

UNRAVELLING THE BACKBONE OF LEAN TRANSFORMATION IN CONSTRUCTION MEGAPROJECTS

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ABSTRACT

Despite growing interest in lean construction for megaprojects, implementation remains fragmented. These complex, high-cost endeavors are prone to delays and inefficiencies, yet there is a limited understanding of how practices interrelate and which serve as foundational enablers. This study addresses this gap by uncovering the causal hierarchy among 35 Lean Construction Practices (LCPs) across six categories. The methodology integrates a literature review, expert input from 15 senior practitioners in Hong Kong and Mainland China, and Fuzzy DEMATEL analysis. Results reveal four Cause categories: Customer Focus & Waste Elimination, Standardization & Process Transparency, Planning & Scheduling, and People Involvement & Continuous Improvement, acting as critical enablers. Key backbone practices include TVD, VSM, Gemba Walks, 5S, BIM, LPS, and PCMAT. In contrast, Flow & Pull Systems and Safety & Quality Assurance are Effect categories, dependent on the prior establishment of foundational systems. The findings emphasize that lean transformation must follow a staged, theory-grounded sequence: cultural and structural practices must precede advanced tools, such as Kanban or TQM. Consequently, this study provides an evidence-based roadmap for prioritizing interventions and accelerating lean maturity in megaprojects.

KEYWORDS

Lean Construction, megaprojects, causal hierarchy, fuzzy DEMATEL, implementation sequencing, backbone practices.

INTRODUCTION

Construction megaprojects represent some of the most ambitious and transformative undertakings in modern infrastructure development. Defined not only by their substantial budgets, often exceeding \$1 billion, but also by their intricate technical, organizational, and socio-political complexity, these projects are distinguished by long timelines, high uncertainty, and significant societal and environmental impacts (Pitsis et al., 2018). Their scale and scope frequently involve multiple stakeholders with diverse interests, making governance, coordination, and risk management particularly challenging (Damayanti et al., 2021). Despite their strategic importance, megaprojects often face persistent cost and schedule overruns, primarily due to the underestimation of complexity and inadequate risk anticipation (Locatelli et al., 2017). Additionally, conflicting stakeholder priorities and power dynamics can lead to

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disputes, delays, and compromised outcomes (Sarkheyli and Rafieian, 2018). Effective coordination across geographically dispersed teams and extended project lifecycles further compounds these difficulties (Pitsis et al., 2018). Addressing such multifaceted challenges requires innovative management approaches, adaptive leadership, and the integration of advanced technologies that support dynamic decision-making and collaboration (Brockmann et al., 2016; Brunet and Cohendet, 2022).

In this context, lean construction (LC) has emerged as a promising methodology for enhancing performance in large-scale construction projects. Rooted in principles of waste reduction, value maximization, and continuous improvement, lean practices offer a structured approach to improving efficiency, quality, and collaboration across complex project environments (Ibrahim et al., 2025a). By identifying and eliminating non-value-adding activities, LC contributes to cost savings, improved scheduling reliability, and enhanced client satisfaction (Idrissi Gartoumi et al., 2024). Tools such as the Last Planner System, Building Information Modeling (BIM), and Lean Six Sigma have demonstrated measurable success in optimizing workflows and fostering cross-functional alignment, even within the volatile and uncertain contexts of megaprojects (Evans et al., 2021).

Despite its transformative potential, the adoption of LC in megaprojects faces significant barriers. Persistent challenges, including deeply entrenched industry norms, fragmented standards, and a shortage of scalable frameworks and specialized competencies, continue to impede its widespread implementation (Evans et al., 2023). Moreover, much of the existing literature treats lean practices as discrete interventions, overlooking their inherent causal interdependencies. From a systems theory perspective, this reductionist approach fails to account for the non-linear interactions within complex project ecosystems. In particular, foundational tools often serve as critical enablers that condition the successful deployment of more advanced practices, a dynamic insufficiently captured in current research (Ibrahim et al., 2025a). While the conceptual premise that lean practices are interdependent and benefit from structured sequencing is well-established in foundational Lean scholarship (Ballard and Tommelein, 2012; Bhawani et al., 2021; Chesworth, 2015; Howell and Ballard, 1998), empirical evidence quantifying these relationships specifically within the high-complexity context of construction megaprojects remains limited. This aligns with contingency theory, which posits that organizational effectiveness depends on the fit between specific practices and their contextual prerequisites. This study is grounded in the hypothesis that LC practices in megaprojects are not independent; rather, they form a structured causal hierarchy in which certain “driver” practices underpin the effectiveness of others (H_1). To address this gap, the primary objective of this study is to map the causal relationships among LCPs, thereby identifying the core “backbone tools” that facilitate full adoption. By applying a systems-based lens, the research aims to provide actionable insights for integrating lean practices more effectively into megaproject delivery systems, enhancing coordination and enabling the industry to harness lean’s full potential in tackling megaproject challenges with greater efficiency and impact.

RESEARCH BACKGROUND

LC IMPLEMENTATION IN CONSTRUCTION MEGAPROJECTS

LC has demonstrated significant adaptability and efficacy in megaproject delivery through the strategic integration of key tools: the Last Planner System® (LPS®) enhances planning reliability amid high variability; BIM enables real-time collaboration and clash detection; Integrated Project Delivery (IPD) and Target Value Design (TVD) foster shared risk/reward and value-driven decision-making (Azhar, 2011; Geraldi et al., 2011; Howell and Ballard, 1998). Empirical evidence from global megaprojects, including Istanbul Grand Airport (Turkey)

(Koseoglu et al., 2018), Mohamed VI Tower (Morocco) (Idrissi Gartoumi et al., 2024) and owner-led projects in China (Li et al., 2021), confirms measurable gains in quality, productivity, stakeholder alignment, and customer satisfaction.

LEAN CONSTRUCTION PRACTICES

LC has evolved from a set of production tools into a holistic management philosophy, especially critical in megaprojects where complexity, fragmentation, and uncertainty demand systemic coordination (

Table 1).

Table 1: LC Practices for Construction Megaprojects Adoption (Ibrahim et al., 2025c, 2025b)

	Code	LC Practice
CWE	CWE 1	Optimize Value/Value Identification
	CWE 2	Waste reduction strategy (reduce cycle time)
	CWE 3	Customer Involvement
	CWE 4	Target Value Design (TVD)
	CWE 5	Value Stream Mapping (VSM)
	CWE 6	Flexible Resources
	CWE 7	Design workshops/big room workshop
FPS	FPS1	Pull Scheduling/planning
	FPS2	Kanban system
	FPS3	Just in Time (JIT)
	FPS4	Integrated project delivery system (IPD)
PCI	PCI 1	Gemba walks
	PCI 2	Kaizen
	PCI 3	Teamwork
	PCI 4	Huddle Meeting
	PCI 5	First run studies (PDCA)
	PCI 6	Training/ Skills development
	PCI 7	Metrics (productivity, quality, safety)
	PCI 8	A3 Report
PAS	PAS1	Last Planner System
	PAS2	PPC Charts
	PAS3	Collaborative Planning
	PAS4	Hoshin Management
SPT	SPT1	Visual Management (VM)
	SPT2	Workplace Organization (5S)
	SPT3	Takt Time
	SPT4	Defined work process
	SPT5	Concurrent Engineering
	SPT6	Building Information Modelling
SQA	SQA1	Fail-safe for quality
	SQA2	Response to defect/Root cause analysis
	SQA3	Plan Conditions and Work Environment in the Construction Industry (PCMAT)
	SQA4	Health/Safety Improvement
	SQA5	Error Proofing (poke-yoke)
	SQA6	Total Quality Management (TQM)

Customer Focus & Waste Elimination (CWE), Flow & Pull Systems (FPS), People Involvement & Continuous Improvement (PCI), Safety & Quality Assurance (SQA), Standardization & Process Transparency (SPT), and Planning & Scheduling (PAS), comprising 35 sub-practices validated for megaproject applicability.

CWE practices (e.g., Target Value Design, Value Stream Mapping) anchor lean efforts in client value definition and waste elimination early in the lifecycle. PCI emphasizes behavioral foundations, Gemba walks, huddles, teamwork, and training, enabling sustained engagement and iterative learning (e.g., Kaizen, A3, PDCA). FPS and PAS operationalize flow through

demand-driven mechanisms such as Pull Scheduling, JIT, Kanban, and the Last Planner System, while IPD and Collaborative Planning foster contractual and relational alignment. SPT leverages Visual Management, 5S, and BIM to create transparency and digital-physical integration, supporting standardization (e.g., Takt Time, Defined Work Processes). Finally, SQA embeds proactive safety (e.g., PCMAT, Health/Safety Improvement) and quality (e.g., RCA, Poka-Yoke, TQM) as outcomes of systemic maturity, not standalone interventions. Collectively, this taxonomy reflects a shift from tool-centric to capability-centric lean thinking, underpinning the need to understand how these practices interact and sequence, especially in high-stakes megaproject environments where partial or misordered adoption often leads to failure.

METHODOLOGY

This study adopts a foundational, causal-mapping approach as Phase 1 of a broader Design Science Research (DSR) agenda aimed at improving lean implementation in megaprojects. While DSR is well-suited for developing and validating implementation artifacts, this initial phase focuses on problem identification, requirements analysis, and the generation of design knowledge, specifically, the causal hierarchy and sequencing logic among Lean Construction Practices (LCPs). The Fuzzy DEMATEL output thus serves as a "structural blueprint" or "pre-artifact" that informs the subsequent design of a testable implementation method. The three-phase, mixed-methods approach employed, (1) systematic literature review, (2) expert-based pairwise survey, and (3) Fuzzy DEMATEL analysis, as illustrated in Figure 1, was selected to rigorously map interdependencies before artifact prototyping.

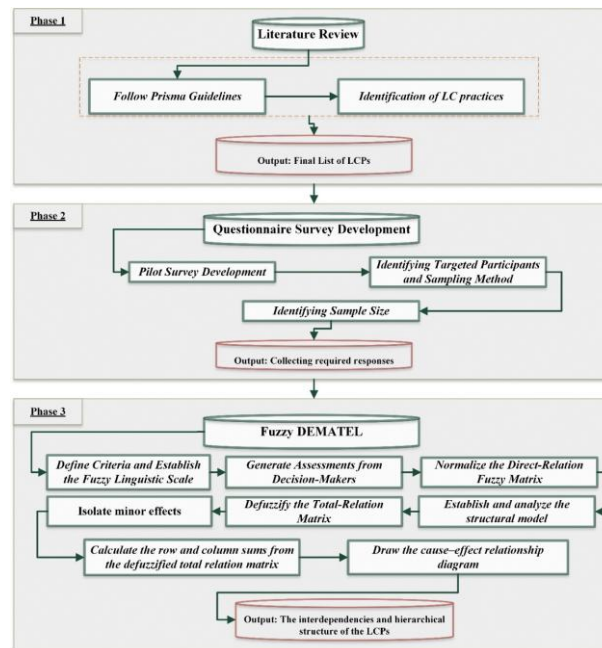


Figure 1: Research methodology

PHASE 1: LITERATURE REVIEW AND IDENTIFICATION OF LCPs

A PRISMA-guided literature review was conducted across Scopus, Web of Science, and Google Scholar to identify peer-reviewed studies (published within the last 20 years) on lean construction practices. Initial search results were screened by title/abstract, followed by full-text evaluation for relevance to megaproject contexts. Guided by iterative team discussions and consensus-building, the review culminated in a refined taxonomy of LCPs, building directly on the validated framework established in our prior work (Ibrahim et al., 2025c, 2025b). This

resulted in the final selection of 35 sub-practices grouped into six core functional categories: CWE, PCI, PAS, SPT, FPS, and SQA, each reflecting both theoretical coherence and empirical grounding in megaproject settings.

PHASE 2: QUESTIONNAIRE SURVEY DEVELOPMENT AND DATA COLLECTION

A structured pairwise comparison questionnaire was developed using a fuzzy linguistic scale (“No influence” to “Very high influence”) to capture expert perceptions of practice interdependencies. To ensure clarity, validity, and reliability, a pilot survey was conducted with 10 specialists from diverse sectors of the construction industry, including design, project management, site operations, and lean consulting. These experts reviewed the questionnaire for question phrasing, logical flow, and overall usability. Their feedback was instrumental in refining the instrument, ensuring that each item accurately captured the intended meaning while maintaining user-friendliness and minimizing ambiguity. Following these revisions, the finalized questionnaire was administered electronically via platforms such as Google Forms to facilitate broad participation and ease of data collection. The survey was conducted between March and September 2024. Experts were purposively selected based on two key criteria: (1) a minimum of ten years of professional experience in construction megaprojects (e.g., high-speed rail, large-scale infrastructure, or urban development programs), and (2) holding at least a bachelor's degree in a relevant field such as civil engineering, construction management, or project management. Given the study's focus on lean implementation in megaprojects, the questionnaire was disseminated specifically in Hong Kong and Mainland China, regions with dense portfolios of complex infrastructure projects and aligned regulatory environments. Consistent with Wang et al. (2021), only individuals involved in projects with total investments surpassing RMB 500 million (0.5 billion CNY) were deemed eligible, thereby ensuring the research remained grounded in high-stakes, real-world megaproject settings. Using this targeted sampling strategy, the study successfully assembled a panel of 15 qualified experts, a sample size aligned with established norms in prior research that applied the FDEMATEL methodology (Akyuz and Celik, 2015; Tabatabaee et al., 2019).

PHASE 3: FUZZY DEMATEL ANALYSIS

The third phase of the research methodology employed the Fuzzy DEMATEL (Decision-Making Trial and Evaluation Laboratory) technique to analyze the collected data and derive insights into the causal relationships and hierarchical structure of LCPs. The Fuzzy DEMATEL technique is a widely recognized multi-criteria decision-making approach that uses graph theory to map and examine the interdependencies among variables in complex systems, providing a systematic framework for uncovering causal links and hierarchical structures (Ibrahim et al., 2026). This multi-step analytical process began with defining criteria and establishing a fuzzy linguistic scale to capture the nuanced qualitative judgments of industry experts on the influence of one LCP on another. The linguistic terms, ranging from “No influence” to “Very high influence”, were converted into triangular fuzzy numbers to accommodate uncertainty and subjectivity in expert assessments. Using this scale, the survey's pairwise comparison responses were aggregated to construct a direct-relation fuzzy matrix, where each element represented the perceived degree of influence of one practice over another. To ensure consistency and comparability across all pairwise comparisons, the direct-relation matrix was normalized using fuzzy arithmetic operations, thereby standardizing the values to a uniform range. Subsequently, the total-relation fuzzy matrix was computed by summing the direct effects and indirect propagation paths through an iterative convergence process. This matrix was then defuzzified using the centroid method, transforming the fuzzy values into crisp numerical scores that enabled precise quantitative analysis while preserving the richness of expert input. To enhance clarity and focus on meaningful relationships, minor or negligible

influences were filtered out by applying thresholding techniques, effectively isolating significant causal links and reducing noise in the dataset (Ibrahim et al., 2025d). With the refined total-relation matrix, the structural model of LCPs was established by calculating two key indicators for each practice: prominence ($D+R$), reflecting the overall degree of influence and being influenced, and net effect ($D-R$), indicating whether a practice acted more as a driver (Cause Group) with positive net effect or an outcome (Effect Group) with negative net effect. These metrics served as the basis for classifying practices by their causal roles and for visualizing their interdependencies.

RESULTS AND DISCUSSION

The Fuzzy DEMATEL method was applied to analyze the causal relationships among LCPs, utilizing expert inputs and quantitative data. This approach enabled the identification of key practices that act as drivers (Cause Group) or outcomes (Effect Group) within lean implementation frameworks. The results were visualized through causal diagrams (Figure 2), which categorizes LCPs into four zones according to their influence and dependence levels. It is important to note that DEMATEL reveals perceived structural relationships based on expert judgment, not absolute causal proof; thus, "Cause" and "Effect" labels indicate directional influence patterns within the system rather than deterministic causation. The FDEMATEL approach was used to quantify the influence and dependence among practices by constructing a total direct–indirect relationship matrix. To enhance analytical clarity, negligible interactions were removed using group-specific threshold values established for each category. This filtering process yielded a refined matrix with zero entries for relationships deemed insignificant, thereby highlighting only the most meaningful causal links. Based on the $D+R$ (sum of prominence) and $D-R$ (net effect) values presented in Table 2, several critical insights emerge regarding the interdependencies among LCPs. The results strongly support H_1 , confirming that LCPs are indeed interdependent and organized into a structured causal hierarchy, with distinct driver (Cause) and dependent (Effect) roles.

From a theoretical perspective, these findings align with Complex Adaptive Systems (CAS) theory, which posits that organizational outcomes emerge from non-linear interactions among interconnected elements rather than isolated interventions. The identification of CWE, PCI, PAS, and SPT as Cause Group categories suggests that lean transformation in megaprojects functions as a systemic capability rather than a toolkit. This theoretical framing advances prior lean research by shifting from tool-centric adoption models to a capability-based sequencing framework, offering novel insights into how lean maturity develops through interdependent practice clusters. While some practice groupings may appear overlapping (e.g., LPS and PPC, or TVD and VSM), the DEMATEL results reflect how experts distinguish their functional influence. For instance, TVD emerged as a strategic driver (Cause) for setting value targets, whereas VSM functioned as a diagnostic enabler (Cause) for mapping workflows. Similarly, while PPC is technically part of LPS, experts perceived LPS as the broader collaborative protocol (Cause) and PPC as a specific reliability metric (Cause) that reinforces planning discipline. These distinctions, while subtle, highlight the granular interdependencies that practitioners navigate in megaproject settings.

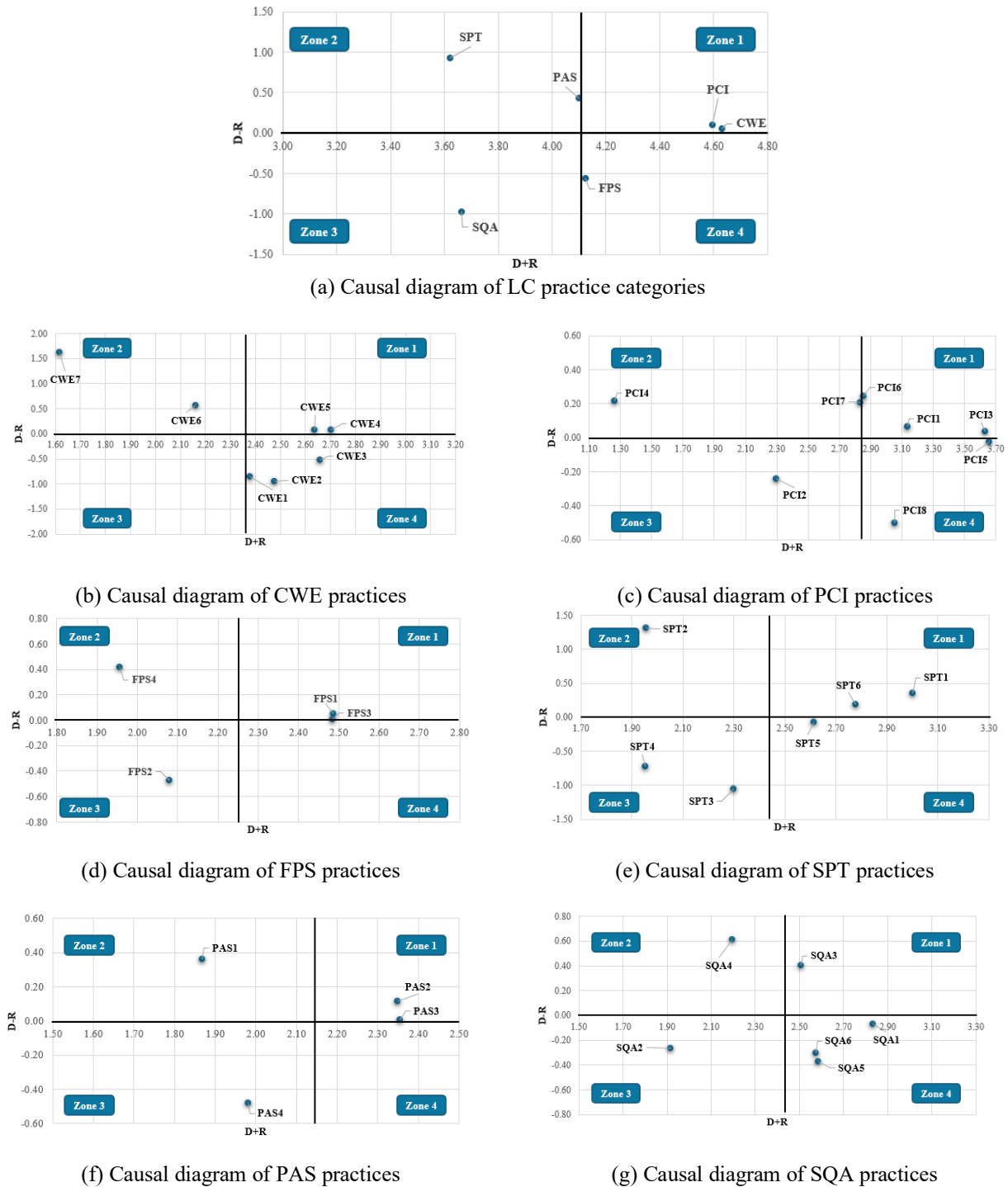


Figure 2: The causal diagrams of Lean Construction Practices (LCPs).

As shown in Figure 2 (a), four categories, CWE, PCI, PAS, and SPT, were identified as part of the Cause Group, meaning they tend to exert greater net influence within the system, enable other practices, and serve as foundational or strategic drivers in lean implementation. These practices form the operational and cultural backbone of lean systems, creating the enabling conditions for more advanced lean practices to be successfully implemented. Conversely, Flow and Pull Systems (FPS) and Safety and Quality Assurance (SQA) were classified under the Effect Group, indicating their dependency on the maturity of core lean systems and their emergence as outcomes rather than initiators. This pattern suggests that flow optimization and quality assurance are emergent properties

of systemic maturity, not standalone achievements, a finding that challenges conventional lean implementation approaches that prioritize workflow tools early in transformation journeys.

Table 2: Cause and effect values

ID	D+R	D-R	Cause/E ffect	Zone	ID	D+R	D-R	Cause/E ffect	Zone
CWE	4.630	0.057	Cause	1	FPS1	2.488	0.052	cause	1
PCI	4.596	0.101	Cause	1	FPS2	2.080	-0.473	effect	3
FPS	4.123	-0.557	Effect	4	FPS3	2.485	0.007	cause	1
SPT	3.620	0.931	Cause	2	FPS4	1.956	0.413	cause	2
PAS	4.100	0.438	Cause	2	SPT 1	3.000	0.359	cause	1
SQA	3.664	-0.970	Effect	3	SPT 2	1.957	1.308	cause	2
CWE 1	2.378	-0.859	effect	4	SPT 3	2.299	-1.059	effect	3
CWE 2	2.476	-0.955	effect	4	SPT 4	1.954	-0.726	effect	3
CWE 3	2.658	-0.515	effect	4	SPT 5	2.614	-0.070	effect	4
CWE 4	2.704	0.075	cause	1	SPT 6	2.779	0.188	cause	1
CWE 5	2.636	0.082	cause	1	PAS 1	1.869	0.363	cause	2
CWE 6	2.162	0.558	cause	2	PAS 2	2.350	0.114	cause	1
CWE 7	1.615	1.615	cause	2	PAS 3	2.355	0.005	cause	1
PCI 1	3.135	0.065	cause	1	PAS 4	1.981	-0.482	effect	3
PCI 2	2.298	-0.244	effect	3	SQA1	2.832	-0.068	effect	4
PCI 3	3.632	0.038	cause	1	SQA2	1.916	-0.266	effect	3
PCI 4	1.263	0.218	cause	2	SQA3	2.509	0.402	cause	1
PCI 5	3.659	-0.026	effect	4	SQA4	2.196	0.608	cause	2
PCI 6	2.857	0.244	cause	1	SQA5	2.586	-0.374	effect	4
PCI 7	2.835	0.208	cause	2	SQA6	2.575	-0.302	effect	4
PCI 8	3.052	-0.502	effect	4					

Within the CWE category Figure 2 (b), the prominence of TVD (CWE 4) and VSM (CWE 5) as Cause Group practices reflects their role in establishing value definitions and systemic visibility early in project lifecycles. These practices create strategic alignment that conditions subsequent operational improvements. This finding is consistent with that of Orihuela et al. (2015) and Rybkowski et al. (2022), who emphasize that TVD achieves optimal results when combined with other lean tools, such as value stream mapping, and supported by a culture of mutual respect and aligned incentives. The classification of Customer Involvement (CWE 3) and Value Identification (CWE 1) as Effect Group practices is particularly noteworthy: it suggests that meaningful customer engagement emerges only after value delivery mechanisms (TVD, VSM) are established, challenging assumptions that customer involvement should precede technical lean tools.

In the PCI category Figure 2(c), the Cause Group status of Gemba Walks (PCI 1), Teamwork (PCI 3), and Training (PCI 6) indicates that behavioral foundations must precede structured improvement methodologies. This sequencing implies that continuous improvement

cultures (Kaizen, A3 Reports, classified as Effect Group) depend on prior establishment of engagement mechanisms and capability development. This progression aligns with Chiarini et al. (2018), who emphasize that Kaizen depends on active employee participation at all levels, not just management. Theoretically, this supports the view that lean is fundamentally a socio-technical system in which human factors condition the effectiveness of technical tools.

The FPS category Figure 2(d), reveals a critical insight: pull-based mechanisms (FPS1, FPS3, FPS4) function as Cause Group practices, while Kanban (FPS2) emerges as an Effect. This suggests that contractual and planning frameworks (IPD, Pull Scheduling) must be established before visual control tools (Kanban) can function effectively, a finding that cautions against implementing Kanban without underlying pull system maturity. This is consistent with findings by Zeng et al. (2024) and Cabrera et al. (2023).

In the SPT category Figure 2(e), 5S (SPT 2) and Visual Management (SPT 1) emerging as Cause Group practices reinforce the importance of physical and informational transparency as prerequisites for standardization. This finding challenges approaches that treat 5S as a standalone "housekeeping" exercise; instead, it functions as a systemic enabler for advanced standardization (Takt Time, Concurrent Engineering, classified as Effect Group). Similarly, while Visual Management and Takt Time appear distinct (communication vs. work structuring), experts perceived Visual Management as a prerequisite enabler for the rhythmic production required by Takt Time.

Within the PAS category Figure 2(f), Last Planner System (PAS 1), Collaborative Planning (PAS 3), and PPC Charts (PAS 2) represent the Cause Group with positive D–R values, forming the structural basis for reliable planning and execution. LPS engages stakeholders in constraint-free planning, PPC charts track performance reliability, and collaborative planning promotes shared understanding and conflict resolution. LPS structures planning into long-term, medium-term, and short-term horizons, increasing planning reliability and reducing waste and delays (Agrawal et al., 2024). The classification of Hoshin Management (PAS 4) as an Effect Group suggests that strategic policy deployment depends on operational planning maturity, with implications for how organizations sequence lean capability development. Although PPC Charts are part of LPS, their distinct Cause Group status highlights their specific role as a performance feedback mechanism that reinforces the broader LPS protocol.

Finally, in the SQA category Figure 2(g), the Cause Group status of PCMAT (SQA3) and Health/Safety Improvement (SQA4) indicates that proactive environmental and behavioral safety measures enable reactive quality tools. Advanced quality mechanisms (TQM, Poka-Yoke—classified as Effect Group) depend on this foundational safety culture, supporting the view that quality and safety are interconnected systemic outcomes rather than isolated compliance requirements. As Salem et al. (2005) highlight, without these foundational practices, fail-safe mechanisms may be inconsistently applied or poorly maintained, ultimately undermining their intended impact. Similarly, TQM, as a comprehensive strategy for long-term success through customer satisfaction and continuous improvement, relies heavily on lean systems and cultural alignment. As noted by Li (2024), TQM thrives only when supported by standardized processes, visual controls, and strong employee engagement, ensuring that quality becomes a shared responsibility across the organization. Indeed, research consistently shows that quality-focused tools often underperform or fail to deliver expected outcomes when foundational lean practices are absent (Li, 2024).

Overall, the Fuzzy DEMATEL analysis provides a hierarchical view of LCPs, revealing a clear progression from foundational enablers to advanced outcomes. The theoretical contribution lies in reframing lean implementation as a capability-building sequence grounded in systemic interdependencies rather than a linear tool-adoption process. By prioritizing Cause Group practices, particularly in customer focus, people involvement, planning, and standardization, organizations can build the structural and cultural conditions necessary for

sustainable lean transformation. However, while this analysis proposes a framework for guidance, it has not yet been empirically validated in a live project environment. Consequently, practitioners should view this roadmap as a structural model requiring adaptation to specific project contexts, rather than a prescriptive rule. Future research should validate this sequencing through longitudinal case studies or action research to transform this structural model into a validated practical tool. This insight provides valuable guidance for practitioners seeking to implement lean strategies systematically, ensuring that advanced tools are deployed only after core systems are firmly established.

CONCLUSIONS

This study reveals that LC in megaprojects follows a logical, hierarchical sequence, not a random toolkit deployment. Using Fuzzy DEMATEL, it identifies four *Cause Group* categories: Customer Focus & Waste Elimination, Standardization & Process Transparency, Planning & Scheduling, and People Involvement & Continuous Improvement, as foundational enablers. Practices such as TVD, Gemba Walks, LPS, 5S, and BIM serve as critical backbone tools. In contrast, Flow & Pull Systems and Safety & Quality Assurance emerge as *Effect Group* outcomes, dependent on prior maturity in the Cause Group. This underscores that lean is an integrated system, not a collection of isolated tools: value definition, team engagement, planning discipline, and process transparency must be established *first* to enable reliable flow, safety, and quality. Organizations seeking effective lean adoption should therefore prioritize investments in foundational enablers, avoiding premature implementation of advanced tools, to build sustainable, scalable lean capabilities in complex megaproject environments. However, several limitations must be acknowledged. First, while this study provides a structural model of interdependencies, it does not include a live case study validation or a testable implementation artifact. The proposed roadmap is based on expert perceptions and causal modeling, not empirical testing in a live project environment. Future research should validate this sequencing through longitudinal case studies or action research to transform this structural model into a validated practical tool. Second, this study's findings reflect the dynamics of lean practice in megaprojects in Hong Kong and Mainland China; the identified hierarchy may not hold universally, particularly in public megaprojects governed by different institutional or contractual models, and should be interpreted within this contextual framework.

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