Cleaner Engineering and Technology 31 (2026) 101158

Contents lists available at ScienceDirect

Cleaner Engineering and Technology

journal homepage: www.sciencedirect.com/journal/cleaner-engineering-and-technology

Critical enablers for lean construction diffusion in megaprojects: A framework for sustainable and efficient infrastructure development

Abdelazim Ibrahim [a,b], Tarek Zayed [a], Zoubeir Lafhaj [c], Ahmed Farouk Kineber [d], Ghasan Alfalah [e], Jingchao Yang [a,*]

[a] Department of Building and Real Estate, the Hong Kong Polytechnic University, Hung Hom, Hong Kong
[b] Department of Civil Engineering, Benha Faculty of Engineering, Benha University, Benha, 13518, Egypt
[c] Laboratoire de Mecanique Multiphysique Multiechelle, LaMcube, UMR 9013, Centrale Lille, CNRS, Centrale Lille Institute, Lille, France
[d] College of Project Management, Built Environment, Asset & Maintenance Management, School of Engineering and Technology, Central Queensland University, Melbourne, Australia
[e] Department of Architecture and Building Science, College of Architecture and Planning, King Saud University, Riyadh, 145111, Saudi Arabia

ARTICLE INFO

Keywords:
Lean construction
Megaprojects
Stakeholder engagement
Fuzzy Synthetic Evaluation (FSE)
Sustainable development

ABSTRACT

Construction megaprojects (CMPs) face persistent challenges, including cost overruns, delays, stakeholder misalignment, and growing demands for sustainability, all of which threaten their success and long-term value. Lean Construction (LC) offers a socio-technical pathway to reconcile scale, speed, and sustainability. Yet, while prior research has identified barriers and success factors for LC adoption, there remains a critical gap in understanding how to prioritize and sequence enablers for systemic diffusion, especially under resource and institutional constraints. Addressing this, the present study reconceptualizes LC implementation as a multi-level diffusion process, wherein the salience of enablers shifts with context, method, and implementation phase. Using a mixed-methods approach, this study begins with a literature review to identify potential LC enablers. Mean score analysis is then used to prioritize significant enablers, while the Fuzzy Relative Importance Index (FRII) assesses their relative significance. Fuzzy Synthetic Evaluation (FSE) ranks the grouped enablers. Data from 379 construction professionals in China informed the analysis, leading to the identification of 30 LCEs. Results reveal six critical components driving LC diffusion, with “Resource and Knowledge Availability” emerging as the most influential, followed by “Planning and Operational Efficiency”, “Process Improvement and Waste Elimination”, and “Strategic and Leadership Initiatives”. The findings underscore the interplay of organizational, operational, and strategic factors in LC implementation. By addressing multi-criteria complexity and expert judgment ambiguity, this study offers actionable insights for practitioners and policymakers. It contributes a robust decision-making framework that supports sustainable and efficient practices, paving the way toward transformative outcomes in CMPs.

1. Introduction

Megaprojects have become a crucial component of modern infrastructure development, driven by aging global populations and rapid economic growth that necessitate substantial investment in public services and socio-economic advancement (Ibrahim et al., 2025b; Locatelli et al., 2017b; Maddaloni et al., 2025). These large-scale initiatives contribute significantly to political, technological, and social progress. They are characterized by huge investment (often hundreds of millions to tens of billions of USD), long durations (5–15+ years), and extreme technical complexity (Locatelli et al., 2017a). Equally defining is their organizational density: megaprojects typically involve dozens, if not hundreds, of entities, including public sponsors, private contractors, design consultants, multiple tiers of subcontractors, equipment suppliers, and regulatory agencies, all operating under dynamic, evolving contractual and governance frameworks (Kumar et al., 2024). This fragmentation often leads to weak inter-organizational trust, misaligned incentives, and chronic coordination failures, particularly when collaboration hinges on informal norms rather than systemic enablers (Chen et al., 2024).

Globally, annual megaproject investments reach $6–9 trillion, nearly 8% of world GDP (D. Landis, 2022). Yet performance remains

---

* Corresponding author.
E-mail address: jingchao-aaron.yang@connect.polyu.hk (J. Yang).

https://doi.org/10.1016/j.clet.2026.101158
Received 18 November 2025; Received in revised form 4 January 2026; Accepted 26 January 2026

stubbornly poor: Flyvbjerg (2017) finds ~90% of megaprojects exceed baseline cost estimates, while Ansar et al. (2017) report that in China's rail sector alone, average cost escalation reaches 30.6% and delays average 25%. These overruns are not merely financial; they reflect deeper systemic dysfunctions: rigid planning, siloed decision-making, reactive risk management, and waste embedded in design–build handovers.

Given rising environmental and resource pressures, there is growing academic interest in sustainable megaproject development that prioritizes ecological responsibility and efficient resource use (Thounaojam and Laishram, 2022; Wang et al., 2020). Experts suggest that transforming the construction industry requires embedding sustainability into large-scale project frameworks, with Lean Construction (LC) emerging as a promising strategy when integrated early in planning and design stages (Babalola et al., 2019; Francis and Thomas, 2020). LC is a process of continuous improvement aimed at reducing waste, enhancing productivity, and improving safety while aligning with client expectations (Abu Aisheh et al., 2022; Meshref et al., 2022). It also contributes to key Sustainable Development Goals (SDGs), particularly SDG 9 (Industry Innovation), SDG 11 (Sustainable Cities), SDG 12 (Responsible Consumption), and SDG 13 (Climate Action), by promoting efficiency, innovation, and reduced environmental impact through optimized material use and circular economy principles (Hasan et al., 2024; Opoku et al., 2024).

In the context of Construction Megaprojects (CMPs), LC has proven effective in addressing common failures such as poor coordination, rework, and schedule delays, thereby improving overall project performance (El-Sabek and McCabe, 2017). For instance, LC practices applied in Qatar, Australia, Peru, and India have led to improved scheduling, cost control, quality, and safety, along with increased stakeholder collaboration and motivation (Flores and Ollero, 2013; Luai et al., 2017; Moon et al., 2018; Ramasamy, 2016). Together, these cases underscore the transformative role of LC in advancing CMPs success. Yet, adoption remains highly uneven, especially in large, publicly funded, or developing economy megaprojects. As Ibrahim et al. (2025b) observe. At the same time, LC has seen success in select flagship projects (e.g., in the US or Northern Europe). Still, its diffusion in complex Chinese megaproject environments remains fragmented, hindered by institutional inertia, skill gaps, regulatory misalignment, and supply chain immaturity. Successful implementation requires identifying and addressing critical enablers, organizational, human, and external factors that influence outcomes (Ballard and Tommelein, 2012). While much research focuses on lean tools, fewer studies examine broader enabling conditions, leading to inconsistent application (Ibrahim et al., 2025c; Li et al., 2020, 2024; Pan and Pan, 2016). The LC implementation gap arises from practical issues, unclear enabler prioritization, resource misallocation, and premature tech adoption without a lean culture, as well as theoretical shortcomings, including tool-centric or static, single-method studies that overlook the need for dynamic sequencing of enablers across megaproject phases. Collectively, these practical ambiguities and theoretical limitations underscore a pressing need, not merely to identify enablers, but to operationalize them through a phased, evidence-based sequencing logic. Scholars emphasize the need to focus on leadership, workforce capabilities, stakeholder engagement, and technology integration, particularly in large-scale projects. While our earlier work (Ibrahim et al., 2025d) established the causal efficacy of CSFs in mitigating LC barriers using PLS-SEM, this study advances the agenda by addressing the critical implementation gap: How can practitioners and policymakers identify, prioritize, and sequence LC enablers to enable systematic, context-sensitive diffusion in CMPs, particularly where institutional, human, and technological readiness are uneven?

To achieve this objective, a mixed-methods approach is employed. Initially, a rigorous systematic literature review is conducted to compile a preliminary set of Lean Construction Enablers (LCEs). Subsequently, empirical data gathered from 379 construction professionals across China are analyzed using three complementary techniques: Mean Score Analysis, the Fuzzy Relative Importance Index (FRII), and Fuzzy Synthetic Evaluation (FSE). These methods collectively enable the prioritization and robust assessment of the identified enablers based on practitioner perceptions. The resulting insights form the foundation of a structured, context-sensitive framework designed to accelerate and sustain LC integration in CMPs, ultimately promoting more resilient, efficient, and sustainable infrastructure delivery.

2. Research background

2.1. LC implementation in Construction Megaprojects

While the core principles of LC are broadly applicable, their implementation varies significantly between small-scale developments and large, complex megaprojects. This variation stems from differences in project scale, organizational structure, stakeholder diversity, resource allocation, and risk profiles (Ibrahim et al., 2025b). In smaller undertakings, typically defined by narrow scope and a limited number of involved parties, LC initiatives tend to emphasize targeted operational efficiencies. Common approaches include just-in-time material logistics, visual management boards, and expedited decision pathways (Koskela, 2000). These environments benefit from direct communication channels and rapid feedback loops, enabling the effective deployment of tools like the Last Planner System (LPS).

In contrast, megaprojects, large-scale initiatives marked by high capital investment, long timelines, and complex supply chains, require lean strategies that go beyond localized tools to address systemic inefficiencies (Flyvbjerg, 2014). Unlike smaller settings, megaprojects demand scalable and adaptive lean frameworks capable of managing cross-organizational coordination, integrating diverse workflows, and aligning strategic goals across multiple actors, including governments, multinational contractors, financiers, and local communities (Toor and Ogunlana, 2010). Therefore, successful LC adoption in these contexts depends not only on technical tools but also on strategic alignment, digital integration, and strong collaboration mechanisms.

Several lean tools have proven effective in addressing the complexities of megaprojects. The Last Planner System® (LPS®), originally designed to improve planning reliability and reduce disruptions, has been successfully adapted for use in large-scale environments where traditional methods struggle with variability and interdependencies (Howell and Ballard, 1998). Similarly, Building Information Modelling (BIM) supports lean practices by enabling real-time data sharing, improving design coordination, and facilitating conflict resolution across project phases (Azhar, 2011). Integrated Project Delivery (IPD) and Target Value Design (TVD) further enhance collaborative decision-making and cost control throughout the project lifecycle, helping stakeholders maintain performance benchmarks through continuous improvement (Geraldi et al., 2011). Together, these tools demonstrate how lean methodologies can be scaled and tailored for significant infrastructure developments. Empirical evidence from global case studies confirms the value of LC in enhancing the outcomes of megaprojects. In Turkey, Koseoglu et al. (2018) found that integrating BIM and lean approaches improved design coordination and construction quality during the Istanbul Grand Airport (IGA) project. In Morocco, Idrissi Gartoumi et al. (2024) reported a reduction in quality defects and an increase in customer satisfaction following the application of lean tools in the Mohamed VI Tower project. Similar benefits were observed in Peru, where Flores and Ollero (2013) documented improved workflow continuity and productivity in public infrastructure work. In the U. S., Lostuvali et al. (2014) noted enhanced collaboration and reduced rework in the Cathedral Hill Hospital project following the adoption of lean principles. In China, Li et al. (2021) developed a BIM-integrated lean framework tailored for owner-led megaprojects, which improved stakeholder alignment and process transparency.

Moving beyond isolated case analyses, researchers have increasingly adopted both qualitative and quantitative approaches to investigate obstacles, integration pathways, and capability structures essential for implementing LC. For example, Evans and Farrell (2021) applied a Delphi consensus method in Qatar to pinpoint and rank key challenges associated with merging BIM with lean methodologies. Building on this work, Evans et al. (2023) conducted in-depth interviews and facilitated focus groups across the Middle East and North Africa region to uncover socio-technical and institutional hurdles that impede the alignment of lean principles with Integrated Project Delivery (IPD). Further, Evans and Farrell (2023) administered surveys to develop a competency framework for integrating lean within Global Integrated Delivery (GID) models, offering practical guidance aligned with sustainability and international standards.

Collectively, these studies underscore the adaptability and transformative potential of LC in managing megaproject complexity. They emphasize the importance of digital tools, collaborative engagement, and context-specific adaptations in overcoming implementation challenges and supporting the development of sustainable infrastructure.

2.2. Lean Construction Enablers (LCEs)

For construction firms to successfully adopt LC, it is essential first to understand the key challenges and prerequisites associated with its implementation. Identifying the factors that influence project outcomes, both positively and negatively, enables organizations to anticipate potential obstacles, address knowledge or resource gaps, and ultimately reduce the risk of failure. However, much of the existing literature tends to focus narrowly on the application of specific lean tools and techniques, often overlooking the broader organizational and human dimensions that underpin their effective use (Pavez and Alarcón, 2006). Furthermore, while prior research into Critical Success Factors (CSFs) has concentrated mainly on internal organizational elements, such as leadership, planning, and team structure (Ballard and Kim, 2007; Pavez and Alarcón, 2006), it frequently neglects external influences that can significantly affect project delivery.

In response to this need, a growing number of studies have sought to systematically identify and classify the factors that drive the successful diffusion of LC. For example, Watfa and Sawalha (2021) categorized 22 success factors into 15 groups, including management commitment, leadership, and communication, based on empirical research conducted in the UAE. Similarly, Demirkesen and Bayhan (2022) classified 27 enabling factors into six main categories, such as motivational, technical, and workforce-related aspects, through a survey-based study in the United States. Other researchers have also contributed valuable insights: Sadikoglu et al. (2024) highlighted the importance of leadership by organizing 20 success factors into four major clusters, while Demirkesen and Bayhan (2020) expanded this classification to include financial, managerial, and cultural dimensions. In Malaysia, Marhani et al. (2023) identified 12 key drivers grouped into management, economic, technical, and communication domains, and provided actionable recommendations such as on-the-job training and localized adaptation of LC practices.

Building upon these contributions and synthesizing findings from multiple regional and methodological contexts, Ibrahim et al. (2025d), proposed a comprehensive categorization framework for enablers of LC implementation. This classification organizes the enablers into six distinct thematic groups, reflecting both internal organizational capabilities and external strategic considerations. These six categories, Strategic and Leadership (SL), Stakeholder Relationship Management (SRM), Resource Knowledge and Availability (RKA), Process Optimization and Efficiency (POE), Performance Improvement and Waste Reduction (PIW), and Technological Innovation (TI), serve as a structured guide for identifying and prioritizing critical success factors in large-scale construction projects. The detailed list of enablers, along with their descriptions, is summarized in Table 1.

Table 1
Identified enablers for implementing LC in CMPs (Ibrahim et al., 2025d).

Construct ID	Enabler code	Description
SL	SL1	Organizational financial capacity to support lean initiatives
	SL2	Promoting awareness aligned with LC processes
	SL3	Support from both governmental bodies and top-level management through policy and regulation
	SL4	A well-defined early-stage strategic vision
	SL5	Implementation of incentive systems such as tax benefits or performance-based rewards
	SL6	Commitment from upper and middle management to integrate lean practices
	SL7	Leadership skills among clients and contractors that encourage knowledge sharing
SRM	SRM1	Efficient stakeholder engagement and development of trust-based relationships
	SRM2	Defining value from the customer's perspective, including needs and expectations
	SRM3	Ensuring alignment with customer requirements
	SRM4	Early participation of critical stakeholders in project planning
	SRM5	Establishing strong communication and collaboration channels with stakeholders
RKA	RKA1	Availability of experienced lean leaders and managers
	RKA2	Provision of continuous employee education to ensure successful lean implementation
	RKA3	Presence of dedicated lean research teams to manage change resistance
	RKA4	Access to adequate resources and familiarity with lean methodologies
	RKA5	Use of adaptable resources and dynamic planning strategies
POE	POE1	Development of logistics, procurement, and material handling systems focused on value creation
	POE2	Application of LC tools such as Just-In-Time (JIT), Last Planner System, Value Stream Mapping, 5S, and Pull Planning
	POE3	Use of visual control techniques to enhance transparency and workflow efficiency
	POE4	Effective coordination mechanisms to address complex project environments
PIW	PIW1	Reduction of waste types such as rework, material shortages, and unnecessary handling
	PIW2	Minimization of variability and improvement of process cycle times
	PIW3	Use of standardized performance indicators linked to continuous improvement goals
	PIW4	Benchmarking against industry-leading organizations
	PIW5	Adoption of standardized improvement tools, including root cause analysis, mistake-proofing (poka-yoke) techniques, and structured defect response protocols
TI	TI1	Integration of digital technologies like Building Information Modeling (BIM)
	TI2	Promotion of modular and prefabricated construction approaches
	TI3	Adoption of circular economy (CE) principles to minimize environmental impact and carbon emissions
	TI4	Exploration of emerging technologies such as Digital Twin and Blockchain integration

2.3. Synthesizing the literature: gaps in scope, method, and contextual applicability

A growing body of research has identified lean enablers across diverse project settings (Evans et al., 2021; Lam et al., 2024). To map

Table 2

Comparative overview of lean enabler studies in construction: Methodologies, regional contexts, and analytical approaches.

Year	Domain	Country	Data Collection	Data Analysis Method	Ref
2020	Construction projects	Saudi Arabia	Survey	Interpretive Structural Modelling (ISM)	Sarhan et al. (2020)
2021	Construction Mega-projects	12 Country	Two-round Delphi survey	Mean Score Ranking, Inter-Rater Agreement (IRA), Spearman's Rank Correlation, Mann-Whitney *U* Test	Evans et al. (2021)
2021	Construction projects	USA	Interviews	Content Analysis Approach	Bhawani et al. (2021)
2021	Construction projects	UAE	Survey	Mean, Relative Importance Index (RII)	Watfa and Sawalha (2021)
2021	Construction projects	Sri Lanka	Survey	Mean, RII, SD	Kariyawasam and Siriwardana (2021a)
2022	Construction projects	Egypt	Interview	Simos', WSM	Meshref et al. (2022)
2022	Construction projects	Morocco	Survey	Mean Score, Standard Deviation	Arabi et al. (2022)
2022	Construction projects	USA	Survey	Interpretive Structural Modelling (ISM)	Aslam et al. (2022)
2022	Construction projects	USA	Survey	Mean Score, Standard Deviation, Exploratory Factor Analysis (EFA), Kruskal-Wallis Test	Demirkesen and Bayhan (2022)
2023	Construction projects	Iran	Survey	AHP, Sensitivity Analysis	Noorzai (2023)
2023	Construction projects	Indonesia	Survey	Certainty Index, Rii, Fuzzy Ahp, Fuzzy-Topsis	Adhi and Muslim (2023)
2023	Residential projects	Malaysia	Survey	Mean Score, Standard Deviation	Marhani et al. (2023)
2024	High-Rise buildings	Hong Kong	Interview	Mean Score, Standard Deviation, Principal Component Analysis, Mann–Whitney *U* Test	Lam et al. (2024)

this landscape, Table 1 consolidates the 30 LCEs derived from Ibrahim et al. (2025d), organized into six thematic constructs. These constructs reflect a holistic view of LC implementation, integrating organizational, operational, and technological dimensions.

However, identifying what enablers matter is insufficient without understanding how, when, and in what priority they should be applied, especially in megaprojects, where scale, fragmentation, and institutional complexity reshape implementation logic. To assess how prior studies approach this challenge, Table 2 presents a comparative analysis of 13 representative empirical studies (2020–2024) that examine LC enablers, categorized by domain, geography, data collection method, and analysis approach. From this synthesis, three persistent gaps emerge:

1. Scenario Misalignment: Over 90% of studies (e.g., (Marhani et al., 2023; Meshref et al., 2022; Watfa and Sawalha, 2021)) focus on *generic construction projects* or SMEs, not *megaprojects.* Only two studies ((Evans et al., 2021; Lam et al., 2024)) explicitly address large-scale complexity, and none are grounded in the *Chinese megaproject context*, where regulatory, cultural, and supply chain dynamics differ markedly from those in Western or Gulf models.
2. Methodological Limitations: The majority rely on single-method approaches: mean scores (e.g.,(Arabi et al., 2022)), RII (e.g., (Kariyawasam and Siriwardana, 2021a)), or ISM (e.g., (Sarhan et al., 2020)). Even hybrid designs (e.g., (Evans et al., 2021) Delphi + non-parametric tests) lack mechanisms to handle linguistic uncertainty or construct-level interdependencies. In contrast, this study employs a three-tiered fuzzy methodology (Mean → FRII → FSE), uniquely capable of quantifying expert judgment fuzziness (via TFNs), ranking individual enablers and grouped constructs simultaneously, and enabling defuzzified, actionable prioritization (ToI) for phased implementation.
3. Implementation Opacity: Most studies conclude with static enabler rankings, offering *no sequencing logic* for real-world rollout, especially under resource or cultural constraints. Our framework advances this by proposing a context-sensitive diffusion roadmap, where foundational capabilities (e.g., RKA) precede higher-order interventions (e.g., TI), aligning with maturity-based lean adoption theory (Ballard and Tommelein, 2012).

Thus, while prior work establishes which factors enable LC, this study answers the critical how: How can LCEs be prioritized, synthesized, and sequenced, using a robust fuzzy methodology to support sustainable LC diffusion in Chinese CMPs? By bridging these gaps in scenario focus, method innovation, and operational applicability, the proposed framework contributes both theoretical nuance and practical utility.

3. Methodology

This study aims to identify, prioritize, and evaluate the key LCEs that facilitate systemic diffusion in CMPs. Accordingly, a systematic, multi-stage methodological approach is adopted, as illustrated in Fig. 1.

In detail, the research begins with a systematic literature review to compile a comprehensive list of potential LC enablers based on existing global and regional studies. Prior to full deployment, a pilot study ensures the clarity and quality of the research instrument, allowing for the collection of data on LC diffusion enablers before the primary survey is conducted. Following data collection, quantitative analysis techniques are applied to assess the significance of these enablers. The gathered data is subjected to thorough analytical procedures, beginning with tests for normal distribution using the Shapiro-Wilk test and an evaluation of internal consistency through Cronbach's Alpha. To determine the relative importance and impact of LCEs, statistical techniques such as mean score analysis and the Fuzzy Relative Importance Index (FRII) are applied. These methods help in prioritizing the key factors influencing the successful adoption of life cycle practices in megaprojects.

Finally, Fuzzy Synthetic Evaluation (FSE) ranks the grouped enablers, providing a structured basis for developing the proposed framework. Through this integrated, multi-stage approach, the resulting framework is both theoretically grounded and addresses both academic and practical gaps in LC implementation for CMPs. Ultimately, the framework is designed to outline the essential requirements for implementing LC and achieving sustainability in megaprojects, offering valuable contributions to both theory and practice.

3.1. Literature review

Scholars in construction management often rely on digital libraries, such as Web of Science (WOS), Scopus, and Google Scholar, for literature reviews and data collection. Among these, Scopus was selected for this study due to its extensive coverage, advanced citation tracking, and superior performance in the social sciences (Norris and Oppenheim, 2007). Comprehensive exploration was conducted using targeted strings and keywords within the parameters of ‘article title/abstract/keywords’ through the advanced document search functionality in Scopus. The search query was carefully constructed. Following the methodology outlined by Ibrahim et al. (2024a), inclusion and exclusion criteria were applied to ensure relevance: peer-reviewed journal articles addressing

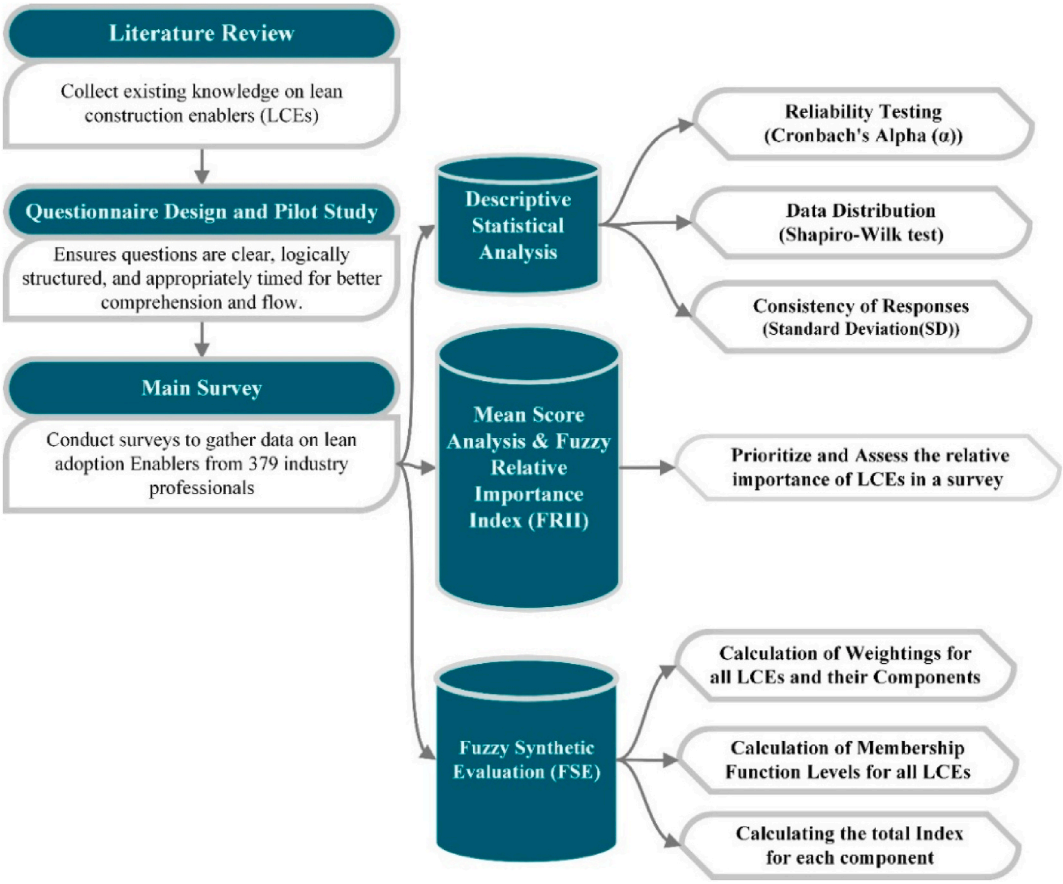

Fig. 1. Overview of the research framework and methodological approach.

LC drivers were included, while studies published before 2000, non-English texts, and inaccessible full texts were excluded. The snowballing technique was also used to identify additional relevant studies by examining references and citations, enhancing the depth of the literature review (Ibrahim et al., 2024b). After rigorous screening, 66 papers were included in the final analysis.

3.2. *Questionnaire design and pilot study*

To operationalize the research aims and empirically test the proposed framework of LCEs, a structured questionnaire was administered to professionals actively engaged in CMPs across Mainland China and Hong Kong. These regions were selected due to their high concentration of large-scale infrastructure projects, mature regulatory environments, and global contributions to construction development (Cheung and Shen, 2017; Liu et al., 2018). The study focused on projects exceeding 0.5 billion Chinese Yuan (CNY), as defined by Wang et al. (2021), as megaprojects in the Chinese context.

China provides a valuable case for studying CMP delivery due to its vast experience managing complex infrastructure developments. Its practices offer insights relevant to both developed and developing countries seeking to replicate rapid growth or address challenges such as risk governance and inter-organizational coordination (He et al., 2015; Xie et al., 2022). Additionally, China's growing emphasis on sustainable development and environmental responsibility aligns well with the goals of LC (Xie et al., 2020).

The primary respondents were senior and mid-level managers directly involved in planning and executing large-scale projects. Participants were asked to base their evaluations on their most recent megaproject to minimize recall bias and ensure contextual relevance (Eriksson et al., 2017), a method commonly used to enhance data validity in similar studies (Ali et al., 2024; Alnaser et al., 2024).

A stratified random sampling technique was employed to ensure broad representation across organizational roles, including contractors, consultants, and developers. A total of 471 digital questionnaires were distributed via Google Forms, with 379 completed responses (80.46%).

At the beginning of the questionnaire, LC was clearly defined as a systematic project management methodology aimed at minimizing waste, enhancing value delivery, and promoting continuous improvement through collaborative tools like Value Stream Mapping (VSM), Last Planner System® (LPS®), and Integrated Project Delivery (IPD) (Howell and Ballard, 1998; Koskela, 2000). Prior to full distribution, a pilot study involving ten industry experts was conducted to assess clarity and consistency in understanding LC concepts. Based on feedback, minor revisions were made to definitions and questions to improve comprehension. As noted by Tabatabaee et al. (2022), such pre-testing is essential for validating research instruments. The final questionnaire used a five-point Likert scale (1 = very low significance, 5 = very high significance) to evaluate the perceived importance of each LCE.

3.3. *Main survey*

3.3.1. *Descriptive statistical analysis*

The mean value is a commonly used statistical measure for evaluating the central tendency of data, especially in studies utilizing ordinal rating scales (Hwang et al., 2018a). In this research, the data analysis process commenced with tests for normality using the Shapiro-Wilk test, alongside an assessment of internal consistency through Cronbach's Alpha. These preliminary steps were conducted to validate the reliability of the measurement instrument and ensure the robustness of the collected responses. To evaluate the relative importance of each enabler, mean scores were computed. A cutoff value of 3.50 on the 5-point Likert scale was adopted as a benchmark to distinguish significant factors from less influential ones. Items scoring above this threshold were interpreted as being closer to “very significant” rather than “moderately significant,” following previously established criteria (Hwang et al., 2018b; Wuni and Shen, 2020). In addition, standard deviation was calculated to assess the variability of respondents' evaluations. This provided further insight into the consistency of responses and supported the accurate identification of key influencing factors (Wuni and Shen, 2022).

3.3.2. Fuzzy Relative Important Index (FRII)

In construction-related studies, the Relative Importance Index (RII) is a commonly employed metric for evaluating the comparative influence or relevance of various drivers or enabling factors (Ayarkwa et al., 2022; Genc, 2023). This method allows researchers to quantitatively assess how respondents perceive the importance of different variables by aggregating their ratings into a single index value. As proposed by Akadiri (2011), RII scores can be categorized into five distinct levels of importance: High (H) when the index ranges from 0.8 to 1.0, Medium-High (M-H) for values between 0.6 and 0.8, Medium (M) for scores from 0.4 to 0.6, Medium-Low (M-L) for values between 0.2 and 0.4, and Low (L) for scores below 0.2.

Nonetheless, conventional RII has limitations when dealing with the inherent subjectivity and imprecision of human evaluations (Ibrahim et al., 2025a). To better accommodate the vagueness inherent in qualitative judgments, fuzzy set theory has been incorporated into the RII methodology, resulting in the Fuzzy Relative Importance Index (FRII). As implemented by Ibrahim et al. (2025e), this refined approach leverages fuzzy membership functions to represent uncertain or ambiguous input data, thereby producing more robust and nuanced prioritization outcomes.

The classical RII is computed using the following Equation (1):

$$\text{Relative Important Index (RII)} = \frac{\sum \mathrm{W_i}}{A{*}N} \quad \textit{for } i = 1 \textit{ to } N \tag{1}$$

where “Wi” represents the importance rating given by the i-th respondent for a specific factor, “A” is the highest possible rating on the scale (e.g., 5 for a 5-point Likert scale), and “N” denotes the total number of respondents.

In the FRII framework, each Likert-scale response is modelled as a Triangular Fuzzy Number (TFN), denoted as (a, b, c), where a, b, and c correspond to the lower, modal, and upper bounds of the fuzzy estimate. The computation of FRII proceeds through four sequential phases:

1) Participant inputs are combined using fuzzy addition. For two TFNs, TFN1 = (a_1, b_1, c_1) and TFN2 = (a_2, b_2, c_2) using Equation (2).

$$\mathrm{TFN_1}(+)\mathrm{TFN_2} = (a_1 + a_2\ , b_1 + b_2\ , c_1 + c_2) \tag{2}$$

This operation is applied iteratively across all respondents to yield an aggregated fuzzy total for each factor.

2) Application of α-cut: To manage the complexity introduced by fuzzy division, the α-cut technique is employed. An α-cut extracts a crisp interval from a fuzzy set at a specified membership level (e.g., α = 0.6, 0.7, 0.8). This transforms the aggregated TFN and the maximum score into interval representations suitable for arithmetic processing.
3) Fuzzy RII Calculation: Using interval arithmetic, the fuzzy RII is derived at each α-level. Given two intervals $A_\alpha = [\ A_{\alpha L}, A_{\alpha U}]$ and $B_L = [\ B_{\alpha L}, B_{\alpha U}]$, the division operator can be applied as follows using Equation (3):

$$A\alpha(\,/\,)B\alpha = \left[\frac{A\alpha_L}{B\alpha_U}, \frac{A\alpha_U}{B\alpha_L}\right] \tag{3}$$

Adapting this to Equation (1), the α-level bounds of the FRII are computed using the following Equation (4):

$$RII\alpha = \left[\frac{W\alpha_L}{N{*}A\alpha_U}, \frac{W\alpha_U}{N{*}A\alpha_L}\right] \tag{4}$$

where and are the lower and upper bounds of the aggregated importance scores at the α-cut level.

4) Defuzzification: Finally, the resulting fuzzy RII is converted into a single crisp value through defuzzification. The geometric centroid method (Equation (5)) recommended by Zammori et al. (2009), is used for this purpose. For a fuzzy number “Fi” with membership function $\mu_A(x)$, the centroid GC(Fi) is calculated as:

$$\mathrm{GC(Fi)} = \frac{\int x\mu_A(x)\,dx}{\int \mu_A(x)dx} \tag{5}$$

This step yields a definitive RII score that integrates uncertainty while preserving interpretability for ranking and decision-making.

3.3.3. Fuzzy Synthetic Evaluation (FSE)

FSE, grounded in fuzzy logic, transforms linguistic criteria into quantifiable forms, enhancing decision-making accuracy by addressing uncertainty and subjectivity (Chan et al., 2024). This makes FSE particularly suitable when performance ratings or criteria weights are not crisp or clearly defined, a common limitation in traditional MCDM methods like AHP and TOPSIS that typically require precise numerical inputs (Guo and Zhao, 2017; Torfi et al., 2010). It also overcomes the limitations of binary logic, making it ideal for evaluating complex events, such as LCEs, in CMPs. FSE has been widely applied in construction research, including BIM adoption (Saka et al., 2022), modular construction (Wuni and Shen, 2020), and circular economy (Wuni and Shen, 2022). Its ability to objectively quantify subjective judgments makes it suitable for this study (Sadiq and Rodriguez, 2004). The FSE process is structured around four key steps, as outlined below:

First, mean scores (MS) for each LCE and its associated components were computed using Equation (6):

$$MS = \frac{\sum (S \times Fr)}{N}, (1 \le MS \le 5) \tag{6}$$

In this equation, S represents the Likert-scale score (ranging from 1 to 5), Fr denotes the frequency of each rating, and N is the total number of valid responses.

Second, weights (W_i) for each enabler and component was calculated using a normalized mean method. For individual enablers, weights were determined via Equation (7):

$$W_i = \frac{MS_i}{\sum_{i=1}^{n} MS_i}, 0 < W_i < 1 \textit{ and } \sum_{i=1}^{n} W_i = 1 \tag{7}$$

Where W_i is the weight assigned to enabler i, and MS_i is its corresponding mean score. Component-level weights W_{Ci} were derived using Equation (8):

$$W_{Ci} = \frac{\sum_{i=1}^{n} MS_i(\textit{for each component})}{\textit{Overall } MS_i} \tag{8}$$

Finally, the full set of enabler weights was expressed in vector form as shown in Equation (9).

$$W_i = (W_1, W_2, W_3, \cdots\cdots, W_n) \tag{9}$$

Third, membership functions (MFs) were established to reflect the degree of belongingness of each element within the fuzzy set. These MFs ranged from 0 to 1 and were calculated using Equation (10):

$$MF_{P_{in}} = \frac{P_{1_{in}}}{LS_1} + \frac{P_{2_{in}}}{LS_2} + \frac{P_{3_{in}}}{LS_3} + \frac{P_{4_{in}}}{LS_4} + \frac{P_{5_{in}}}{LS_5} \tag{10}$$

Here, $P_{1_{in}}$ through $P_{5_{in}}$ represent the percentage of respondents assigning ratings from 1 to 5, and LS_1 to LS_5 correspond to the respective Likert scale levels.

For higher-level components, Level 1 membership functions were derived based on the results of Level 2. Specifically, the membership function Di for component i was calculated using Equation (11).

$$D_i = W_i \bigotimes R_i \tag{11}$$

where W_i is the weighting vector obtained from Equation (9), R_i is the fuzzy matrix of enablers under that component, utilizing the fuzzy composition operator ($\otimes$). The detailed structure of R_i is presented in Equation (12)

$$R_i = \begin{vmatrix} MF_{Ei1} \\ MF_{Ei2} \\ \cdots \\ MF_{Ein} \end{vmatrix} = \begin{vmatrix} E_{1_{i1}} & E_{2_{i1}} & E_{3_{i1}} & E_{4_{i1}} & E_{5_{i1}} \\ E_{1_{i2}} & E_{2_{i2}} & E_{3_{i2}} & E_{4_{i2}} & E_{5_{i2}} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ E_{1_{in}} & E_{1_{in}} & E_{1_{in}} & E_{1_{in}} & E_{1_{in}} \end{vmatrix} \tag{12}$$

The degree of membership, d_{in}, is derived from the calculation of D_i as shown in Equation (13).

$$D_i = W_i \bigotimes R_i = (W_1, W_2, W_3, W_4, \cdots\cdots\cdots, W_n) \bigotimes \begin{vmatrix} E_{1_{i1}} & E_{2_{i1}} & E_{3_{i1}} & E_{4_{i1}} & E_{5_{i1}} \\ E_{1_{i2}} & E_{2_{i2}} & E_{3_{i2}} & E_{4_{i2}} & E_{5_{i2}} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ E_{1_{in}} & E_{1_{in}} & E_{1_{in}} & E_{1_{in}} & E_{1_{in}} \end{vmatrix} = (d_{i1}, d_{i2}, \cdots, d_{in}) \tag{13}$$

Finally, the Total Index (ToI) for each component was computed to provide an overall evaluation score using Equation (14):

$$ToI_i = \sum_{i=1}^{n} D_{Ci} \times LS_i \tag{14}$$

In this formula, D_{Ci} represents the fuzzy evaluation value of the component, and LS_i denotes the corresponding Likert scale level. This final index enables a comprehensive ranking and prioritization of LCEs based on their relative importance and effectiveness.

4. Results and discussion

This section provides a comprehensive analysis of the findings obtained from survey data, aimed at identifying and evaluating the key enablers of LC diffusion in CMPs. The analysis begins with an assessment of data reliability and normality to ensure the validity of subsequent statistical interpretations. This is followed by a detailed overview of the demographic characteristics of the respondents, offering context for the perspectives gathered. The significance of these enablers is then rigorously examined through statistical analysis, including mean score analysis, standard deviation, and FRII, which is used to assess the significance and level of importance of LCEs. Finally, fuzzy synthetic evaluation is applied to determine the relative importance of each construct, providing actionable insights that can guide improvements in lean implementation within large-scale construction projects.

4.1. *Evaluation of data reliability and normality*

Before conducting the primary statistical analysis, the dataset was evaluated for reliability and normality to ensure its suitability for further processing. Cronbach's Alpha was used to assess the internal consistency of the Likert-scale responses across all enablers. The results showed Cronbach's Alpha values exceeding 0.967 for each construct, indicating excellent reliability and consistency in the respondents' evaluations. To examine the distribution of the data, the Shapiro-Wilk test was employed, using a significance threshold of 0.05. All computed p-values were found to be less than 0.05, leading to the rejection of the null hypothesis that the data follows a normal distribution. This finding confirms that the dataset exhibits a non-normal distribution, which is commonly observed in studies involving relatively small sample sizes, as supported by previous research (Hwang et al., 2017; Shan et al., 2017). Despite the non-normality, the high internal consistency and overall quality of the data support its use in subsequent analyses, including structural equation modeling and fuzzy synthetic evaluation. These findings collectively affirm the validity and robustness of the collected responses, enabling the drawing of meaningful conclusions in this study.

4.2. *Methodological positioning: Why FRII–FSE outperforms single-method alternatives in megaproject contexts*

Given the non-normal distribution of responses (confirmed via the Shapiro-Wilk test, $p < 0.05$), conventional parametric techniques (e.g., AHP, crisp RII, or TOPSIS) would be statistically inappropriate and practically limiting for three key reasons.

First, AHP assumes precise, consistent pairwise judgments, yet megaproject professionals often express enabler importance linguistically (e.g., “fairly important” or “very important”), a nuance captured by TFNs in FRII but lost in AHP's 1–9 scale. Second, TOPSIS requires predefined ideal/nadir solutions, which are ill-suited when all 30 LCEs are inherently positive (i.e., no enabler is “undesirable”), making distance-to-ideal rankings artificially constrained. Third, single-factor mean analysis, or RII, ignores construct-level interdependencies, for instance, how RKA (e.g., lean-trained staff) enables effective use of TI (e.g., BIM), a synergy explicitly modelled via FSE's hierarchical aggregation.

As summarized in Table 3, our hybrid FRII–FSE workflow bridges these gaps:

- FRII quantifies relative importance under linguistic uncertainty,
- FSE synthesizes enabler-to-construct relationships, and
- Defuzzified ToI yields actionable, phased rankings, not just static lists.

FSE accounts for quality (distribution tightness, skew) and interdependence, not just scale. Thus, the method itself advances LC implementation science, moving beyond identification toward contextual operationalization.

While the FRII–FSE approach offers robust handling of linguistic uncertainty and hierarchical aggregation, key advantages in megaproject contexts, it is not without limitations. First, FSE relies on aggregated expert perceptions, meaning that results reflect collective subjective judgments rather than objective performance metrics. While TFNs mitigate crisp rating bias, they do not eliminate underlying cognitive or cultural biases in interpretation (e.g., what constitutes ‘high’ resource availability may vary across organizational cultures). Second, the method's outputs are context-dependent: the ToI rankings are calibrated to the specific sample (379 professionals in China) and

Table 3
Comparative summary of evaluation methods in LC enabler studies.

Method	Key Strength	Key Limitation	Typical Use Case	Suitability for CMP Enabler Prioritization
Mean Score	Simplicity, transparency	Ignores weighting, fuzziness	Initial screening (e.g., (Watfa and Sawalha, 2021))	Low
AHP	Hierarchical weighting, intuitive logic	Crisp judgment, consistency burden	CSF ranking (e.g., (Noorzai, 2023))	Medium
TOPSIS	Multi-criteria distance-based ranking	Requires ideal solutions; sensitive to normalization	Technology selection (e.g., (Adhi and Muslim, 2023))	Medium
FRII–FSE (Proposed)	Fuzzy uncertainty modeling + construct synthesis	Slightly higher computational load	Phased enabler rollout in complex, multi-stakeholder environments	High

Table 4
Survey results and statistical analysis of LCEs.

(Reliability- Cronbach's Alpha = 0.967)

Enabler Code	Percentage of Respondents Scoring					Mean	SD	Rank	FRII	Level of Imp	P-value
	VL	L	M	H	VH						
Strategic and Leadership (SL)											
SL1	0.5%	10.6%	32.5%	32.5%	24.0%	3.689	0.969	5	0.7	M-H	0.000[a]
SL2	0.8%	9.8%	32.2%	37.2%	20.1%	3.660	0.933	7	0.7	M-H	0.000[a]
SL3	1.1%	9.2%	25.1%	38.8%	25.9%	3.792	0.966	2	0.8	H	0.000[a]
SL4	1.1%	9.2%	26.4%	36.4%	26.9%	3.789	0.977	3	0.8	H	0.000[a]
SL5	0.8%	10.3%	30.9%	36.7%	21.4%	3.676	0.950	6	0.7	M-H	0.000[a]
SL6	0.5%	7.7%	29.8%	36.1%	25.9%	3.792	0.932	1	0.8	H	0.000[a]
SL7	0.5%	9.8%	27.2%	36.1%	26.4%	3.781	0.963	4	0.8	H	0.000[a]
Stakeholder and Relationship Management (SRM)											
SRM1	0.8%	9.2%	27.7%	38.3%	24.0%	3.755	0.949	2	0.8	H	0.000[a]
SRM2	0.8%	8.7%	28.8%	39.6%	22.2%	3.736	0.928	3	0.8	H	0.000[a]
SRM3	0.3%	8.4%	32.5%	38.8%	20.1%	3.699	0.893	5	0.8	H	0.000[a]
SRM4	0.8%	9.8%	28.5%	39.6%	21.4%	3.710	0.937	4	0.8	H	0.000[a]
SRM5	0.3%	8.7%	29.0%	38.5%	23.5%	3.763	0.918	1	0.8	H	0.000[a]
Resource and Knowledge Availability (RKA)											
RKA1	0.8%	2.6%	36.4%	37.2%	23.0%	3.789	0.853	3	0.8	H	0.000[a]
RKA2	0.5%	2.6%	38.5%	35.4%	23.0%	3.776	0.848	5	0.8	H	0.000[a]
RKA3	0.8%	2.9%	35.9%	38.5%	21.9%	3.778	0.847	4	0.8	H	0.000[a]
RKA4	0.5%	2.9%	31.4%	42.0%	23.2%	3.844	0.829	1	0.8	H	0.000[a]
RKA5	0.8%	3.4%	31.4%	39.1%	25.3%	3.847	0.869	2	0.8	H	0.000[a]
Planning and Operational Efficiency (POE)											
POE1	0.8%	9.2%	27.2%	43.0%	19.8%	3.718	0.913	4	0.8	H	0.000[a]
POE2	0.3%	8.4%	31.4%	35.6%	24.3%	3.752	0.927	3	0.8	H	0.000[a]
POE3	0.5%	6.1%	32.2%	38.3%	23.0%	3.770	0.889	2	0.8	H	0.000[a]
POE4	0.8%	9.5%	25.9%	37.5%	26.4%	3.792	0.966	1	0.8	H	0.000[a]
Process Improvement and Waste Elimination (PIW)											
PIW1	0.8%	9.0%	26.1%	39.3%	24.8%	3.784	0.946	2	0.8	H	0.000[a]
PIW2	0.5%	9.0%	27.7%	39.3%	23.5%	3.763	0.930	3	0.8	H	0.000[a]
PIW3	0.8%	7.7%	29.0%	37.2%	25.3%	3.786	0.937	1	0.8	H	0.000[a]
PIW4	0.8%	9.8%	31.1%	37.2%	21.1%	3.681	0.941	5	0.8	H	0.000[a]
PIW5	0.5%	8.7%	31.7%	36.9%	22.2%	3.715	0.925	4	0.8	H	0.000[a]
Technology and Innovation (TI)											
TI1	0.5%	9.2%	30.9%	37.7%	21.6%	3.707	0.927	1	0.8	H	0.000[a]
TI2	0.3%	8.7%	32.5%	39.1%	19.5%	3.689	0.893	2	0.8	H	0.000[a]
TI3	0.5%	9.8%	33.2%	34.3%	22.2%	3.678	0.944	3	0.7	M-H	0.000[a]
TI4	0.8%	10.0%	34.3%	35.9%	19.0%	3.623	0.930	4	0.7	M-H	0.000[a]

Note: [a] Significance was observed in the Shapiro-Wilk test at $\alpha = 0.05$, where $p < 0.05$.

may not directly transfer to other institutional, regulatory, or supply-chain environments, particularly where stakeholder power dynamics or lean maturity differ significantly. Future applications of this framework should therefore consider triangulation with qualitative validation (e.g., case-based process tracing) or sensitivity analyses to test robustness across subgroups (e.g., public vs. private sectors).

4.3. Respondent background information

The demographic characteristics of the 379 survey participants reflect a diverse yet highly experienced pool of professionals, predominantly representing Mainland China (63.85%), with the remaining portion (36.15%) originating from Hong Kong. This distribution ensures a balanced representation of perspectives from both regions, contributing to the relevance and applicability of the study's findings within the broader Chinese construction context. Most respondents work on residential (43.54%) and infrastructure/transportation (29.02%) projects, reflecting a focus on urban development. A majority are employed in the private sector (70.98%), with fewer in the public sector (27.70%), suggesting findings are more relevant to private practices. Over half (55.15%) have 11–15 years of experience, indicating a mature perspective, while only 8.71% have 1–5 years and 9.76% have 16+ years, emphasizing mid-career professionals as the key demographic.

4.4. Assessment of significant Lean Construction Enablers

The findings are summarized in Table 4 illustrate the pivotal role that

LCEs play in advancing the successful diffusion of LC within CMPs. All identified enablers surpassed the threshold mean value of 3.50, with standard deviations below 1.0, indicating a high level of agreement among respondents regarding their significance. These results provide a strong foundation for understanding the key enablers behind lean implementation and offer actionable insights for practitioners aiming to enhance project outcomes through systematic lean integration.

In the category of Resource and Knowledge Availability (RKA), two enablers stood out: “Using Flexible Resources and Adaptive Planning” (RKA5; mean = 3.847) and “Adequate Resource Availability and Familiarity with Lean Techniques” (RKA4; mean = 3.844). These findings highlight the importance of both technical proficiency and adaptive capacity in resource management, aligning closely with previous studies by Demirkesen and Bayhan (2022) who emphasized resource availability as a key motivator, and Bayhan et al. (2019) who underscored the need for clear technical direction. Similarly, Kariyawasam and Siriwardana (2021b) pointed to stakeholder awareness of lean principles as a complementary requirement, reinforcing the idea that lean adoption hinges not only on available resources but also on organizational readiness and stakeholder engagement.

Strategic and Leadership (SL) emerged as another vital domain influencing lean diffusion, with “Commitment by Top and Middle Management” (SL6; mean = 3.792) and “Government and Top Organizational Management Support” (SL3; mean = 3.792) receiving the highest rankings. The relatively low standard deviation for SL6 further indicates a strong consensus among respondents regarding the indispensable role of leadership in fostering a lean culture. These findings corroborate those of Lam et al. (2024), who identified institutional support, particularly from governmental and upper-level management, as a crucial factor in enabling sustainable lean transformation across complex project environments.

Within the Process Improvement and Waste Elimination (PIW) category, “Standardized Metrics and Continuous Improvement Strategies” (PIW3; mean = 3.786) and “Eliminating Waste” (PIW1; mean = 3.784) were recognized as core enablers. These results reflect the foundational principles of lean methodology, where continuous improvement and waste reduction are central to achieving operational excellence. These findings align with Arabi et al. (2022), who emphasized the importance of fostering a continuous improvement mindset among employees to enhance lean adoption outcomes.

Stakeholder and Relationship Management (SRM) was also identified as a crucial component of lean success, with “Building Relationships with Stakeholders” (SRM5; mean = 3.763) and “Effective Stakeholder Management and Trust-Building” (SRM1; mean = 3.755) emerging as top contributors. These findings align with those of Yunus et al. (2017), who highlighted the importance of transparent communication and collaborative governance structures in facilitating lean implementation. Strong stakeholder alignment appears to be a prerequisite for sustaining lean initiatives, particularly in large-scale and multi-stakeholder environments such as CMPs.

Planning and Operational Efficiency (POE) was another central theme, with “Comprehensive Coordination and Adaptation to Complexity” (POE4; mean = 3.792) and “Visual Management Tools and Techniques” (POE3; mean = 3.770) ranked highly by respondents. These results suggest that lean implementation benefits greatly from proactive planning and visual control mechanisms that enhance coordination and transparency across project phases. As noted by Arabi et al. (2022), similarly emphasized proactive planning as a key driver of lean success.

Finally, Technology and Innovation (TI) played a significant role, with “Adopting New Construction Technologies (i.e., BIM)” (TI1; mean = 3.707) and “Enhancing Modular Integrated Construction” (TI2; mean = 3.689) identified as leading enablers. These findings underscore the growing influence of digitalization and advanced construction methods in supporting lean objectives. Kariyawasam and Siriwardana (2021b) reinforced the importance of technological advancement as a critical enabler for lean implementation.

Table 5
Mean values for (LCEs) and their relative weights across key constructs.

Construct	LCE (ID)	LCE Mean Score	Constructs Mean	LCE Weights	Constructs Weights
SL	SL3	3.792	26.177	0.145	0.233
	SL6	3.792		0.145	
	SL4	3.789		0.145	
	SL7	3.781		0.144	
	SL1	3.689		0.141	
	SL5	3.675		0.140	
	SL2	3.660		0.140	
SRM	SRM5	3.763	18.662	0.202	0.166
	SRM1	3.755		0.201	
	SRM2	3.736		0.200	
	SRM4	3.710		0.199	
	SRM3	3.699		0.198	
RKA	RKA5	3.847	19.034	0.202	0.169
	RKA4	3.844		0.202	
	RKA1	3.789		0.199	
	RKA3	3.778		0.199	
	RKA2	3.776		0.198	
POE	POE4	3.792	19.034	0.252	0.134
	POE3	3.770		0.251	
	POE2	3.752		0.250	
	POE1	3.718		0.247	
PIW	PIW3	3.786	18.728	0.202	0.167
	PIW1	3.784		0.202	
	PIW2	3.763		0.201	
	PIW5	3.715		0.198	
	PIW4	3.681		0.197	
TI	TI1	3.707	14.697	0.252	0.131
	TI2	3.689		0.251	
	TI3	3.678		0.250	
	TI4	3.623		0.246	

The FRII analysis classified most enablers as high importance (H), with a few categorized as medium-high (M-H), reflecting their substantial influence on lean implementation. Collectively, these findings reveal the multifaceted nature of lean diffusion in CMPs, highlighting the interdependence of resource flexibility, strategic leadership, process optimization, stakeholder collaboration, effective planning, and technological innovation. By aligning these enablers with targeted strategies, construction professionals can better navigate the complexities of lean integration and maximize the potential of lean methodologies in large-scale projects.

4.5. *FSE for determining the relative importance of the LCEs constructs*

This section presents the application of FSE to assess the relative importance of the identified LCE constructs. Building upon earlier statistical and structural analyses, FSE is employed to quantify the performance and significance of each construct based on expert evaluations and fuzzy logic principles. The results are used to calculate Membership Functions (MFs), derive fuzzy synthetic values, and ultimately determine the Total Index (ToI) for each LCE component.

4.5.1. *Calculation of mean Scores for LCE constructs*

Table 5 presents the mean scores and total mean values computed for each enabler and its associated components using Equation (6).

Among all categories, SL emerged as the most influential construct, with a total mean value of 26.177, driven by proactive decision-making and effective leadership practices. Closely following were RKA and POE, both recording total mean values of 19.034, highlighting the importance of adequate resources, knowledge transfer, and streamlined operations. SRM scored 18.662, emphasizing the need for strong collaboration and communication across project stakeholders. Meanwhile, PIW scored 18.728, underscoring the need to minimize inefficiencies. Technology and Innovation (TI) recorded the lowest total mean of 14.697, although this still indicates a notable role in advancing LC practices.

4.5.2. Determination of weights for LCE constructs

The weights for each enabler were calculated using the normalized mean method outlined in Equation (7), and the results are presented in Table 5. Given that the mean score of SL3 is 3.792 and SL contains 7 SLs, the weight of SL3 was computed as follows:

$$W_{\mathrm{SL3}} = \frac{3.792}{3.792 + 3.792 + 3.789 + 3.781 + 3.689 + 3.675 + 3.660} = .145$$

Using the same approach, the weights for each component are calculated and are also displayed in Table 5. Considering that SRM has a total mean score of 18.662, its weighting was computed as follows:

$$W_{\mathrm{SRM}} = \frac{18.662}{18.662 + 26.177 + 19.034 + 19.034 + 18.728 + 14.697} = .166$$

Using the same approach, the weightings of the remaining LCEs/ Components were computed using Equation (8) and shown in Table 5.

Based on the weightings of the six components, the ordered importance of the components is as follows: SL (0.233), RKA (0.169), PIW (0.167), SRM (0.166), POE (0.134), and TI (0.131). SL holds the highest weighting, emphasizing its pivotal role in driving LC through proactive leadership. RKA and SRM follow, with weightings of 0.169 and 0.166, respectively, highlighting the importance of resource allocation, collaboration, and effective communication. PIW, with a weighting of 0.167, underscores the need to minimize inefficiencies, while POE (0.134) and TI (0.131) stress the importance of streamlined planning and innovation. These findings highlight the importance of striking a balance between leadership, stakeholder engagement, and process efficiency to successfully implement LC in CMPs.

4.5.3. Membership function Evaluation for Lean Construction Enablers

To further assess the significance of each LCE, the Membership Function Level 2 (MF2) values were calculated based on participants' survey responses using Equation (10). The computed MF2 values for all enablers are summarized in Table 6. These values reflect the degree to which each enabler belongs to the fuzzy set of "significant LCEs." For example, RKA1 received response distributions of 0.8%, 2.6%, 36.4%, 37.2%, and 23% for significance levels 1 through 5, respectively.

Using Equation (10), the MF of RKA1 was computed as follows:

$$MF_{\mathrm{RKA1}} = \frac{.008}{LS_1} + \frac{.026}{LS_2} + \frac{.364}{LS_3} + \frac{.372}{LS_4} + \frac{.23}{LS_5}$$

Alternatively, the MF of RKA1 is expressed as (0.008, 0.026, 0.364,0.372,0.230), as shown in Table 6. Using the same approach, the MFs of the remaining LCEs were computed.

The MF1 of the Components for LC enablers was computed from their weighting functions and fuzzy matrices. For example, the weighting function of POE - Planning and Operational Efficiency (Table 5) and its fuzzy matrix (Table 6) can be expressed as:

$$W_{\mathrm{POE}} = (.252, .251, .250, .247)$$

$$R_{\mathrm{POE}} = \left| \begin{array}{c} MF_{\mathrm{POE4}} \\ MF_{\mathrm{POE3}} \\ MF_{\mathrm{POE2}} \\ MF_{\mathrm{POE1}} \end{array} \right| = \left| \begin{array}{ccccc} 0.008 & 0.095 & 0.259 & 0.375 & 0.264 \\ 0.005 & 0.061 & 0.322 & 0.383 & 0.230 \\ 0.003 & 0.084 & 0.314 & 0.356 & 0.243 \\ 0.008 & 0.092 & 0.272 & 0.430 & 0.198 \end{array} \right|$$

Using Equation (11), the resulting MF1 value for POE was computed as:

$$MF_{\mathrm{POE}} = D_{\mathrm{POE}} = (.252, .251, .250, .247) \otimes \left| \begin{array}{ccccc} 0.008 & 0.095 & 0.259 & 0.375 & 0.264 \\ 0.005 & 0.061 & 0.322 & 0.383 & 0.230 \\ 0.003 & 0.084 & 0.314 & 0.356 & 0.243 \\ 0.008 & 0.092 & 0.272 & 0.430 & 0.198 \end{array} \right| = (0.006, 0.083, 0.292, 0.386, 0.234)$$

This method was consistently applied across all components to generate their respective MF1 profiles, which are summarized in Table 7 below.

4.5.4. Total Index (ToI) calculation and ranking of LCE components

The Total Index (ToI) for each component was calculated using FSE to assess the significance of LCEs in CMPs. While SL initially held the highest weighting, the ToI rankings revealed a different order, prioritizing components based on their overall impact rather than the number of LCEs.

The ToI for all components is calculated using Equation (14), and the results for the remaining components, as well as the total components, are presented in Table 8. As an illustrative example, the ToI for Resource and Knowledge Availability (RKA) was calculated as:

Table 6

Membership functions (level 2) for lean construction enablers.

Enabler Codes	MF Level 2				
SL1	0.005	0.106	0.325	0.325	0.240
SL2	0.008	0.098	0.322	0.372	0.201
SL3	0.011	0.092	0.251	0.388	0.259
SL4	0.011	0.092	0.264	0.364	0.269
SL5	0.008	0.103	0.309	0.367	0.214
SL6	0.005	0.077	0.298	0.361	0.259
SL7	0.005	0.098	0.272	0.361	0.264
SRM1	0.008	0.092	0.277	0.383	0.240
SRM2	0.008	0.087	0.288	0.396	0.222
SRM3	0.003	0.084	0.325	0.388	0.201
SRM4	0.008	0.098	0.285	0.396	0.214
SRM5	0.003	0.087	0.290	0.385	0.235
RKA1	0.008	0.026	0.364	0.372	0.230
RKA2	0.005	0.026	0.385	0.354	0.230
RKA3	0.008	0.029	0.359	0.385	0.219
RKA4	0.005	0.029	0.314	0.420	0.232
RKA5	0.008	0.034	0.314	0.391	0.253
POE1	0.008	0.092	0.272	0.430	0.198
POE2	0.003	0.084	0.314	0.356	0.243
POE3	0.005	0.061	0.322	0.383	0.230
POE4	0.008	0.095	0.259	0.375	0.264
PIW1	0.008	0.090	0.261	0.393	0.248
PIW2	0.005	0.090	0.277	0.393	0.235
PIW3	0.008	0.077	0.290	0.372	0.253
PIW4	0.008	0.098	0.311	0.372	0.211
PIW5	0.005	0.087	0.317	0.369	0.222
TI1	0.005	0.092	0.309	0.377	0.216
TI2	0.003	0.087	0.325	0.391	0.195
TI3	0.005	0.098	0.332	0.343	0.222
TI4	0.008	0.100	0.343	0.359	0.190

Table 7
Level 1 membership functions (MF1) for LCE constructs.

Constructs	Di				
SL	0.008	0.095	0.291	0.363	0.244
SRM	0.006	0.090	0.293	0.389	0.222
RKA	0.007	0.029	0.347	0.384	0.233
POE	0.006	0.083	0.292	0.386	0.234
PIW	0.007	0.088	0.291	0.380	0.234
TI	0.005	0.094	0.327	0.367	0.206

Table 8
The total Index for the components enhancing LC Adoption in CMPs.

Code	Component	Index	Ranking
RKA	Resource and Knowledge Availability	**3.807**	1
POE	Planning and Operational Efficiency	**3.758**	2
PIW	Process Improvement and Waste Elimination	**3.746**	3
SL	Strategic and Leadership	**3.740**	4
SRM	Stakeholder and Relationship Management	**3.733**	5
TI	Technology and Innovation	**3.674**	6

$$ToI_{\mathrm{RKA}} = (0.007, 0.029, 0.347, 0.384, 0.233) \otimes \begin{pmatrix} 1 \\ 2 \\ 3 \\ 4 \\ 5 \end{pmatrix} = 3.807(1st)$$

Following this approach, the ToI values for all six components were computed and ranked accordingly, as shown in Table 8.

This study identifies and organizes LCEs into a strategic roadmap, offering a clear and actionable pathway to enhance project performance while addressing the unique complexities inherent in CMPs, as illustrated in Fig. 2. Through the prioritization of these enablers using FSE, it becomes evident that all six critical components play a significant role in influencing the successful implementation of lean practices. Among them, Resource and Knowledge Availability (RKA) emerge as the most influential component, with the highest Total Index (ToI) of 3.807, underscoring its foundational importance in driving sustainable lean diffusion.

The prominence of RKA highlights the necessity of ensuring adequate access to both tangible resources and lean-related knowledge across project teams. When teams are equipped with sufficient tools, skilled personnel, and a solid understanding of lean principles, they become better positioned to identify inefficiencies, streamline workflows, and achieve measurable improvements in cost, time, and quality outcomes (Zarifa Zulkeflee et al., 2022). In this context, qualified lean managers and internal champions play a pivotal role. These individuals not only lead by example but also foster a culture of continuous improvement by engaging team members, reinforcing lean values, and sustaining momentum throughout the project lifecycle (Demirkesen and Bayhan, 2020). Moreover, identifying additional champions within the project team is essential to extend the reach of lean initiatives beyond initial planning phases. These champions, often natural leaders with a deep understanding of lean methodologies, can inspire their peers, promote behavioural change, and ensure that lean practices are consistently applied and adapted to evolving project needs (Bhawani et al., 2021). Therefore, addressing knowledge gaps through targeted training and capacity-building initiatives is crucial for empowering employees to adapt lean tools effectively, drive innovation, and contribute meaningfully to lean implementation efforts. Without a strong foundation in Resource and Knowledge Availability, even well-intentioned lean initiatives may struggle to gain traction or deliver lasting impact, further emphasizing its central role in achieving sustainable success in complex megaproject environments.

The second principal component, Planning and Operational Efficiency (POE), ranks second in significance with a Total Index (ToI) of 3.758. As a core enabler of LC diffusion in megaprojects, POE plays a foundational role in driving value creation, optimizing resource utilization, and minimizing waste throughout the project lifecycle. At its core, effective planning involves establishing structured methodologies for implementation, detailed cost and schedule estimation, and logistics systems that are strategically aligned with value-driven objectives (Watfa and Sawalha, 2021). By designing procurement and material movement plans that prioritize value creation, organizations can ensure efficient resource allocation, reduce redundancies, and enhance the seamless flow of both materials and information across complex supply chains.

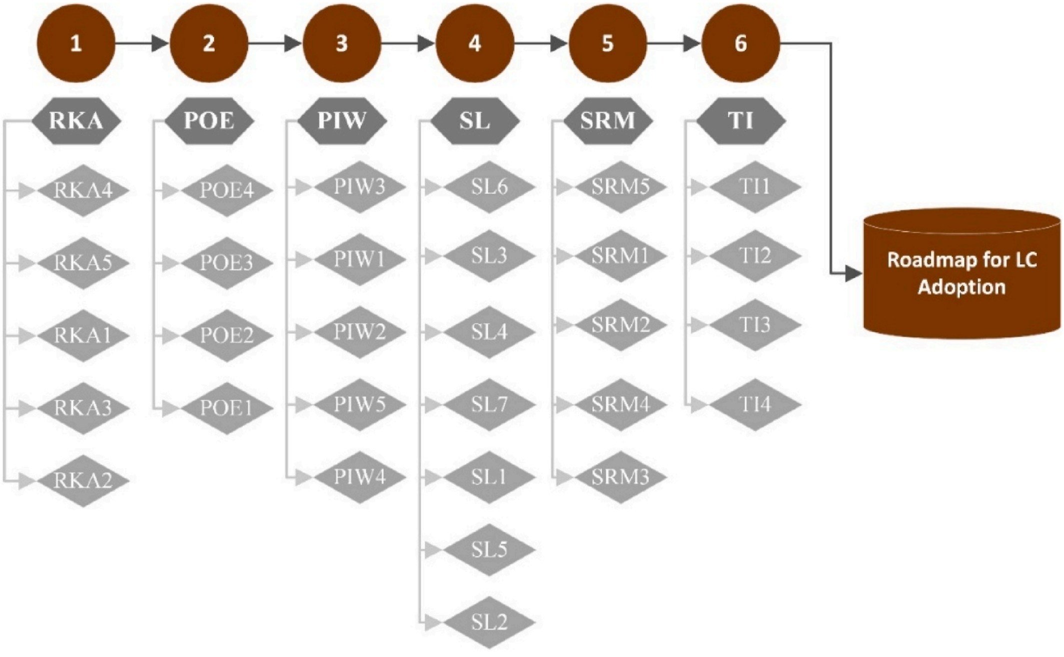

Fig. 2. Roadmap for implementing LC in CMPs.

This strategic alignment of planning processes improves operational clarity and enhances organizational agility. When systematically integrated with lean principles, these practices support streamlined workflows, improved responsiveness to change, and more informed decision-making under uncertainty (Alvim and Galizio, 2020). The application of well-established LC tools, such as the Last Planner System, 5S, Value Stream Mapping, Just-In-Time (JIT), and Pull Flow, further amplifies efficiency by identifying and eliminating bottlenecks, reducing idle time, and fostering continuous workflow improvements (Agrawal et al., 2024; Gao and Low, 2014). These tools serve as practical mechanisms that empower teams to maintain high levels of productivity and adaptability, even in the dynamic and unpredictable environments typical of large-scale construction projects. Equally important is the role of visual management techniques, which significantly enhance communication and transparency across all project phases. These tools enable real-time progress tracking, early issue detection, and swift corrective actions, capabilities that are especially critical in megaprojects where delays can trigger cascading disruptions. Given the inherent complexity of such projects, characterized by multiple stakeholders, interdependent tasks, and evolving requirements, comprehensive coordination and flexibility become essential success factors. Effective coordination ensures the seamless integration of diverse processes, minimizes conflicts, and maintains adaptability in response to shifting conditions (Zegarra and Alarcón, 2019). By focusing on these factors, POE significantly strengthens its lean adoption strategies, streamlines operations, and successfully delivers complex, large-scale CMPs with improved outcomes.

The third most influential component identified in this study is Process Improvement and Waste Elimination (PIW), which ranks third with a Total Index (ToI) of 3.746. PIW plays a central role in advancing LC practices within megaprojects by focusing on enhancing efficiency and reducing non-value-adding activities that hinder project performance. After developing a lean plan, the next step involves identifying strategies to track alignment and drive continuous improvement (Sarhan, S., Pasquire, C., Elnokaly, A., and Pretlove, 2019). Tools such as monthly scorecards, project dashboards, and self-reported surveys are practical for monitoring progress and ensuring alignment (Bhawani et al., 2021). Eliminating waste, such as double handling, material constraints, scrap, and changeovers, streamline operations, reduces costs, and enhances productivity (Sweis et al., 2016). Reducing variability and cycle time ensures greater predictability and consistency, minimizing delays and improving task completion rates (Bajjou and Chafi, 2018). Standardized metrics, such as Percent Plan Complete (PPC), quality, and productivity metrics, help track performance and foster a culture of continuous improvement. Benchmarking with industry leaders allows organizations to adopt best practices, stay competitive, and achieve higher efficiency (Ying et al., 2022). These monitoring and improvement tools facilitate early identification and resolution of inefficiencies, ultimately enhancing project outcomes regarding quality, cost, and schedule adherence.

The fourth principal component, Strategic and Leadership (SL), ranks fourth with a Total Index (ToI) of 3.74. SL enablers are critical drivers for LC diffusion in megaprojects, as they align organizational strategy with lean principles and ensure strong leadership commitment (Yadav et al., 2023). Financial capability is crucial, as it determines the ability to invest in lean tools, training, and resources, without which lean adoption may be hindered (Shurrab and Hussain, 2018). Enhancing awareness of lean principles ensures stakeholders are informed and motivated to embrace lean strategies, fostering a culture of continuous improvement (Aslam et al., 2020). Support from government bodies and senior management also plays a pivotal role, as policy frameworks and regulatory incentives can drive lean adoption across the industry (Idrissi Gartoumi et al., 2024). A well-defined strategic vision from the early stages ensures that lean practices are embedded into project planning and execution, creating alignment and clarity in objectives (Moaveni et al., 2019). Incentive structures, such as tax rebates, public subsidies, or performance-linked rewards, serve as powerful motivators for contractors and developers to prioritize lean methodologies (Sadikoglu et al., 2024). Crucially, active commitment from both top management and middle-tier leaders is indispensable; their engagement signals organizational priority and facilitates bottom-up implementation (Sarhan et al., 2020). Moreover, clients and lead contractors who exhibit strong lean-oriented leadership foster an environment of trust, cross-organizational collaboration, and knowledge exchange, reinforcing adherence to lean values throughout the project lifecycle (Saini et al., 2018). Collectively, these strategic and leadership-oriented enablers establish the vision, institutional support, and motivational infrastructure necessary to embed lean practices meaningfully within the intricate ecosystems of megaprojects.

The fifth principal component, Stakeholder and Relationship Management (SRM), ranks fifth with a Total Index (ToI) of 3.733. SRM is a crucial enabler for LC diffusion in megaprojects, as it fosters collaboration and maintains strong relationships among all project participants (Li et al., 2021). Successful lean diffusion relies on stakeholder alignment to meet their needs while minimizing conflicts and inefficiencies. Effective stakeholder management and trust-building create a collaborative environment, enhancing communication and decision-making for smooth lean implementation (Ying et al., 2022). By fostering open communication and mutual understanding, SRM contributes to a more cooperative environment, supporting efficient decision-making and smoother execution of lean strategies. A key element of SRM is the definition of value from the customer's perspective, which ensures that project outcomes align with client requirements and deliver maximum utility (Bajjou and Chafi, 2018). Addressing these expectations not only enhances satisfaction but also minimizes unnecessary expenditures and inefficiencies (Sarhan et al., 2020). Furthermore, involving key stakeholders early in the project lifecycle enables the integration of lean principles from the initial planning stages, facilitating proactive identification of potential challenges and shared goal setting (Alsehaimi et al., 2014). Establishing strong interpersonal and institutional relationships reinforces commitment to lean values and promotes a culture of collaboration and accountability (Abusalem, 2020). These SRM-related enablers significantly contribute to creating a unified, transparent, and value-driven project environment, which is essential for the effective adoption and sustainability of lean practices in CMPs.

The sixth principal component, Technology and Innovation (TI), ranks last with a Total Index (ToI) of 3.674. Despite its lower ranking, TI is a pivotal enabler for LC diffusion in megaprojects, enabling the use of cutting-edge tools and processes that optimize efficiency and reduce waste (Idrissi Gartoumi et al., 2024). Innovative technologies streamline operations and support lean goals such as value creation, continuous improvement, and waste elimination (Najafi et al., 2024; Yadav et al., 2023). Adopting new construction technologies, such as BIM, improving project coordination, visualization, and data management, enhancing planning and execution, while reducing errors (Li et al., 2021). Modular Integrated Construction promotes prefabrication and standardization, reducing construction time, material waste, and improving quality control (Goh and Goh, 2019). Integrating CE principles reduces waste, lowers carbon emissions, and optimizes resource use, aligning with Lean's sustainability goals (Benachio et al., 2021). Advanced technologies like Digital Twin and Blockchain enhance project monitoring, real-time data tracking, and transparent information sharing, improving decision-making and reducing risks (Altan and Işık, 2023; Kifokeris and Tezel, 2023). Together, these TI enablers drive efficiency, sustainability, and innovation, contributing to the successful diffusion of LC in megaprojects.

5. Toward context-responsive lean sustainability: Theoretical anchoring, empirical validation, and boundary conditions for global transfer

While the identified LCEs demonstrate strong internal coherence with sustainability frameworks (e.g., 3P, TBL), their operational relevance extends only as far as their contextual validity. Megaprojects are inherently embedded in institutional ecosystems, shaped by regulation, culture, and procurement norms, that mediate how, when, and whether enablers like Resource and Knowledge Availability or Strategic Leadership can be effectively deployed. This section therefore moves beyond what matters to where and why it works, integrating theoretical alignment with critical reflection on boundary conditions. By anchoring the framework in existing sustainability literature (5.1) and explicitly examining its transferability beyond the Chinese context (5.2), we position lean not as a universal template, but as a context-responsive strategy, one whose scalability depends on deliberate adaptation, not replication.

5.1. Theoretical synergies: aligning LCEs with sustainability frameworks (3P, TBL, and stakeholder governance)

The prioritized LCEs identified in this study align closely with the key dimensions and frameworks proposed in the literature on sustainability in megaprojects. The emphasis on Resource and Knowledge Availability (RKA), Planning and Operational Efficiency (POE), and Process Improvement and Waste Elimination (PIW) reflects the foundational role of people, process, and performance measurement, elements central to the 3P framework (Purpose, People, Process) introduced by Wang et al. (2020). By investing in lean-capable human resources, embedding standardized metrics, and reducing waste through continuous improvement practices, this research supports the integration of lean principles into broader sustainable development strategies for megaprojects. Moreover, the findings resonate with conceptual models that link sustainability with influencing factors such as stakeholder engagement, governance, and risk management (Chen et al., 2021; Thounaojam and Laishram, 2022). The high ranking of Strategic and Leadership (SL) and Stakeholder and Relationship Management (SRM) enablers underscores the importance of proactive leadership commitment and collaborative stakeholder involvement, both of which are essential for embedding sustainability across all project phases. This aligns with Romestant (2020) and Senaratne et al. (2024), who stress that meaningful sustainability outcomes require early and active engagement of diverse stakeholders to address socio-economic and environmental concerns. Additionally, the prioritization of Measurement & Improvement and Waste Elimination ties directly to the Triple Bottom Line (TBL) concept, particularly the ecological and economic pillars. The use of lean KPIs, such as material waste rates and defect tracking, complements advanced risk assessment tools like RAMSCOM and ANP-BOCR (Coskun et al., 2023; Subaie et al., 2023), contributing to more responsible resource use and cost efficiency in large-scale projects.

Finally, while Technology and Innovation (TI) ranked lowest among the constructs, its positioning as an enabler to be adopted after foundational lean capabilities mirrors recent calls for technology integration within a robust sustainability framework (Cottafava et al., 2024). Emphasizing digital tools like BIM and CE principles in design and procurement phases aligns with efforts to enhance transparency, reduce environmental impact, and support long-term sustainable value creation.

5.2. Boundary conditions and transfer protocol: From local calibration to global relevance

While the FRII–FSE framework was empirically calibrated using data from 379 professionals in Mainland China and Hong Kong, its broader applicability must account for contextual contingencies across regulatory, cultural, and contractual landscapes. Three key implementation challenges arise when transferring the framework internationally:

First, regulatory misalignment may hinder enabler sequencing. For instance, in jurisdictions where labor mobility is restricted (e.g., some Gulf states), RKA, particularly “availability of experienced lean leaders” (RKA1), may require supplementation with localized upskilling or expatriate mentorship, rather than direct recruitment. Similarly, in environments where sustainability mandates are weak, TI enablers like circular economy (TI3) may lack policy or market pull, necessitating SRM-driven value co-creation (e.g., client–contractor green incentives) to compensate. Second, cultural norms shape lean readiness. High power-distance cultures (e.g., Egypt, Malaysia) may accelerate SL-driven top-down lean mandates but resist POE/PIW bottom-up process improvements (e.g., frontline waste walks), requiring middle-management “lean champions” to bridge the gap. Conversely, in low-uncertainty-avoidance contexts (e.g., Netherlands, Australia), adaptive planning (RKA5, POE4) is more readily accepted, whereas in high-uncertainty settings, rigid baseline plans may initially prevail, demanding stronger change-management support (SL2, SL7). Third, contractual fragmentation limits system-level diffusion. In adversarial procurement models (e.g., traditional design-bid-build in the U.S.), the foundation phase (RKA + SRM) may need to be contracted at the owner level (e.g., integrated briefing + prequalification of lean-capable bidders), rather than left to individual contractors. Hybrid models, such as embedding lean KPIs (e.g., PPC ≥80%) into FIDIC Red Book performance clauses, can create contractual “hooks” for lean without overhauling procurement.

To mitigate these challenges, we recommend a three-step transfer protocol:

1. Diagnostic assessment of institutional readiness (e.g., using a lean maturity matrix).
2. Contextual recalibration of construct weights (e.g., via localized FSE using regional expert panels); and
3. Phased piloting, starting with low-risk, high-visibility packages (e.g., site logistics under POE) before scaling to design or supply-chain integration.

A promising avenue to enrich this forward-looking agenda is the integration of patent-based prospective Life Cycle Assessment (LCA), as advanced by Spreafico (2025). By analyzing global patent filings (e.g., in WIPO or USPTO databases), one can identify emerging lean-digital innovations (e.g., AI-powered Last Planner optimization, blockchain-based waste tracking, or prefabrication robotics) and project their potential environmental impacts prior to market diffusion. This enables early assessment of trade-offs, such as the energy footprint of digital twins versus their potential to reduce rework-related emissions, thereby informing eco-design at the strategy level. When combined with our FRII–FSE framework, patent-based LCA could transform TI from the lowest-ranked current enabler (ToI = 3.674) into a prospectively weighted pillar, guiding policymakers in aligning R&D investments, procurement incentives (e.g., green patents in prequalification), and upskilling pathways with high-impact, low-regret innovation trajectories.

6. Implications

This study identifies six key constructs that enable the successful diffusion of LC in megaprojects: RKA, POE, PIW, SL, SRM, and TI. Based on their prioritization, the following strategic implications are derived:

(i) Build lean capacity: RKA was ranked highest, underscoring the need for training programs, recruitment of lean leaders, and internal knowledge systems to support sustainable implementation.

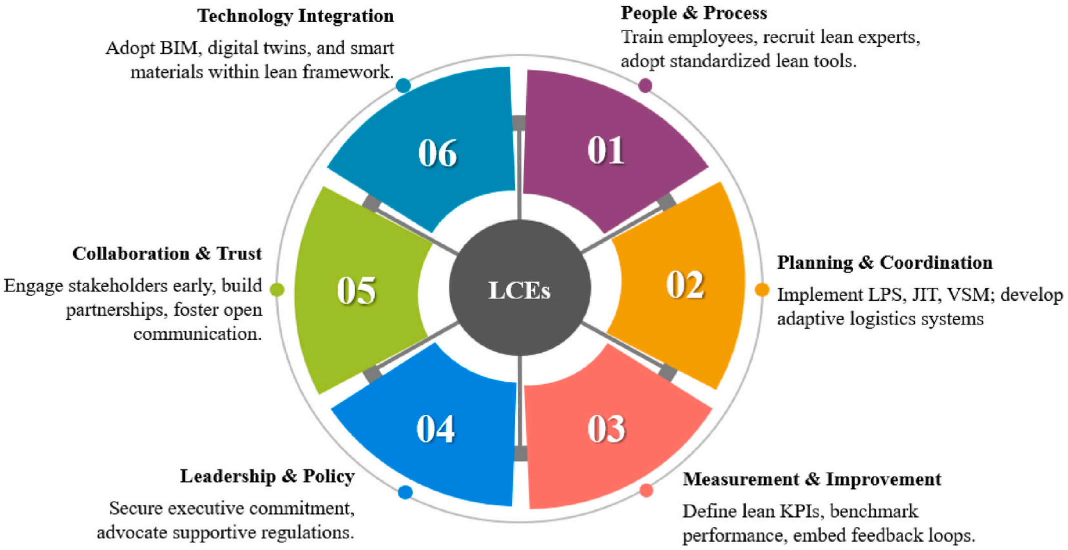

Fig. 3. Radar diagram of LCEs prioritized for sustainable megaprojects.

(ii) Improve planning and coordination: POE emphasizes the importance of lean tools like LPS, VSM, and JIT to reduce delays and enhance real-time decision-making.
(iii) Standardize performance metrics: PIW highlights the need for consistent KPIs (e.g., waste rates, PPC) and continuous improvement practices such as root cause analysis.
(iv) Secure leadership commitment: SL shows that visible support from top management and policy incentives from government are essential for embedding lean at scale.
(v) Foster stakeholder collaboration: SRM reinforces the value of early engagement, trust-building, and collaborative problem-solving to align expectations and reduce conflict.
(vi) Integrate technology strategically: TI ranks lowest, suggesting it should complement, not replace, lean fundamentals like process discipline and waste reduction.

A visual roadmap (Fig. 3) illustrates how these enablers must work together, with human and process capabilities forming the foundation, followed by planning, measurement, and leadership support. Technology integration is positioned as a secondary enabler, most effective when built upon established lean maturity. These findings offer actionable guidance for practitioners and policymakers seeking to implement LC principles sustainably within complex megaproject environments.

While the FSE-based ranking establishes what enablers matter most (RKA > POE > PIW > SL > SRM > TI), successful LC diffusion requires who does what, when, and how. To enhance practical relevance, this section proposes a stakeholder-stratified roadmap, structured around three implementation phases aligned with lean maturity:

(i) Foundation Phase (RKA + SRM): Build capability & trust
(ii) Execution Phase (POE + PIW): Optimize workflows & eliminate waste
(iii) Transformation Phase (SL + TI): Institutionalize & scale innovation

Guided by the empirical ToI scores and enabler-level insights, the following role-specific pathways ensure coordinated, context-aware adoption, particularly critical in China's fragmented megaproject ecosystem.

6.1. *Owners/construction units (e.g., Government Agencies, developers)*

As agenda-setters, owners should drive LC diffusion in three phases: (1) Foundation, mandate ≥2 lean-certified staff per team and fund lean academies (RKA), while co-creating Integrated Partnering Charters with shared KPIs (SRM); (2) Execution, tie payments to lean performance metrics (e.g., PPC ≥85%, defect rate ≤2%) (POE/PIW); and (3) Transformation, advocate policy incentives (e.g., tax rebates, lean-based prequalification) (SL). Critically, technology mandates (e.g., BIM) should be deferred until RKA and POE foundations are verified, ensuring tools enable, rather than substitute for, lean maturity.

6.2. *Contractors (general & trade subcontractors)*

Contractors, as on-site executors, should advance LC in three phases: (1) Foundation, deliver JIT lean upskilling (e.g., 5S/toolbox training pre-task): and maintain a lean knowledge repository (RKA), while assigning coordination liaisons for inter-trade alignment (SRM); (2) Execution, implement LPS® with pull sequencing, digital 5S boards, and cross-trade hubs (POE), alongside weekly waste walks and root-cause defect logs (PIW); (3) Transformation, tie middle-management bonuses to lean KPIs (e.g., PPC, rework %) (SL), and deploy BIM only after POE workflows stabilize, ensuring tech augments, not disrupts, process discipline.

6.3. *Design Firms*

Design Firms, as value shapers, should embed LC early in three phases: (1) Foundation, co-locate BIM coordinators on-site and co-define customer value profiles with end-users (SRM); (2) Execution, apply BIM-integrated VSM and DfMA to eliminate rework and material waste (POE/PIW); (3) Transformation, pioneer modular/circular design (e.g., reusable components) (TI), but only when RKA (designer competency) and POE (planning reliability) are mature.

6.4. *Supervision/consulting units*

Supervision Units, as assurance providers, must evolve from auditors to lean coaches: (1) Foundation, audit lean readiness (e.g., training logs, adaptive planning): (RKA); (2) Execution, monitor lean performance via scorecards tracking PPC, visual controls, and defect rates, not just safety/compliance (POE/PIW) (3) Transformation, certify lean milestones (e.g., “RKA Achieved”); to trigger milestone payments (SL), institutionalizing LC as a contractual deliverable.

6.5. Material & equipment suppliers

Material Suppliers, as flow enablers, should support lean logistics in three phases: (1) Foundation, co-develop adaptive JIT plans using shared demand forecasts (RKA); (2) Execution, deliver kitted/sequenced materials and real-time inventory dashboards to reduce buffer stock and handling (POE/PIW) (3) Transformation, launch CE take-back schemes (e.g., for reusable formwork); (TI), contingent on stable POE coordination and RKA planning capacity.

6.6. Government & regulatory bodies

Government Agencies, as system shapers, should enable lean diffusion strategically: (1) Foundation & Execution, issue minimum lean competency requirements and fund pilot projects (RKA/SRM); (2) Transformation, embed lean criteria in national procurement (e.g., prequalification, tax rebates) and fund public–private lean-digital testbeds (SL/TI), but prioritize capability-building (RKA/POE) over tech mandates, recognizing that LC maturity must precede digital scaling.

7. Conclusion

This study develops a comprehensive framework to support the diffusion of Lean Construction (LC) in CMPs, with a focus on the Chinese context. Unlike prior LC enabler studies focused on small-scale or single-method assessments, this work advances implementation science by integrating fuzzy multi-criteria evaluation with megaproject-specific contextualization, enabling practitioners to sequence interventions in alignment with resource readiness. Using a mixed-methods approach, including mean score analysis, FRII, and Fuzzy Synthetic Evaluation (FSE), the research identifies and prioritizes 30 key LC Enablers (LCEs), grouped into six constructs: Resource and Knowledge Availability (RKA), Planning and Operational Efficiency (POE), Process Improvement and Waste Elimination (PIW), Strategic Leadership (SL), Stakeholder Relationship Management (SRM), and Technology Integration (TI). Among these, RKA emerged as the most influential, emphasizing the need for skilled personnel, training programs, and knowledge-sharing systems. While TI ranked lowest, it is still seen as a strategic complement to foundational lean practices rather than a driver. The findings align with sustainability frameworks such as the Triple Bottom Line (TBL) and 3P model (Purpose, People, Process), demonstrating how lean principles can advance SDG 9 (industrial innovation), SDG 11 (sustainable cities), and SDG 12 (responsible consumption). By linking lean practices with sustainability goals, this study offers actionable insights for practitioners and policymakers aiming to improve performance and reduce environmental impacts in megaprojects.

Despite its contributions, the study focuses on China, limiting generalizability across different regulatory and cultural contexts. Additionally, while LCEs were validated through quantitative modeling, real-world case studies are needed to test their practical applicability. Moreover, while FSE provides a mathematically sound mechanism to synthesize subjective inputs, its outputs remain contingent on the sample's professional background, regional norms, and lean exposure, underscoring the need for contextual recalibration before applying the framework in other megaproject ecosystems (e.g., Middle East, Sub-Saharan Africa, or Latin America). This study's outcomes provide a foundation for future research aimed at integrating advanced digital technologies and sustainability strategies with LC frameworks to enhance performance and reduce waste in megaprojects. Specifically, the application of Digital Twin (DT) technology offers significant potential for enabling real-time data integration, simulation-based decision-making, and lifecycle performance monitoring, thereby supporting dynamic lean interventions across complex construction workflows. Similarly, Blockchain technology can be leveraged to enhance transparency, traceability, and smart contract automation within lean supply chains, addressing key challenges related to procurement inefficiencies, supplier accountability, and information asymmetry. Additionally, embedding CE principles into LC practices presents a strategic pathway for minimizing material waste, extending resource lifecycles, and promoting regenerative design approaches. Future studies should focus on developing integrated models that systematically align DT, Blockchain, and CE strategies with the prioritized LCEs identified in this research. Also, future studies could apply this framework across megaproject phases (e.g., planning vs. construction) via repeated surveys or case-based longitudinal tracking, to quantify how enabler weights shift in response to evolving complexity, risk, and stakeholder maturity. These efforts will advance theoretical understanding and support the practical implementation of digitally enabled, sustainable lean systems in megaproject environments, contributing to operational efficiency and environmental sustainability goals.

CRediT authorship contribution statement

Abdelazim Ibrahim: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Conceptualization. **Tarek Zayed:** Writing – review & editing, Supervision, Resources. **Zoubeir Lafhaj:** Writing – review & editing, Supervision. **Ahmed Farouk Kineber:** Writing – review & editing, Resources. **Ghasan Alfalah:** Writing – review & editing, Supervision, Resources. **Jingchao Yang:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This paper's publication is supported by the Ongoing Research Funding Program (ORF-2025-899), King Saud University, Riyadh, Saudi Arabia.

Data availability

Data will be made available on request.

References

Abu Aisheh, Y.I., Tayeh, B.A., Alaloul, W.S., Almalki, A., 2022. Health and safety improvement in construction projects: a lean construction approach. Int. J. Occup. Saf. Ergon. 28, 1981–1993. https://doi.org/10.1080/10803548.2021.1942648.

Abusalem, O., 2020. Towards last planner system implementation in Gaza Strip, Palestine. Int. J. Constr. Manag. 20, 367–384. https://doi.org/10.1080/15623599.2018.1484861.

Adhi, A.B., Muslim, F., 2023. Development of stakeholder engagement strategies to improve sustainable construction implementation based on lean construction principles in Indonesia. Sustainability (Switzerland) 15. https://doi.org/10.3390/su15076053.

Agrawal, A.K., Zou, Y., Chen, L., Abdelmegid, M.A., González, V.A., 2024. Moving toward lean construction through automation of planning and control in last planner system: a systematic literature review. Dev. Built Environ. 18. https://doi.org/10.1016/j.dibe.2024.100419.

Akadiri, O.P., 2011. Development of a multi-criteria Approach for the Selection of Sustainable Materials for Building Projects. PhD Thesis - University of Wolverhampton, pp. 1–437.

Ali, A.H., Zayed, T., Abdulai, S.F., Wang, R.D., 2024. A comprehensive framework for examining the influence of tower crane safe operations on sustainable practices in modular integrated construction. Eng. Constr. Archit. Manag. https://doi.org/10.1108/ECAM-05-2024-0657.

Alnaser, A.A., Ali, A.H., Elmousalami, H.H., Elyamany, A., Gouda Mohamed, A., 2024. Assessment framework for BIM-digital twin readiness in the construction industry. Buildings 14, 1–26. https://doi.org/10.3390/buildings14010268.

Alsehaimi, A.O., Fazenda, P.T., Koskela, L., 2014. Improving construction management practice with the last planner system: a case study. Eng. Constr. Archit. Manag. 21, 51–64. https://doi.org/10.1108/ECAM-03-2012-0032.

Altan, E., Işık, Z., 2023. Digital twins in lean construction: a neutrosophic AHP – BOCR analysis approach. Eng. Constr. Archit. Manag. 31, 5029–5056. https://doi.org/10.1108/ECAM-11-2022-1115.

Alvim, S., Galizio, O., 2020. Lean supply chain management: a lean approach applied to distribution-a literature review of the concepts, challenges and trends. J. Lean Syst. 1–20.

Ansar, A., Flyvbjerg, B., Budzier, A., Lunn, D., 2017. Big IS fragile: an attempt at theorizing scale. Oxford Handbook Megaproject Manag. 1, 60–95.

Arabi, S., Bajjou, M.S., Chafi, A., El Hammoumi, M., 2022. Evaluation of critical success factors (CSFs) to lean implementation in Moroccan SMEs: a survey study. 2022 2nd Int. Conf. Innov. Res. App. Sci Engi. Technol. IRASET 2022, 1–10. https://doi.org/10.1109/IRASET52964.2022.9737950.

Aslam, M., Gao, Z., Smith, G., 2020. Exploring factors for implementing lean construction for rapid initial successes in construction. J. Clean. Prod. 277, 123295. https://doi.org/10.1016/j.jclepro.2020.123295.

Aslam, M., Gao, Z., Smith, G., Huang, Y., Orr, M., 2022. Development of Interpretative Structural Modelling (ISM) based lean construction implementation framework. Lean Constr. J.

Ayarkwa, J., Joe Opoku, D.G., Antwi-Afari, P., Man Li, R.Y., 2022. Sustainable building processes' challenges and strategies: the relative important index approach. Clean Eng. Technol. 7, 100455. https://doi.org/10.1016/j.clet.2022.100455.

Azhar, S., 2011. Building Information Modeling (BIM): trends, benefits, risks, and challenges for the AEC industry. Leader. Manag. Eng. 11, 241–252. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127.

Babalola, O., Ibem, E.O., Ezema, I.C., 2019. Implementation of lean practices in the construction industry: a systematic review. Build. Environ. 148, 34–43. https://doi.org/10.1016/j.buildenv.2018.10.051.

Bajjou, M.S., Chafi, A., 2018. The potential effectiveness of lean construction principles in reducing construction process waste: an input-output model. J. Mech. Eng. Sci. 12, 4141–4160.

Ballard, G., Kim, Y.-W., 2007. Roadmap for lean implementation at the project level sustainable construction view project lean and green view project. Constr. Industry Inst.

Ballard, G., Tommelein, I., 2012. Lean management methods for complex projects. Eng. Proj. Organ. J. 2, 85–96. https://doi.org/10.1080/21573727.2011.641117.

Bayhan, H.G., Demirkesen, S., Jayamanne, E., 2019. Enablers and barriers of lean implementation in construction projects. IOP Conf. Ser. Mater. Sci. Eng. 471. https://doi.org/10.1088/1757-899X/471/2/022002.

Benachio, G.L.F., Freitas, M. do C.D., Tavares, S.F., 2021. Interactions between lean construction principles and circular economy practices for the construction industry. J. Construct. Eng. Manag. 147. https://doi.org/10.1061/(asce)co.1943-7862.0002082.

Bhawani, S., Messner, J., Leicht, R., 2021. Key planning steps enabling systematic lean implementation on construction projects. Lean Constr. J. 2021, 204–227.

Chan, D.W.M., Olawumi, T.O., Saka, A.B., Ekundayo, D., 2024. Comparative analysis of the barriers to smart sustainable practices adoption in the construction industry between Hong Kong and Nigeria. Int. J. Constr. Manag. 24, 1499–1509. https://doi.org/10.1080/15623599.2022.2108973.

Chen, X., Wang, T., Liu, Y., Dou, Z., 2024. Configurational path to collaborative innovation in large and complex construction projects. Buildings 14, 117. https://doi.org/10.3390/buildings14010117.

Chen, Z., Agapiou, A., Li, H., Xu, Q., 2021. A TRIZ approach to reliable megaproject sustainability. Front Built Environ. 7. https://doi.org/10.3389/fbuil.2021.650699.

Cheung, S.O., Shen, L., 2017. Concentration analysis to measure competition in megaprojects. J. Manag. Eng. 33. https://doi.org/10.1061/(asce)me.1943-5479.0000464.

Coskun, C., Dikmen, I., Birgonul, M.T., 2023. Sustainability risk assessment in mega construction projects. Built. Environ. Proj. Asset. Manag. 13, 700–718. https://doi.org/10.1108/BEPAM-10-2022-0153.

Cottafava, D., Corazza, L., Shams Esfandabadi, Z., Torchia, D., 2024. Megaprojects from the lens of business and management studies: a systematic literature review. J. Publ. Aff. 24. https://doi.org/10.1002/pa.2937.

Landis, J.D., 2022. The megaproject challenge. In: Megaprojects for Megacities. Edward Elgar Publishing, pp. 1–39. https://doi.org/10.4337/9781803920634.00007.

Demirkesen, S., Bayhan, H.G., 2022. Critical success factors of lean implementation in the construction industry. IEEE Trans. Eng. Manag. 69, 2555–2571. https://doi.org/10.1109/TEM.2019.2945018.

Demirkesen, S., Bayhan, H.G., 2020. A lean implementation success model for the construction industry. EMJ - Eng. Manag. J. 32, 219–239. https://doi.org/10.1080/10429247.2020.1764834.

El-Sabek, L.M., McCabe, B.Y., 2017. Coordination challenges of production planning & control in international mega-projects: a case study. Lean Constr. J. 2017, 25–29.

Eriksson, P.E., Larsson, J., Pesämaa, O., 2017. Managing complex projects in the infrastructure sector — a structural equation model for flexibility-focused project management. Int. J. Proj. Manag. 35, 1512–1523. https://doi.org/10.1016/j.ijproman.2017.08.015.

Evans, M., Farrell, P., 2023. A strategic framework managing challenges of integrating lean construction and integrated project delivery on construction megaprojects, towards global integrated delivery transformative initiatives in multinational organisations. J. Eng. Des. Technol. 21, 376–416. https://doi.org/10.1108/JEDT-08-2021-0402.

Evans, M., Farrell, P., 2021. Barriers to integrating building information modelling (BIM) and lean construction practices on construction mega-projects: a Delphi study. Benchmarking 28, 652–669. https://doi.org/10.1108/BIJ-04-2020-0169.

Evans, M., Farrell, P., Elbeltagi, E., Dion, H., 2023. Barriers to integrating lean construction and integrated project delivery (IPD) on construction megaprojects towards the global integrated delivery (GID) in multinational organisations: lean IPD&GID transformative initiatives. J. Eng. Des. Technol. 21, 778–818. https://doi.org/10.1108/JEDT-02-2021-0070.

Evans, M., Farrell, P., Mashali, A., Zewein, W., 2021. Critical success factors for adopting building information modelling (BIM) and lean construction practices on construction mega-projects: a Delphi survey. J. Eng. Des. Technol. 19, 537–556. https://doi.org/10.1108/JEDT-04-2020-0146.

Flores, G., Ollero, C., 2013. Productivity improvement applying production management in projects with repetitive activities. Proc. 21st Annual Conference of the International Group for Lean Construction, pp. 160–169.

Flyvbjerg, B., 2017. Introduction: the iron law of megaproject management. Oxford Handbook Megaproject Manag. 1–18.

Flyvbjerg, B., 2014. What you should know about megaprojects and why: an overview. Proj. Manag. J. 45, 6–19. https://doi.org/10.1002/pmj.21409.

Francis, A., Thomas, A., 2020. Exploring the relationship between lean construction and environmental sustainability: a review of existing literature to decipher broader dimensions. J. Clean. Prod. 252. https://doi.org/10.1016/j.jclepro.2019.119913.

Gao, S., Low, S.P., 2014. The last planner system in China's construction industry — a SWOT analysis on implementation. Int. J. Proj. Manag. 32, 1260–1272. https://doi.org/10.1016/j.ijproman.2014.01.002.

Genc, O., 2023. Identifying principal risk factors in Turkish construction sector according to their probability of occurrences: a relative importance index (RII) and exploratory factor analysis (EFA) approach. Int. J. Constr. Manag. 23, 979–987. https://doi.org/10.1080/15623599.2021.1946901.

Geraldi, J., Maylor, H., Williams, T., 2011. Now, let's make it really complex (complicated). Int. J. Oper. Prod. Manag. 31, 966–990. https://doi.org/10.1108/01443571111165848.

Goh, M., Goh, Y.M., 2019. Lean production theory-based simulation of modular construction processes. Autom. ConStruct. 101, 227–244. https://doi.org/10.1016/j.autcon.2018.12.017.

Guo, S., Zhao, H., 2017. Fuzzy best-worst multi-criteria decision-making method and its applications. Knowl. Base Syst. 121, 23–31. https://doi.org/10.1016/j.knosys.2017.01.010.

Hasan, S., Işık, Z., Demirdöğen, G., 2024. Evaluating the contribution of lean construction to achieving sustainable development goals. Sustainability (Switzerland) 16. https://doi.org/10.3390/su16083502.

He, Q., Luo, L., Hu, Y., Chan, A.P.C., 2015. Measuring the complexity of mega construction projects in China-A fuzzy analytic network process analysis. Int. J. Proj. Manag. 33, 549–563. https://doi.org/10.1016/j.ijproman.2014.07.009.

Howell, G.A., Ballard, G., 1998. Implementing lean construction: understanding and action. 6th Annual Conference of the International Group for Lean Construction 1–9.

Hwang, B.G., Shan, M., Looi, K.Y., 2018a. Knowledge-based decision support system for prefabricated prefinished volumetric construction. Autom. ConStruct. 94, 168–178. https://doi.org/10.1016/j.autcon.2018.06.016.

Hwang, B.G., Shan, M., Looi, K.Y., 2018b. Key constraints and mitigation strategies for prefabricated prefinished volumetric construction. J. Clean. Prod. 183, 183–193. https://doi.org/10.1016/j.jclepro.2018.02.136.

Hwang, B.G., Shan, M., Xie, S., Chi, S., 2017. Investigating residents' perceptions of green retrofit program in mature residential estates the case of Singapore. Habitat Int. 63, 103–112. https://doi.org/10.1016/j.habitatint.2017.03.015.

Ibrahim, A., Abdelkhalek, S., Zayed, T., Meshref, A.N., 2025a. Assessment of lean construction practices in developing countries using fuzzy relative importance index. Eng. Manag. J. 1–21. https://doi.org/10.1080/10429247.2025.2536551.

Ibrahim, A., Abdelkhalek, S., Zayed, T., Qureshi, A.H., Mohammed Abdelkader, E., 2024a. A comprehensive review of the key deterioration factors of concrete bridge decks. Buildings 14. https://doi.org/10.3390/buildings14113425.

Ibrahim, A., Faris, N., Zayed, T., Qureshi, A.H., Abdelkhalek, S., Abdelkader, E.M., 2024b. Application of infrared thermography in concrete bridge deck inspection: current practices, challenges and future needs. Nondestr. Test. Eval. 1–44. https://doi.org/10.1080/10589759.2024.2443810, 00.

Ibrahim, A., Zayed, T., Lafhaj, Z., 2025b. Trends and gaps in lean construction practices for construction of megaprojects : a critical review. Alex. Eng. J. 118, 174–193. https://doi.org/10.1016/j.aej.2025.01.046.

Ibrahim, A., Zayed, T., Lafhaj, Z., 2025c. A comprehensive model for lean construction practices for sustainable megaproject delivery. Sustain. Dev. https://doi.org/10.1002/sd.70313.

Ibrahim, A., Zayed, T., Lafhaj, Z., 2025d. Bridging barriers to lean construction adoption in megaprojects: a data-driven contribution to sustainable development using SEM. Environ. Dev. Sustain. https://doi.org/10.1007/s10668-025-06424-9.

Ibrahim, A., Zayed, T., Lafhaj, Z., 2025e. Prioritizing lean construction practices for effective megaproject delivery. In: Annual Conference of the International Group for Lean Construction, IGLC. International Group for Lean Construction, pp. 70–81. https://doi.org/10.24928/2025/0145.

Idrissi Gartoumi, K., Aboussaleh, M., Zaki, S., 2024. Implementing lean construction to improve quality and megaproject construction: a case study. J. Finan. Manag. Property Constr. 29, 1–22. https://doi.org/10.1108/JFMPC-12-2022-0063.

Kariyawasam, D.T., Siriwardana, C.S.A., 2021a. Feasibility study on, enablers and barriers for the implementation of lean construction and the applicability of visual management practices through forms of digital communication in the Sri Lankan industry. Mercon 2021 - 7th International Multidisciplinary Moratuwa Engineering

Research Conference. Proceedings, pp. 681–686. https://doi.org/10.1109/MERCon52712.2021.9525758.

Kariyawasam, D.T., Siriwardana, C.S.A., 2021b. Feasibility study on, enablers and barriers for the implementation of lean construction and the applicability of visual management practices through forms of digital communication in the Sri Lankan industry. Mercon 2021 - 7th International Multidisciplinary Moratuwa Engineering Research Conference. Proceedings, pp. 681–686. https://doi.org/10.1109/MERCon52712.2021.9525758.

Kifokeris, D., Tezel, A., 2023. Blockchain and lean construction: an exploration of bidirectional synergies and interactions. Architect. Eng. Des. Manag. 1–19. https://doi.org/10.1080/17452007.2023.2263873.

Koseoglu, O., Sakin, M., Arayici, Y., 2018. Exploring the BIM and lean synergies in the Istanbul Grand Airport construction project. Eng. Constr. Archit. Manag. 25, 1339–1354. https://doi.org/10.1108/ECAM-08-2017-0186.

Koskela, L., 2000. An Exploration Towards a Production Theory and Its Application to Construction. VTT Publications.

Kumar, V., Singh, R., Pandey, A., 2024. Multiple stakeholders' critical success factors scale for success on large construction projects. Asian J. Civil Eng. 25, 1691–1705. https://doi.org/10.1007/s42107-023-00871-3.

Lam, E.W.M., Chan, A.P.C., Olawumi, T.O., Wong, I., Kazeem, K.O., 2024. Critical factors that influence lean premise design implementation: a case of Hong Kong high-rise buildings. Architect. Eng. Des. Manag. 1–17. https://doi.org/10.1080/17452007.2024.2302416.

Li, M., Ma, Z., Tang, X., 2021. Owner-dominated building information modeling and lean construction in a megaproject. Front. Eng. Manag. 8, 60–71. https://doi.org/10.1007/s42524-019-0042-3.

Li, P., Lu, Y., Xiao, X., 2024. Proposing a development framework for sustainable architecture, engineering, and construction industry in China: challenges, best practice, and future directions. Front. Struct. Civ. Eng. 18, 805–814. https://doi.org/10.1007/s11709-024-1102-2.

Li, S., Fang, Y., Wu, X., 2020. A systematic review of lean construction in Mainland China. J. Clean. Prod. https://doi.org/10.1016/j.jclepro.2020.120581.

Liu, Z., Wang, L., Sheng, Z., Gao, X., 2018. Social responsibility in infrastructure megaprojects: a case study of ecological compensation for Sousa chinensis during the construction of the Hong Kong-Zhuhai-Macao Bridge. Front. Eng. Manag. https://doi.org/10.15302/j-fem-2018084.

Locatelli, G., Invernizzi, D.C., Brookes, N.J., 2017a. Project characteristics and performance in Europe: an empirical analysis for large transport infrastructure projects. Transp. Res. Part A Policy Pract 98, 108–122. https://doi.org/10.1016/j.tra.2017.01.024.

Locatelli, G., Mikic, M., Kovacevic, M., Brookes, N., Ivanisevic, N., 2017b. The successful delivery of megaprojects: a novel research method. Proj. Manag. J. 48, 78–94. https://doi.org/10.1177/875697281704800506.

Luai, E.-S., Mccabe, B., El-Sabek, L.M., Eng, P., Mccabe, B.Y., 2017. Coordination challenges of production planning & control in international mega-projects: a case study. Lean Constr. J.

Maddaloni, F. Di, Meira, L.H., de Andrade, M.O., de Melo, I.R., Castro, A., Locatelli, G., 2025. The dark legacy of megaprojects: a case of local disengagement, missed opportunities, and social value dissipation. Int. J. Proj. Manag. 43, 102676. https://doi.org/10.1016/j.ijproman.2025.102676.

Marhani, M.A., Haris, I.N.A., Rooshdi, R.R.R.M., Ismail, N.A.A., Sahamir, S.R., 2023. The critical success factors of lean construction implementation in residential projects. Malaysian Constr. Res. J. (MCRJ) 61.

Meshref, A.N., Abdelfattah, E., Elkasaby, A., Ibrahim, A., 2022. S. Electing Key Drivers for a Successful Lean Construction Implementation Using Simos ' and WSM : the Case of Egypt.

Moaveni, S., Banihashemi, S.Y., Mojtahedi, M., 2019. A conceptual model for a safety-based theory of lean construction. Buildings 9, 1–11. https://doi.org/10.3390/buildings9010023.

Moon, S., Xu, S., Hou, L., Wu, C., Wang, X., Tam, V.W.Y., 2018. RFID-aided tracking system to improve work efficiency of scaffold supplier: stock management in australasian supply chain. J. Construct. Eng. Manag. 144. https://doi.org/10.1061/(asce)co.1943-7862.0001432.

Najafi, M., Sheikhkhoshkar, M., Rahimian, F., 2024. Editorial: innovation and lean practices for sustainable construction project management; emerging technologies, strategies and challenges. Smart Sustain. Built Environ. 13, 473–478. https://doi.org/10.1108/SASBE-05-2024-406.

Noorzai, E., 2023. Evaluating lean techniques to improve success factors in the construction phase. Constr. Innov. 23, 622–639. https://doi.org/10.1108/CI-05-2021-0102.

Norris, M., Oppenheim, C., 2007. Comparing alternatives to the web of science for coverage of the social sciences' literature. J. Informetr. 1, 161–169. https://doi.org/10.1016/j.joi.2006.12.001.

Opoku, A., Solomon Adewumi, A., Lok, Leung, Lawrence), K., Amoh, E., 2024. Lean construction and SDGs: delivering value and performance in the built environment. In: The Elgar Companion to the Built Environment and the Sustainable Development Goals. Edward Elgar Publishing, pp. 294–314. https://doi.org/10.4337/9781035300037.00027.

Pan, W., Pan, M., 2016. Status quo and future development of lean construction in Hong Kong. WBC16 Proceedings: Volume IV-Understanding Impacts and Functioning of Different Solutions.

Pavez, I., Alarcón, L.F., 2006. Qualifying people to support lean construction in contractor organizations. Understanding and Managing the Construction Process: Theory and Practice - 14th Annual Conference of the International Group for Lean Construction, IGLC-14, pp. 513–524.

Ramasamy, G., 2016. A critical study of various lean techniques in practice and developing a framework for different construction building projects. Article Int. J. Chem. Sci.

Romestant, F., 2020. Sustainability agencing: the involvement of stakeholder networks in megaprojects. Ind. Mark. Manag. 89, 535–549. https://doi.org/10.1016/j.indmarman.2019.09.005.

Sadikoglu, E., Jäger, J., Demirkesen, S., Baier, C., Oprach, S., Haghsheno, S., 2024. Investigating the impact of lean leadership on construction project success. EMJ - Eng. Manag. J. 36, 206–220. https://doi.org/10.1080/10429247.2023.2245317.

Sadiq, R., Rodriguez, M.J., 2004. Fuzzy synthetic evaluation of disinfection by-products - a risk-based indexing system. J. Environ. Manag. 73, 1–13. https://doi.org/10.1016/j.jenvman.2004.04.014.

Saini, M., Arif, M., Kulonda, D.J., 2018. Critical factors for transferring and sharing tacit knowledge within lean and agile construction processes. Constr. Innov. 18, 64–89. https://doi.org/10.1108/CI-06-2016-0036.

Saka, A.B., Chan, D.W.M., Wuni, I.Y., 2022. Knowledge-based decision support for BIM adoption by small and medium-sized enterprises in developing economies. Autom. ConStruct. 141, 104407. https://doi.org/10.1016/j.autcon.2022.104407.

Sarhan, J.G., Xia, B., Fawzia, S., Karim, A., Olanipekun, A.O., Coffey, V., 2020. Framework for the implementation of lean construction strategies using the interpretive structural modelling (ISM) technique: a case of the Saudi construction industry. Eng. Constr. Archit. Manag. 27, 1–23. https://doi.org/10.1108/ECAM-03-2018-0136.

Sarhan, S., Pasquire, C., Elnokaly, A., Pretlove, S., 2019. Lean and sustainable construction: a systematic critical review of 25 years of IGLC research. Lean Constr. J. 20, 1–20, 2019. https://www.leanconstruction.org/media/docs/lcj/2019/LCJ_19_004.pdf.

Senaratne, S., KC, A., Rai, S., 2024. Stakeholder management challenges and strategies for sustainability issues in megaprojects: case studies from Australia. Built. Environ. Proj. Asset. Manag. 14, 414–431. https://doi.org/10.1108/BEPAM-11-2022-0183.

Shan, M., Hwang, B., Wong, K.S.N., 2017. A preliminary investigation of underground residential buildings: advantages, disadvantages, and critical risks. Tunn. Undergr. Space Technol. 70, 19–29. https://doi.org/10.1016/j.tust.2017.07.004.

Shurrab, J., Hussain, M., 2018. An empirical study of the impact of lean on the performance of the construction industry in UAE. J. Eng. Des. Technol. 16, 694–710. https://doi.org/10.1108/JEDT-09-2017-0095.

Spreafico, C., 2025. How can patent-based prospective life cycle assessment be used for eco-design? Res. Eng. Des. 36, 5. https://doi.org/10.1007/s00163-025-00447-z.

Subaie, A.A. Al, Faisal, MohdN., Aouni, B., Sabir, L. Bin, 2023. ISO 21500 and the sustainability focused ANP-BOCR framework for subcontractor selection in megaprojects. Proj. Manag. J. 54, 474–490. https://doi.org/10.1177/87569728231152419.

Sweis, G.J., Hiyassat, M., Al-Hroub, F.F., 2016. Assessing lean conformance by first-grade contractors in the Jordanian construction industry. Constr. Innov. 16, 446–459. https://doi.org/10.1108/CI-04-2015-0024.

Tabatabaee, S., Mohandes, S.R., Ahmed, R.R., Mahdiyar, A., Arashpour, M., Zayed, T., Ismail, S., 2022. Investigating the barriers to applying the internet-of-things-based technologies to construction site safety management. Int. J. Environ. Res. Publ. Health 19, 868. https://doi.org/10.3390/ijerph19020868.

Thounaojam, N., Laishram, B., 2022. Issues in promoting sustainability in mega infrastructure projects: a systematic review. J. Environ. Plann. Manag. 65, 1349–1372. https://doi.org/10.1080/09640568.2021.1941810.

Toor, S. ur R., Ogunlana, S.O., 2010. Beyond the "iron triangle": stakeholder perception of key performance indicators (KPIs) for large-scale public sector development projects. Int. J. Proj. Manag. 28, 228–236. https://doi.org/10.1016/j.ijproman.2009.05.005.

Torfi, F., Farahani, R.Z., Rezapour, S., 2010. Fuzzy AHP to determine the relative weights of evaluation criteria and Fuzzy TOPSIS to rank the alternatives. Appl. Soft Comput. 10, 520–528. https://doi.org/10.1016/j.asoc.2009.08.021.

Wang, G., Wu, P., Wu, X., Zhang, H., Guo, Q., Cai, Y., 2020. Mapping global research on sustainability of megaproject management: a scientometric review. J. Clean. Prod. 259, 120831. https://doi.org/10.1016/j.jclepro.2020.120831.

Wang, G., Zhou, K., Wang, D., Wu, G., Xie, J., 2021. Tensions in governing megaprojects: how different types of ties shape project relationship quality? Int. J. Proj. Manag. 39, 799–814. https://doi.org/10.1016/j.ijproman.2021.08.003.

Watfa, M., Sawalha, M., 2021. Critical success factors for lean construction: an empirical study in the UAE. Lean Constr. J. 2021, 1–17.

Wuni, I.Y., Shen, G.Q., 2022. Developing critical success factors for integrating circular economy into modular construction projects in Hong Kong. Sustain. Prod. Consum. 29, 574–587. https://doi.org/10.1016/j.spc.2021.11.010.

Wuni, I.Y., Shen, G.Q., 2020. Fuzzy modelling of the critical failure factors for modular integrated construction projects. J. Clean. Prod. 264, 121595. https://doi.org/10.1016/j.jclepro.2020.121595.

Xie, L., Huang, M., Xia, B., Skitmore, M., 2022. Megaproject environmentally responsible behavior in China: a test of the theory of planned behavior. Int. J. Environ. Res. Publ. Health 19, 6581. https://doi.org/10.3390/ijerph19116581.

Xie, L., Lin, G., Hon, C., Xia, B., Skitmore, M., 2020. Comparing the psychosocial safety climate between megaprojects and non-megaprojects: evidence from China. Appl. Sci. 10, 8809. https://doi.org/10.3390/app10248809.

Yadav, S., Samadhiya, A., Kumar, A., Majumdar, A., Garza-Reyes, J.A., Luthra, S., 2023. Achieving the sustainable development goals through net zero emissions: innovation-driven strategies for transitioning from incremental to radical lean, green and digital technologies. Resour. Conserv. Recycl. 197. https://doi.org/10.1016/j.resconrec.2023.107094.

Ying, F.J., Zhao, N., Tookey, J., 2022. Achieving construction innovation in best value procurement projects: new Zealand mega projects study. Constr. Innov. 22, 388–403. https://doi.org/10.1108/CI-11-2020-0182.

Yunus, R., Noor, S.R.M., Abdullah, A.H., Nagapan, S., Hamid, A.R.A., Tajudin, S.A.A., Jusof, S.R.M., 2017. Critical success factors for lean thinking in the application of Industrialised Building System (IBS). IOP Conf. Ser. Mater. Sci. Eng. 226. https://doi.org/10.1088/1757-899X/226/1/012045.

Zammori, F.A., Braglia, M., Frosolini, M., 2009. A fuzzy multi-criteria approach for critical path definition. Int. J. Proj. Manag. 27, 278–291. https://doi.org/10.1016/j.ijproman.2008.03.006.

Zulkeflee, Zarifa, Nawanir, Gusman, Ghani, Airin Abdul, Aripin, Norhana, 2022. The importance of lean knowledge management for a successful lean management implementation in the Malaysian public sector. Int. J. Industr. Manag. 16, 13–24. https://doi.org/10.15282/ijim.16.1.2022.9005.

Zegarra, O., Alarcón, L.F., 2019. Coordination of teams, meetings, and managerial processes in construction projects: using a lean and complex adaptive mechanism. Prod. Plann. Control 30, 736–763. https://doi.org/10.1080/09537287.2019.1578905.