness ($p < 0.001$, VIF < 5) strengthens its utility for decision-makers prioritizing CSF implementation in megaprojects.

Table 11 summarizes the key evaluation metrics for the path model, offering a comprehensive assessment of its explanatory power and predictive validity. Below, we elaborate on the implications of each metric and their collective significance:

The R^2 value of 0.263 indicates that the predictors in the model explain 26.3% of the variance in the dependent variable(s). While R^2 values above 26% are often considered strong in social sciences and behavioural research, this result suggests a meaningful explanatory capacity for the constructs under study. However, the remaining unexplained variance (73.7%) highlights potential opportunities for future research to incorporate additional variables or moderators that could further account for the outcomes.

The Q^2 value "0.252" exceeds the zero threshold, confirming the model's predictive relevance. This result aligns with the R^2 value, reinforcing that the model explains variance and generalizes well to unseen data. A $Q^2 > 0$ is often considered strong in PLS-SEM studies, and this value suggests the model is practically useful for forecasting.

The F^2 value of 0.356 signifies a large effect size. This implies that the predictors exert substantial influence on the dependent constructs. For instance, a specific predictor with an F^2 of 0.356 would explain 35.6% of the incremental variance in the outcome variable when added to the model, underscoring its theoretical and practical relevance.

The metrics demonstrate a robust model with both explanatory and predictive utility. The alignment between R^2 and Q^2 values suggests consistency between explanation and prediction, while the large F^2 effect size emphasizes the practical significance of the predictors.

4.3 From statistical insights to actionable strategies

While the R^2 value of 0.263 indicates that the model explains 26.3% of the variance in LCBs, this represents a practically meaningful proportion in complex megaprojects, where outcomes are influenced by unpredictable factors (e.g., geopolitical risks, supply chain disruptions). The large F^2 effect size (0.356) further underscores that the identified CSFs have disproportionate influence relative to other unmeasured variables. For example, improving CSFs like stakeholder collaboration or lean training can yield outsized reductions in LCBs, even in chaotic environments.

Table 11 Path model evaluation metrics and interpretations

Tested Value	Value	Indication
R^2	0.263	High Impact
Q^2	0..252	There is a predictive relevance
F^2	0.356	Large Effect

4.3.1 Hypothetical scenario: applying the model in practice

Consider a **high-speed rail megaproject** facing delays due to stakeholder conflicts, budget overruns, and inefficient workflows. A project manager could use this model to prioritize interventions:

Step 1: focus on high-impact CSFs

- **Strategic leadership (SL):** Assign a dedicated lean leadership team to align stakeholders and enforce lean principles ($\beta = 0.243$).
- **Resource knowledge allocation (RKA):** Conduct lean training workshops for subcontractors to reduce rework ($\beta = 0.193$).
- **Digital tools (TI):** Implement Building Information Modeling for real-time collaboration, addressing technology's $\beta = 0.158$ effect on CSFs.

Step 2: Monitor LCB reduction

- The model predicts that improving CSFs by one standard unit reduces LCBs by 51% ($\beta = 0.512$ for CSFs $\rightarrow$ LCBs). For instance, enhancing stakeholder collaboration (SRM, $\beta = 0.173$) could mitigate delays caused by miscommunication.

Step 3: Validate with metrics

- Track reductions in **schedule overruns** (linked to procedural barriers, PB $\rightarrow$ LCBs $\beta = 0.892$) and **cost deviations** (linked to financial barriers, FB $\rightarrow$ LCBs $\beta = 0.894$) to quantify ROI from CSF implementation.

4.3.2 The model provides a decision-making hierarchy:

- Prioritize CSFs with the Largest β-values: Allocate resources to SL, RKA, and PIW first.
- Target Dominant LCBs: Address stakeholder (SB $\rightarrow$ LCBs, $\beta = 0.958$) and knowledge barriers (TKB $\rightarrow$ LCBs, $\beta = 0.918$) early, as they have the most substantial negative impacts.
- Leverage Digital Tools: Use the $\beta = 0.158$ effect of TI $\rightarrow$ CSFs to justify investments in AI-driven risk analytics or IoT-enabled progress tracking.

Table 12 operationalizes the model's statistical findings into actionable strategies for real-world construction projects.

5 Discussion

The discussion section of this study is structured to address three interconnected themes critical to advancing the understanding of LC adoption in megaprojects. First, we analyze the role of LC factors in mitigating barriers, exploring how strategic leadership, resource

availability, process innovation, stakeholder collaboration, technological integration, and operational planning collectively drive lean implementation. This analysis is grounded in empirical data from PLS-SEM, quantifying the causal relationships between these factors and barrier reduction.

Second, we conduct a comparative analysis with recent research on LeanBIM and Integrated Project Delivery (IPD) frameworks. By synthesizing findings from prior studies, we highlight recurring barriers (e.g., regulatory gaps, resistance to change) and critical success factors (e.g., leadership support, cross-disciplinary collaboration), while demonstrating how the current study's integrated PLS-SEM model bridges gaps in existing literature by explicitly linking CSFs to barrier mitigation.

Finally, we contextualize these insights within China's evolving regulatory and cultural landscape, where national policies like the"Ecological Civilization"framework and digitalization mandates (e.g., BIM, Big Data) create opportunities and challenges for LC adoption. This section underscores the need to adapt lean methodologies to China's unique institutional environment, balancing top-down sustainability goals with localized project execution.

Together, these subsections provide a holistic perspective on LC adoption, integrating empirical evidence, cross-study comparisons, and region-specific contextualization to inform theory and practice in construction management.

5.1 LC factors and their impact on mitigating LC barriers

Strategic and leadership (SL) factors are key drivers of LC adoption in megaprojects ($\beta = 0.243$). These factors ensure alignment with lean principles through leadership commitment, financial capability, awareness, and government support. Strong leadership fosters collaboration and incentivizes lean adoption (Lam et al., 2024; Yadav et al., 2023). This aligns with Sarhan & Fox (2013), who emphasized that strategic leadership is essential for fostering a lean culture, addressing educational gaps, and ensuring adequate support to overcome barriers to LC implementation—similarly, Evans et al. (2021) highlighted that top organizational management support is one of the most significant BIM CSFs that enhance Lean-BIM synergy in megaprojects.

Resource and Knowledge Availability (RKA) significantly influence LC adoption ($\beta = 0.193$). The presence of qualified lean managers, training programs, and lean-focused education ensures successful implementation and minimizes resistance to change (Demirkesen & Bayhan, 2020; Watfa & Sawalha, 2021; Yunus et al., 2017). This aligns with Singh & Rathi (2022), who emphasized that Lean-focused education equips managers and employees with the necessary skills to implement lean practices effectively, thereby reducing resistance to change. So, ensuring adequate resources and fostering familiarity with lean techniques empower organizations to adapt swiftly and maintain a competitive edge. The establishment of lean research groups is pivotal in navigating lean methodologies'complexities. Without a solid foundation in RKA, even the most well-intentioned lean initiatives may falter, underscoring its critical role in driving sustainable success.

Process Improvement and Waste Elimination (PIW) are crucial ($\beta = 0.188$) for optimizing efficiency and minimizing waste through standardized metrics, benchmarking, and lean tools such as root cause analysis and defect response plans (Sarhan et al., 2019). These tools help identify and address issues before they escalate, improving the quality and efficiency of projects. Together, these PIW factors significantly contribute to the effective

Table 12 Translating model metrics into actionable strategies for LC management

Model Metric	Real-World Translation	Example Action
SL → CSFs (β = 0.243)	Strategic leadership drives alignment and accountability	Hire a Lean Coordinator to oversee daily operations
CSFs → LCBs (β = 0.512)	Every 10% improvement in CSFs reduces LCBs by ~5.1%	Train 50% of staff in lean methods to cut delays by 10–15%
$F^2 = 0.356$	CSFs have 35.6% more influence on LCBs than unmeasured variables	Allocate 35% of contingency budgets to CSF initiatives

adoption of LC by promoting continuous improvement, reducing waste, and optimizing processes in megaprojects. This aligns with Berawi et al. (2023), who emphasized that root cause analysis and defect response plans are critical for identifying and addressing the underlying causes of inefficiencies and defects. Organizations can prevent recurrence and improve overall project outcomes by systematically analyzing and responding to defects. Similarly, Balkhy et al.(2021) highlighted that benchmarking helps identify critical barriers to LC, such as lack of management support, low awareness, and insufficient training, which are common across various contexts.

Stakeholder and Relationship Management (SRM) fosters collaboration and alignment among project participants ($\beta = 0.173$). Trust, early stakeholder involvement, and a customer-centric approach improve efficiency and reduce conflicts (Sadikoglu et al., 2024). Finally, building strong relationships with stakeholders promotes a culture of collaboration and mutual respect, ensuring that everyone is committed to the success of the project and the adoption of lean practices (Abusalem, 2020). Collectively, these SRM factors contribute to a more cohesive, efficient, and successful lean implementation in megaprojects.

Technology and Innovation (TI) enhances LC adoption ($\beta = 0.158$) by leveraging digital solutions such as BIM, Modular Integrated Construction, and Digital Twin (DT), improving coordination and waste reduction (Idrissi Gartoumi et al., 2024; Najafi et al., 2024). This finding aligns with Evans et al. (2021), who emphasized that critical success factors of BIM drive the Lean-BIM synergy, enabling construction organizations to adopt BIM technologies and integrate them with LC approaches for optimal benefits in megaprojects. Additionally, Altan & Işık (2023) highlighted the collaborative nature of DT and LC, noting that the application of AI technologies within DT strongly interacts with LC principles.

Planning and Operational Efficiency (POE) play a vital role ($\beta = 0.154$) by applying LC tools such as the Last Planner System, Just-In-Time, and Value Stream Mapping. Effective planning, logistics, and coordination ensure smooth execution and adaptability in megaprojects (Agrawal et al., 2024; Zegarra & Alarcón, 2019). Together, these factors drive successful LC adoption, improving efficiency, reducing waste, and enhancing project outcomes in megaprojects.

5.2 Comparative analysis with recent research

The synthesis of prior research on LC adoption, LeanBIM and IPD adoption in construction megaprojects reveals recurring themes, methodological diversity, and gaps in understanding the interplay between CSFs and barriers. Table 13 summarizes key studies, highlighting their focus areas, methodologies, and findings. The current study builds on this foundation by introducing a novel integrated framework (Fig. 5) that explicitly links CSFs to barrier mitigation through SEM. Below, we analyze how this study extends existing knowledge.

5.2.1 Key themes and insights from prior studies

(i) Barriers to LeanBIM/IPD Adoption

- Regulatory and Financial Constraints: Multiple studies (Evans et al., 2023; Evans & Farrell, 2021; A. Singh et al., 2024) consistently identify a lack of government-mandated BIM/LC standards, insufficient financial incentives, and high software/train-

Table 13 Overview of LC implementation frameworks in prior literature

Ref	Data Collection Method	Focus of Study	Analysis Method	Key Finding
(Evans & Farrell, 2021)	Delphi survey	Barriers	Descriptive/inferential stats (Cronbach's α, Shapiro–Wilk, mean ranking)	- Lack of BIM/LC regulations - Industry resistance to LeanBIM adoption - High software/training costs
(Evans et al., 2021)	Delphi survey	CSFs	Cronbach's α, mean ranking, Shapiro–Wilk, Kendall's, chi-squared, IRA, Spearman's	- Cross-disciplinary collaboration - Top management support - Robust coordination/planning - Early 3D design visualization
(Evans et al., 2022)	Questionnaire survey	CSFs	Principal components analysis (PCA), percentage scoring, descriptive/inferential stats, SEM	- Enhanced collaboration in design, construction, and engineering management - Improved coordination/planning - Senior management support - Early 3D visualization of designs
(Evans & Farrell, 2023)	Semi-structured interviews, focus groups, survey	Barriers	Cronbach's α, ANOVA, correlation analysis, PCA	- Lack of government incentives/policies - Limited IPD experience - Resistance to IPD adoption - Poor integration of LC/IPD practices
(Evans et al., 2023)	Semi-structured interviews, focus groups, survey	Barriers	Descriptive/inferential stats (percentage scoring, PCA)	- Absence of BIM/LC standards - Insufficient government support - High software costs - Resistance to change - High training costs
(Singh et al., 2024)	Survey	Barriers	Fuzzy AHP (fAHP)	- Rigid procurement protocols and authorization processes - Inadequate emphasis on client priorities and misaligned understanding of consumer requirements - Underutilization of design-build procurement methodologies - Ineffective management practices and absence of strategic leadership capabilities

Table 13 (continued)

Ref	Data Collection Method	Focus of Study	Analysis Method	Key Finding
(Lam et al., 2024)	Semi-structured interviews, survey	CSFs	Average score and standard deviation metrics, Mann–Whitney U test (non-parametric statistical method), principal components analysis (PCA) and factor analysis (FA)	- Government's involvement and support - clear definition of the LPD objectives in design stage -Sustainable management (waste reduction)

ing costs as primary barriers. These findings align with the current study's identification of Technological and Knowledge Barriers (TKB) and Financial Barriers (FB) in Fig. 5. Notably, Evans and Farrell (Evans & Farrell, 2021) ranked the absence of mandatory BIM/LC standards and regulations as the highest-priority barrier.

- Resistance to Change: Industry resistance to adopting LeanBIM/IPD practices is a recurring theme (Evans & Farrell, 2023; Evans et al., 2023). This mirrors the Stakeholder Barriers (SB) construct in the current model, emphasizing organizational inertia and cultural resistance.

(ii) Critical Success Factors (CSFs) for LeanBIM/IPD

- Leadership and Collaboration: Research by Evans et al. (2021) and Lam et al. (2024) identifies top management support and cross-disciplinary collaboration as critical success factors (CSFs). Evans et al. ranked top management support as the second most significant factor, whereas Lam et al. identified it as the most critical. These findings align with the Strategic and Leadership (SL) and Stakeholder and Relationship Management (SRM) dimensions in this framework ($\beta = 0.243$) as the most significant drivers to overcome the barriers.
- Process Innovation: Evans et al. (2022) and Lam et al. (2024) emphasize improved coordination/planning and sustainable waste reduction practices. These resonate with the Process Improvement and Waste Elimination (PIW) and Technology and Innovation (TI) constructs in Figure

(iii) Methodological Diversity

- Prior studies employ qualitative (e.g., Delphi surveys, semi-structured interviews) and quantitative methods (e.g., PCA, ANOVA). While these approaches effectively isolate barriers or CSFs, they often fail to capture their dynamic interplay. For instance, Singh et al. (2024) uses Fuzzy AHP to prioritize barriers but does not explore how CSFs mitigate them.

5.2.2 Novel contributions of the current study

(i) Integrated Framework for Barrier Mitigation: Unlike prior studies that treat barriers and CSFs in isolation, the current PLS-SEM model (Fig. 5) demonstrates how CSFs directly influence barrier mitigation. For example:

- Strategic Leadership (SL) reduces Organizational and Attitudinal Barriers (OAB) by fostering buy-in and alignment (path coefficient $= 0.512$, $p < 0.001$).
- Resource and Knowledge Availability (RKA) alleviates Technological and Knowledge Barriers (TKB) by improving access to tools and expertise (path coefficient $= 0.193$, $p < 0.001$).

(ii) Emphasis on Holistic Process Improvement: The model underscores the cascading impact of CSFs on operational efficiency. For instance, Process Improvement and Waste Elimination (PIW) enhances LC outcomes, which in turn mitigates Process Barriers (PB) (path coefficient $= 0.188$, $p < 0.001$). This integration addresses a gap in prior research, which rarely examines how process innovations systematically reduce barriers.

(iii) Quantitative Validation of Relationships: By employing PLS-SEM, the study statistically validates the strength and directionality of relationships between constructs.

For example, Stakeholder and Relationship Management (SRM) significantly influences LC (CSFs) (path coefficient = 0.243, $p < 0.001$), confirming its critical role in overcoming resistance highlighted in prior studies (Evans & Farrell, 2023).

(iv) Focus on Sustainable Outcomes: The inclusion of Sustainable Management (waste reduction) in (Lam et al., 2024) is echoed in the current model's PIW dimension, linking LeanBIM/IPD adoption to environmental sustainability, a dimension underexplored in prior research.

While prior studies have identified discrete barriers and CSFs, the current research offers a unified perspective by quantitatively linking these elements within a causal framework. The PLS-SEM model highlights actionable pathways for mitigating barriers through strategic leadership, resource allocation, and process innovation. This integrative approach not only enriches theoretical understanding but also provides practitioners with a roadmap for successful LeanBIM/IPD implementation in construction megaprojects.

5.3 Cultural and regulatory factors shaping LC adoption in China: synergies with green development and technological innovation

In recent years, China's regulatory landscape has undergone a transformative shift toward sustainability and digitalization, creating both opportunities and challenges for LC adoption. The government's prioritization of green development under the "Ecological Civilization" (EC) framework, a cornerstone of national policy since 2012, has redefined construction priorities. EC transcends traditional environmentalism, positioning itself as a holistic reform project integrating economic, social, political, cultural, and ecological objectives (Islam & Wang, 2023). Central to this vision are principles of sustainable production and consumption, which align synergistically with Lean Construction's emphasis on waste reduction, process efficiency, and value maximization (Tian et al., 2021). For instance, initiatives like "Beautiful China" and "Park City", designed to scale urban green spaces, are not merely ecological endeavours but also policy drivers demanding innovative construction methodologies to balance rapid urbanization with resource efficiency (Miao & Tan, 2025).

Concurrently, China's aggressive push for construction digitalization has created a fertile ground for Lean practices. The 2016–2020 Outline for Construction Industry Informatization mandated the integration of Building Information Modeling (BIM) and Big Data (BD) technologies, enabling smarter project management through data-driven insights (Xia et al., 2023). This policy directive directly supports Lean's reliance on real-time data visualization and collaborative planning. For example, BIM's ability to simulate workflows and predict bottlenecks aligns with Lean's *Last Planner System*, while BD analytics enhance decision-making by uncovering inefficiencies in material use or labor allocation. Such technological adoption is not merely a regulatory compliance exercise but a strategic enabler of Lean's core tenets: transparency, continuous improvement, and stakeholder integration.

However, the interplay between policy ambition and cultural-regulatory realities introduces complexity. While the EC framework encourages sustainable production, its implementation often prioritizes large-scale, state-driven projects through State-Owned Enterprises (SOEs), which traditionally favor speed and scale over granular efficiency. This tension underscores the need for Lean methodologies to adapt to China's unique governance model, where top-down mandates coexist with localized experimentation. For instance, pilot programs under the *"green building"* initiative have allowed SOEs to test

Lean-inspired prefabrication techniques, reducing on-site waste while adhering to rigid building codes (Xia et al., 2023).

China's regulatory emphasis on sustainability and digital innovation offers a unique pathway for LC to thrive, provided methodologies are contextualized to navigate cultural and institutional barriers. Future success hinges on aligning Lean tools (e.g., BIM-integrated pull planning) with policy priorities like carbon neutrality, while cultivating localized training programs to empower transient workforces. By framing Lean not as a foreign import but as a complementary strategy to achieve *Ecological Civilization*, stakeholders can unlock transformative efficiencies in the world's largest construction market.

6 Policy implications

6.1 Theoretical implications

This study makes a significant theoretical contribution by expanding the understanding of LC adoption in megaprojects through a robust statistical approach. While previous studies have identified barriers and success factors for LC, they have not quantitatively modelled the relationships between these variables. By employing Partial Least Squares Structural Equation Modelling (PLS-SEM), this study provides empirical evidence demonstrating how CSFs can mitigate LCBs. The findings contribute to the growing body of knowledge on construction project management, Lean principles, and organizational behaviour in megaprojects by offering a validated framework that explains the mechanisms driving LC adoption.

Additionally, this study extends the theoretical discourse on systemic inefficiencies in megaprojects, reinforcing theories on cost overruns and mismanagement by linking them to lean implementation challenges. The research also bridges the gap between LC and innovation diffusion theories, providing a new perspective on how success factors can facilitate industry-wide lean adoption. This contribution enriches the academic literature by offering a structured and quantitative approach to evaluating lean implementation strategies in large-scale construction projects.

6.2 Practical implications

From a practical standpoint, this study provides actionable insights for construction managers, policymakers, and industry stakeholders to enhance the adoption of LC in megaprojects. The validated framework identifies the most influential success factors that reduce LC adoption barriers, enabling decision-makers to prioritize strategic interventions.

6.2.1 Guidance for project managers

- Leadership Training Programs: Prioritize lean leadership development to align stakeholder goals and reduce conflicts (linked to Strategic Leadership, $\beta = 0.243$).
- Digital Tool Integration: Deploy BIM 360 and Digital Twin technologies to simulate workflows and mitigate waste (supported by Technology & Innovation, $\beta = 0.158$).

- Lean Certification: Establish partnerships with institutions to deliver certified training in tools like Last Planner System and Value Stream Mapping (tied to Resource & Knowledge Availability, $\beta = 0.193$).

6.2.2 Policy and industry adoption

- Incentive Programs: Introduce tax rebates for megaprojects adopting lean practices, such as modular construction or Just-In-Time delivery (aligned with Process Improvement, $\beta = 0.188$).
- Standardized Guidelines: Develop national lean frameworks for megaprojects, incorporating metrics like waste reduction rates and schedule adherence (linked to Planning & Operational Efficiency, $\beta = 0.154$).

6.2.3 Global scalability

- Belt and Road Initiative (BRI): Adapt the framework to BRI projects by tailoring CSFs to local governance and stakeholder dynamics.
- SDG Alignment: Embed decarbonization metrics into lean workflows to support SDG 9 (Resilient Infrastructure) and SDG 12 (Responsible Consumption).

Ultimately, this study bridges theory and practice, offering a data-driven roadmap for construction firms and policymakers to maximize the benefits of LC in megaprojects, ensuring long-term industry transformation and improved project outcomes.

7 Conclusion

This study provides a first-of-its-kind, statistically validated framework that establishes a clear link between Critical Success Factors (CSFs) and the mitigation of Lean Construction Barriers (LCBs) in megaprojects, utilizing Partial Least Squares Structural Equation Modelling (PLS-SEM). By integrating a mixed-method approach, comprising a systematic literature review, expert interviews, and a survey involving 379 construction professionals, the research effectively bridges existing theoretical and practical gaps in scaling lean construction (LC) adoption.

A key outcome of this study is the development of a PLS-SEM model that confirms the significant influence of CSFs on reducing LCBs. The results show strong explanatory power, with an R^2 value of 0.263, indicating that approximately 26.3% of the variance in LCBs can be explained by CSFs. Furthermore, the Q^2 value of 0.252 highlights its predictive relevance, while an effect size (F^2) of 0.356 underscores the substantial impact of these success factors on mitigating barriers. Among the identified CSFs, Strategic Leadership emerged as the most influential factor ($\beta = 0.243$), emphasizing the importance of leadership commitment, financial backing, and stakeholder alignment in cultivating a lean culture. Closely following were Resource & Knowledge Availability ($\beta = 0.193$), highlighting the role of training and lean expertise in overcoming resistance to change, and Process Improvement ($\beta = 0.188$), where tools such as root cause analysis and benchmarking contribute significantly to workflow optimization and waste reduction. The findings also highlight the distinctive value of this research. First, it addresses the high stakes yet under-researched domain of megaprojects, offering

insights crucial for managing complex governance structures, extended timelines, and significant socio-economic impacts. Second, although the data was collected in China, the principles underlying the framework, such as leadership engagement, workforce training, and the use of digital tools, are broadly applicable, making the model adaptable for global megaprojects.

Despite its notable contributions, this study has several limitations that warrant attention in future research. First, although the sample size of 379 participants ensures statistical robustness, the geographical focus on China may limit the generalizability of the findings to other regions with differing regulatory, economic, and cultural contexts. Therefore, expanding the scope to include international comparisons would help validate the framework's applicability across diverse construction environments. Second, the reliance on self-reported survey data introduces the potential for response bias; thus, incorporating qualitative case studies or longitudinal analyses could enhance the reliability and depth of the findings. Moreover, while the PLS-SEM model effectively captures static relationships between CSFs and LCBs, it does not account for dynamic external factors such as shifting government policies or rapid technological advancements that may affect lean adoption over time. Looking ahead, several promising avenues for future research emerge from this study. Longitudinal assessments of the CSF-LCB framework in live megaprojects—such as smart cities, renewable energy hubs, or urban transit systems, could provide valuable insights into its real-world effectiveness. Additionally, examining how CSFs and LCBs evolve across different project phases and economic cycles through time-series research would further enrich our understanding of lean implementation dynamics. Investigating the role of policy and regulatory frameworks in enabling LC adoption, and identifying gaps in current practices—can inform more supportive institutional environments.

Another critical area involves extending the current model to incorporate technology readiness and digital maturity. Specifically, exploring how organizational preparedness for technologies like AI, blockchain, or Digital Twin influences the effectiveness of CSFs in mitigating LCBs could yield important insights. Similarly, assessing digital maturity—including BIM integration and data-driven decision-making capabilities—as a mediating variable can clarify how such capabilities strengthen the impact of CSFs like Technology and Innovation on lean adoption. Finally, while LC inherently promotes efficiency and waste reduction, its alignment with sustainability and circular economy principles remains underexplored. Future work should examine how LC practices such as Just-In-Time delivery, prefabrication, and design for disassembly contribute to material waste reduction and lower embodied carbon emissions. Investigating synergies between LC tools (e.g., Value Stream Mapping) and circular strategies (e.g., recycling, remanufacturing), along with analyzing real-world examples of LC-enabled emission reductions, will further solidify its role in sustainable megaproject delivery. By building on these findings and addressing the outlined limitations, future research can refine lean construction strategies, ensuring their successful implementation across varied megaproject settings while advancing the broader goals of efficiency, innovation, and sustainability in the global construction industry.

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