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Research Article

An integrated lean-digital framework for optimizing civil- engineering supply chains: mixed-methods evidence from multi-project case analyses

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Abstract:

All around, civil engineering megaprojects are still struggling with budget overruns, schedule slippage, and disjointed supply-chain coordination. This paper conducts an embedded, multiple-case study of publicly recorded projects spanning Asia, Africa and the Middle East. Using a pragmatist mixed-methods approach, we thematically coded secondary reports, audits and peer-reviewed case narratives; descriptive statistics were used to investigate related cost- and time-performance data. Convergent triangulation found four common levers distinguishing better performers, early strategic alignment among stakeholders, proactive scenario-based risk management and digitally enabled transparency through (BIM) and (IoT) twins. Collaborative contracting cultures such as Integrated Project Delivery. Projects using these levers reduced lead-time variation by as much as 17% and cost overruns by 4–6 percentage points. Building on these ideas, we suggest an Integrated Lean-Digital Framework cascading through Strategic Alignment, Collaborative & Digital Integration, Operational Execution and Continuous Improvement & Sustainability. Though reliance on secondary data reduces statistical generalizability, deliberate case selection and cross-source triangulation improve transferability, therefore offering a consistent path to fight fragmentation. This synthesis offers practical advice for managers and politicians.

1. Introduction

Though still plagued by persistent cost overruns, late deliveries and quality deficiencies that erode public confidence, civil-engineering megaprojects remain vital to national growth [29, 20]. Unlike manufacturing, every construction project is a one-off prototype shaped by site constraints, bespoke designs and shifting stakeholder coalitions; these factors disrupt information flows and raise coordination costs, making supply-chain performance the decisive driver of overall project success [26]. During the past two decades, several distinct remedies have emerged. Lean- construction thinking targets non-value-adding activities [31], systems-thinking exposes interdependencies [10, 12], Building Information Modelling (BIM) and digital twins create transparent, data-rich environments [30, 21], while Integrated Project Delivery and agile management realign incentives around shared objectives [22, 34]. Case evidence shows that, although each paradigm delivers measurable gains, isolated adoption rarely eliminates underlying fragmentation; cultural inertia, uneven digital maturity and misaligned contracts routinely dilute impact [31, 28]. Consequently, scholars now advocate hybrid strategies that fuse efficiency- oriented lean tools with digitally enabled transparency and resilience-centered systems models, yet empirical validations of such holistic approaches remain limited [6, 35]. The present study addresses that gap by developing and testing an Integrated Lean–Digital Framework designed to optimize civil-engineering supply chains across four cascading layers: strategic alignment, collaborative and digital integration, operational execution, and continuous improvement with sustainability as shown in (Fig. 1). Guided by a pragmatist mixed-methods stance [18, 3], the research asks how critical supply-chain drivers influence project performance and resilience, how digital tools and integrated management practices enhance coordination, and what end-to-end roadmap can minimize disruptions from planning through hand-over. Evidence is drawn from multiple publicly documented projects across Asia, Africa and the Middle East, where thematic coding of secondary case records is combined with descriptive statistics on cost, schedule and quality metrics to uncover recurrent success factors and failure modes [14, 36]. By demonstrating that no single paradigm lean, agile, digital or systems-oriented suffices in isolation and that context-sensitive hybridization is essential for taming project volatility, the study advances construction-management scholarship. Practically, it offers project managers a step-by-step guide for reducing fragmentation, strengthening risk preparedness and embedding sustainability into everyday operations.

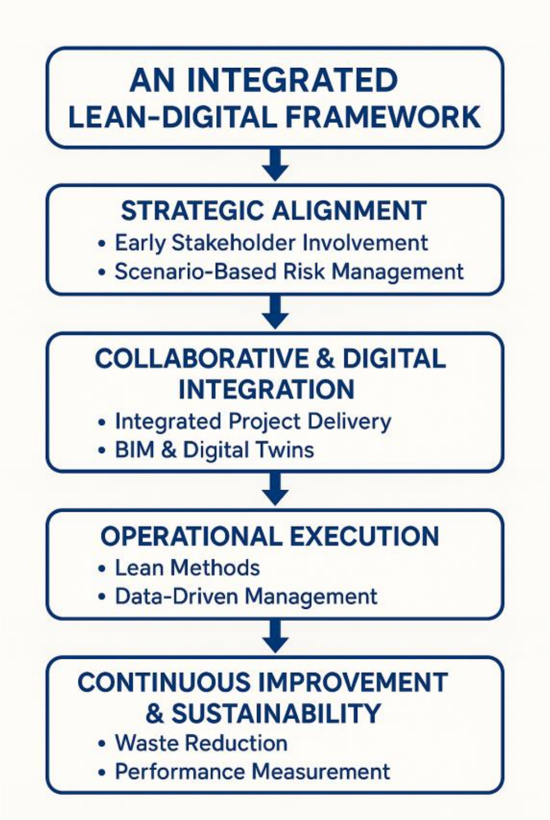

Figure 1. *The Integrated Lean-Digital Framework for optimizing civil-engineering supply chains.*

1.1. Literature Review

Chronic fragmentation, cost overruns and logistical uncertainty have civil-engineering supply chains repeatedly criticized. Comparative examinations of road, rail and building projects show that transient coalitions, adversarial procurement and poor information hand-offs trigger persistent delays and budget drift [29, 28, 20]. Pryke argues that lowest-price tendering corrodes trust and blocks data-sharing [29], while Krainer et al. link the dysfunction to design-bid-build silos that magnify coordination effort and invite scope creep and rework [20]. Quantitative snapshots from fourteen case studies reinforce the scale of the problem: median cost growth hovers around 13–14 percent and schedule slippage averages three to four weeks [38, 20].

1.2. Lean Construction and Waste Reduction

Early scholars translated Toyota's waste-elimination logic to construction, advocating pull flow, just-in-time deliveries and visual process control. Mapping value streams can cut material-handling waste and shorten lead times [30]; yet field work in Saudi Arabia shows that cultural inertia, skills gaps and inconsistent management commitment blunt lean benefits [31]. Where disciplined Last- Planner routines and continuous-improvement loops were embedded, projects reported smoother workflow and fewer change orders, confirming lean's potential as a baseline efficiency engine [35].

1.3. Systems Thinking and Dynamic Capabilities

Lean alone offers limited visibility into systemic knock-on effects. Systems-thinking research views construction supply chains as interdependent networks governed by feedback loops and adaptive capacity [10]. Dynamic-capability studies in Gulf and Indonesian projects demonstrate that sensing, learning and reconfiguring resources rather than static process maps drive resilience to price shocks and policy shifts [25]. Scenario-based simulations that layer risk metrics onto the (SCOR) plan-source-make-deliver domains further show how multi-sourcing or inventory buffers temper both cost penalties and recovery time after disruptions [12].

1.4. Digitalization: BIM and Digital Twins

The most transformative recent strand foregrounds Building Information Modelling and its digital-twin evolution. (BIM) supports clash detection, 4D/5D scheduling and a single source of truth, while IoT-enabled twins add live data streams for predictive logistics and 'what-if' rescheduling [27, 21]. Case reports credit these tools with tighter route planning and reduced rework yet warn that, without common data standards, supportive contracts and comprehensive training, sophisticated platforms deliver only fragmentary gains [27, 26]. SMEs in Nigeria and South Africa echo these barriers, citing cost, limited skills and managerial ambivalence as chief inhibitors of full-scale adoption [2, 33].

1.5. Agile Management and Integrated Project Delivery

To complement lean and digital solutions, researchers have imported Agile Project Management and Integrated Project Delivery into the construction lexicon. Short iterative cycles, daily stand-ups and collocated teams enable rapid reprioritization when site conditions shift, while (IPD) harmonizes financial incentives so designers, contractors and key suppliers all benefit from joint cost-schedule targets [22, 34]. Empirical work in Indonesia and Iran finds that early-contractor involvement under IPD improves procurement timelines and material flow, especially when paired with IoT-based tracking of prefabricated components [24, 21]. Nevertheless, legal unfamiliarity and risk-averse cultures slow uptake outside flagship projects [28].

1.6. Risk, Resilience and Ethical Procurement

COVID-19, commodity volatility and geopolitical upheavals have renewed attention on supply- chain resilience. Pakistani and Indonesian cases document how backup suppliers, adaptive sequencing and flexible contracts cushioned pandemic shocks [7, 37]. Conversely, South-African studies expose governance failures collusion, fraudulent certification and under-qualified vendors that offset technical advances and reignite cost creep [23]. These findings reinforce arguments that resilience is as much an ethics-and-governance question as a planning or technology challenge [6, 32].

1.7. Toward Hybrid, End-To-End Frameworks

Across the literature a consensus emerges: discrete tools lean, systems modelling, BIM/digital twins, agile or IPD produce incremental gains, but lasting improvement arises when they are woven into an integrated roadmap that aligns strategic objectives, data infrastructure, operational routines and collaborative incentives [6, 32, 35]. Calls for such hybrid frameworks exceed concrete validations, leaving questions about interoperability, contractual scaffolding and scalability across diverse regulatory contexts [10, 12]. By synthesizing these strands, the present study positions its Integrated Lean–Digital Framework as a response to that gap, contending that strategically sequenced convergence of waste reduction, systems-based resilience and digital transparency offers the most credible route to curing the sector's fragmentation malaise.

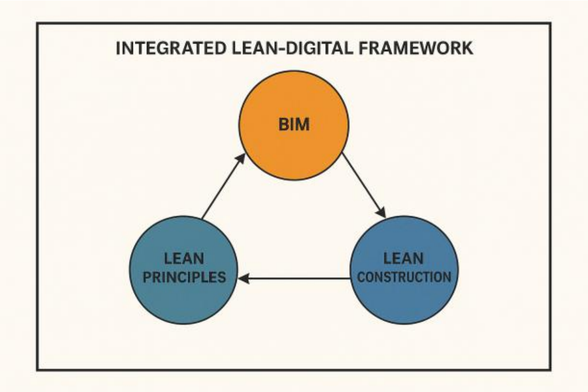

Figure 2. *Interactive relationship between Building Information Modeling (BIM) and Lean Construction principles.*

3. Methodology

To capture both the quantifiable results and the more complex, relational processes that influence civil-engineering supply-chain performance, this study adopts a pragmatist mixed-methods stance that privileges "what works" over allegiance to any single philosophical camp, allowing statistical analysis and qualitative insight to coexist in one explanatory frame [18, 3, 8].

3.1 Research Design and Philosophical Stance

The inquiry is structured as an embedded multiple-case study that relies exclusively on secondary sources [14, 36]. Multiple civil-engineering projects across Asia, Africa and the Middle East were chosen because their publicly available records provided rich evidence of both success and failure in Lean adoption, BIM use and collaborative contracting. Purposeful sampling combined three logics criterion, maximum variation and confirming/disconfirming to test emerging explanations against rival evidence [14].

3.2Data Collection Procedures

Documents were retrieved through a structured protocol for secondary analysis [36]. Keyword searches of government portals, professional archives and academic databases yielded audits, cost

***Table 1**. Case-Study Selection Matrix*

Project	Region	Project Type	Project Scale	Data Richness
Kathmandu Valley Building Projects	Asia	Design–Bid–Build (public + private)	Medium	High – 34 project questionnaires + official docs
Public-Sector Procurement Projects, South Africa	Africa	Traditional public procurement	Medium-Large	High – National Treasury sanction database, audits
COVID-19 Risk-Management Innovations, Indonesia	Asia	Large infra / commercial	Large	High – 329-respondent survey, (SEM)
Consulting-Service Collaboration, Tanzania	Africa	Consulting / design services	Small-Medium	Moderate – 171-firm survey
(SME) Material-Management Practices, South Africa	Africa	Small contractors (CIDB 1-4)	Small	Moderate – mixed-methods logs + interviews
Manufacturing / Construction Complexity, Saudi Arabia	Middle East	Manufacturing supply / infrastructure	Medium-Large	High – survey + (PLS-SEM)
Construction Team Competence, Iraq	Middle East	Public & private construction	Medium-Large	High – 300-manager (SEM)
Siliwangi Road-Widening Project, Indonesia	Asia	Road infrastructure (SCOR-tracked)	Medium	High – SCOR KPIs, cost & schedule logs
Dynamic Capabilities & Resilience, Saudi Arabia	Middle East	Large building / infrastructure	Large	High – survey, structural-equation modelling
Pandemic Impacts on Construction Projects, Pakistan	Asia	Mixed (public / private)	Medium-High	Moderate-High – mixed case reports
(IPD–IoT) Integration for Sustainable (SCM), Iran	Middle East	(IPD + IoT) building / infra	Medium-Large	High – fuzzy (SWARA) + (ARAS) expert surveys
AHP-Based Material Decision Tool for (MSMEs	Multiple (various Regions)	(MSME) construction	Small	Moderate – (AHP) interviews + site observations

reports, tender records and peer-reviewed case studies. Inclusion criteria required relevance to construction supply chains, publication within the past 10–15 years and sufficient detail on cost, schedule or stakeholder interactions; materials falling short were excluded. All files were catalogued in a secure repository with metadata for rapid cross-referencing. Ethical safeguards centered on confidentiality and intellectual-property

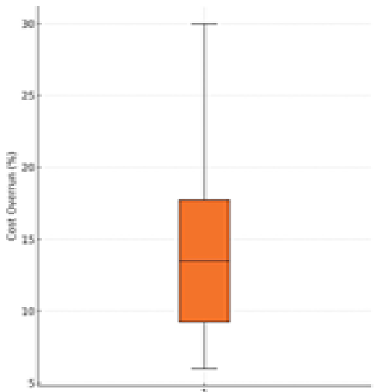

***Figure 3.** Cost-Overrun Box-Plot*

integrity; sensitive business data were masked where necessary, and reliance on publicly available documents avoided human-subject complications [36].

3.3 Analytical Strategy

Two analytic streams ran in parallel. In the qualitative strand, meaning units were inductively and deductively coded with a codebook capturing themes such as communication bottlenecks, risk-management practices and technology adoption; constant comparison and triangulation across document types reinforced credibility [14]. In the quantitative strand, numeric data cost-overrun percentages, lead-time indices were cleaned, checked for consistency and subjected to descriptive statistics. Where comparable metrics existed across cases, exploratory cross-tabulations probed associations between integrated supply-chain practices and performance outcomes. Findings were merged through convergent triangulation, cross-verifying narrative themes (e.g., “lack of real-time visibility") against schedule-variance data and weaving complementary insights into a joint display that linked qualitative explanations to quantitative trends [8].

3.4 Trustworthiness, Validity and Limitations

Credibility was strengthened by sourcing documents from multiple repositories and cross-checking themes with numeric indicators [14]. A transparent audit trail of coding decisions ensured dependability, while thick descriptions of each case context fostered transferability. Quantitative reliability rested on documenting metric provenance and screening datasets for definitional consistency [36]. Relying solely on secondary data limits exploration beyond archival records and may constrain statistical generalizability, yet broad geographic and project-type coverage enhances the transferability of insights, and the pragmatist lens justifies the emphasis on actionable patterns over universal laws [36]. Taken together, this mixed-methods design provides a robust foundation for the ensuing results and discussion, enabling clear connections from documented practice to measured performance and, ultimately, to the proposed Integrated Lean– Digital Framework.

4. Results and Discussion

Cost growth clustered around a median 13 - 14 % across the several projects studied; schedule slippage averaged three to four weeks, verifying the ongoing overruns reported in prior research. Lead-time variance histogram analysis indicated a long-tailed distribution suggesting structural rather than stochastic reasons, with a small number of projects bearing the majority of delays as shown in Figure 3. Measurable benefits appeared when projects used integrated techniques. For instance, the Indonesian road-widening pilot that integrated (BIM) based dashboards with (SCOR) metrics reduced lead-time by 17% and cost variance by 4-6 percentage points. Programs responding to COVID-19 in Indonesia revealed that multi-sourcing and agile crisis cells had cost penalties to 8% compared to a 15 % baseline and halved recovery time to 30 days. On the other hand, South- African public-sector projects hurt by fraudulent tendering experienced ongoing schedule disturbance and lost 5-7 pp of cost efficiency as shown in Figure 4 and Figure 5.

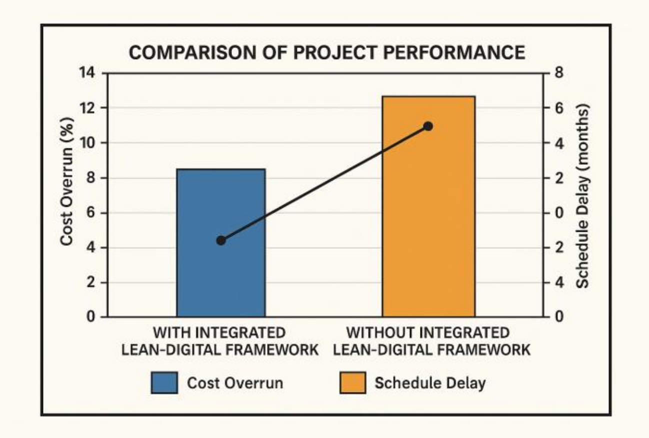

Figure 4. *Comparison of cost overruns and schedule delays between projects with and without the Integrated Lean-Digital Framework.*

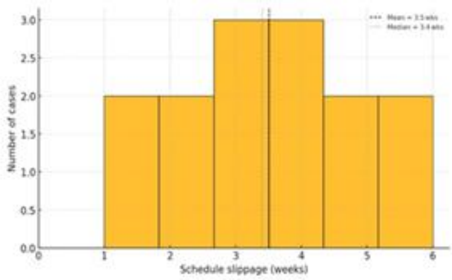

Figure 5. *lead time variance histogram (n= projectts)*

4.2 Qualitative Themes and Cross-Case Synthesis

Inductive coding produced high-frequency drivers, validated in the Driver × Outcome Matrix as shown in Table 2 below:

Table 2. *Driver × Outcome Matrix*

Driver	Cost performance	Reliability / quality KPIs	Resilience / recovery	Data Richness	Illustrative cases
Communication & coordination quality	↑– poor communication added 12-18 % to budgets; early contractor involvement cut overruns	↑ – design-update lags created 2-4 wk delays	↑ – on-time material calls ↑ perfect-order fulfilment	↔ – limited direct effect once a major shock occurred	Kathmandu Valley; (SME) SA; Indonesian road project
Risk management & contingency planning	↑ –multi-sourcing held cost penalty at ≤ 8 % vs 15 % baseline	↑ – recovery time halved (30 d vs 60 d)	↔	↑ – quickest bounce-back across COVID-19 cases	COVID-19 Indonesia; Iraqi competence (SEM)

Technology adoption / digital integration (BIM, IoT), dashboards	↑ – (SCOR) dashboards cut cost variance 4-6 pp	↑ – lead-time ↓ 17 % on road-widening	↑ – KPI transparency boosted perfect-order 13 %	↑ – IoT tracking flagged disruptions early	Indonesian road project; (IPD-IoT) Iran
Lean / Agile collaborative practices	↑ – pull scheduling trimmed wastage (≤ 10 % overrun)	↑ – stand-ups shaved 1-2 wks off short-term look-aheads	↑ – defect re-work rates fell	↑/↔ – agile teams adapted faster, but only with risk buffers	Lean/Agile Saudi; Tanzanian consulting
Procurement ethics & governance	↑ – fraud-free tenders avoided 5-7 pp cost inflation	↑ – fewer stop-work notices shortened schedules	↔ – quality effects indirect	↔ – limited influence on shock recovery	(SA) public procurement; Pakistan public vs private
Knowledge sharing & learning culture	↑ – lessons-learned reuse cut estimating errors	↑ – knowledge-infusion improved task coordination	↑ – service-quality scores ↑ in consultancy cases	↔ – culture alone insufficient without buffers	Tanzanian consulting; Maced knowledge cases
Resilience / redundancy design	↔ – redundancy raises carrying cost (buffers) but prevents extreme overruns	↑ – scenario drills cut recovery to ≤ 25 d	↔	↑ – redundancy & drills biggest driver of rapid recovery	Thai mega-infra resilience; COVID-19 multi-sourcing

4.3 Validation of the Integrated Lean-Digital Framework

Mapping empirical findings onto the proposed four-level model shows a strong fit between framework levers and observed (KPI) shifts as shown in Figure 6.

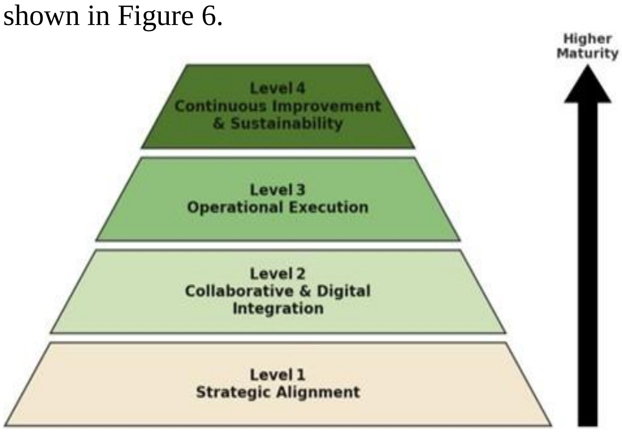

Figure 6. *four level supply chain optimization frameworks*

- Level 1 - Strategic Alignment. Projects that articulated shared cost-schedule-quality goals at inception (e.g., Iraqi competence (SEM)) recorded fewer change orders and narrower cost variance.
- Level 2 - Collaborative & Digital Integration. (BIM/IoT) hubs coupled with (IPD) contracts shortened information latency and boosted perfect-order fulfilment in the Iranian (IPD) pilot and Indonesian road project .
- Level 3 - Operational Execution. Pull logistics, Last-Planner stand-ups and visual (KPI) boards stabilized workflow, trimming wastage to below 10 % in the Saudi lean-agile cases.
- Level 4 - Continuous Improvement & Sustainability. Projects hosting Kaizen reviews and lessons-learned registers (e.g., Thai resilience scenarios) achieved faster recovery after shocks and lower re-work rates.

Table 3 shows the components of the framework that are compatible with the research questions as shown below:

Table 3. Framework Components Aligned to Research Questions

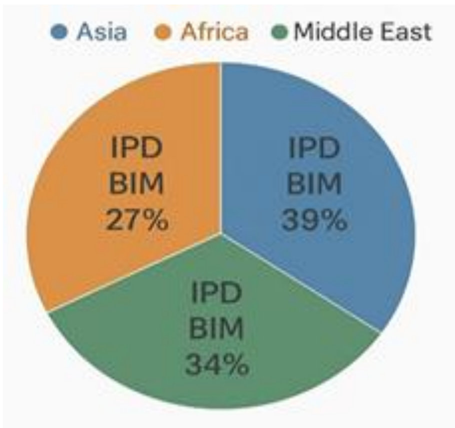

Figure 7. *Regional distribution of (IPD) and (BIM) adoption across Asia, Africa, and the Middle East.*

***Table 3**. Framework Components Aligned to Research Questions*

Framework component	Core elements in the framework	Primary research questions addressed	Illustrative (KPI) or outcome focus
Level 1- Strategic Alignment	Vision-driven supply-chain goals Governance structure & responsibility map High-level risk appetite & funding model	RQ-1 – What strategic factors most strongly determine supply-chain efficiency in civil-engineering projects?	Cost variance ↓ Contract change orders ↓
Level 2- Collaborative & Digital Integration	(BIM)/ digital-twin data hub Cloud-based document sharing & e-procurement Multi-party partnering agreements (IPD / alliance	RQ-2 – How do collaborative practices and digital tools enable more resilient & responsive supply chains?	Perfect-order fulfilment ↑ Information-latency ↓
Level 3- Operational Execution	Pull-logistics & takt planning Last-Planner stand-ups and visual KPI board (SCOR) aligned metrics & exception-response loops	RQ-3 – Which operational practices translate strategic intent into day-to-day performance gains?	Lead-time variance ↓ On-site inventory turns ↑
Level 4-Continuous Improvement & Sustainability	(PDCA)/ Kaizen review cycle Data-driven lessons-learned register Carbon-aware supply-chain decisions & (CSR) scoring	RQ-4 – How can continuous-improvement mechanisms sustain gains and embed social–environmental value	Re-work ↓ (CO_2) per m^3 concrete

4.4 Comparative insights by project context

The Case-Study Selection Matrix shows that while benefits are not limited to megaprojects, they do scale with project maturity. While big Saudi manufacturing complexes needed complex (ERP/SEM) coupling to buffer complexity impacts, medium-scale Indonesian and Nepali projects used agile stand-ups and minimal (BIM) to control early payment delays. But small and medium-sized enterprises found it difficult to obtain capital and knowledge, which indicated a need for gradual rollouts and focused legislative assistance.

4.5 Discussion: theoretical and practical implications

The findings theoretically broaden Lean Construction by incorporating redundancy and scenario- based resilience components usually considered "waste" in classic lean logic into a whole optimization story. While digital twins provide the data backbone enabling real-time adaptation, systems-thinking increases visibility of feedback loops. The convergence of these threads strengthens the case for hybrid, context-sensitive frameworks promoted [6,23].

Practically, managers should:

• Before design freeze, ensure early strategic alignment by means of shared-risk contracts and joint risk workshops.

• Invest in mobile dashboards tuned to (SME) capacity, lightweight, interoperable digital tools common-data environments.

• Daily collaborative practices stand-ups, pull scheduling should be embedded to convert strategic intent into shop-floor discipline.

• Establish ongoing improvement cycles that capture knowledge, adjust (KPIs) and include sustainability measures.

By means of standards for data exchange, tax incentives for (BIM) uptake, and enforcement of anti-corruption initiatives, policy makers can hasten adoption by addressing governance gaps undermining supply-chain integrity.

4.6 Limitations and avenues for future study

Heterogeneity across sources limits rigorous statistical inference; reliance on secondary data restricts control over metric definitions and contextual granularity. Triangulation across multiple different initiatives, however, improves transferability. Emerging as urgent next actions are longitudinal studies tracking framework maturation, more investigation of interoperability criteria, and inclusion of carbon-footprint (KPIs).

5.Conclusions

This paper aimed to find ways for civil-engineering supply chains to overcome ongoing fragmentation, budget drift, and schedule volatility. The study validated three research findings by triangulating thematic evidence and descriptive metrics from multiple different projects. Performance first depends on early, open alignment among owners, designers, contractors, and suppliers. Projects that held joint-risk workshops prior to design freeze and used incentive-sharing contracts reported less late design changes and more tighter cost variance. Second, digitally enabled collaboration increases efficiency only when combined with governance and cultural readiness. Though they offered little advantage in hostile tender settings, (BIM) dashboards, (IoT) trackers, and 4D/5D scheduling quickened information flow, highlighting the interdependence of technology and trust. Third, lean waste-reduction benefits long-term only when nested within dynamic-capability routines that sense, absorb, and adapt to disturbance.

Drawing on these results, the study proposed an Integrated Lean-Digital Framework structured into four cascading layers:

- Strategic Alignment.
- Collaborative & Digital Integration.
- Operational Execution.
- Continuous Improvement & Sustainability.

Mapping empirical results onto this framework showed a clear correlation between layered adoption and enhanced key-performance indicators: lead-time variance dropped by up to 17 percent, and cost overruns fell four to six percentage points on projects that progressed through all four layers. The framework thus offers practitioners a phased road map flexible to project size and digital maturity by embedding redundancy, scenario-based resilience, and live data feedback elements usually considered opposed to classic lean logic, therefore extending lean-construction theory.

The exclusive use of secondary data creates limitations by limiting control over metric definitions and preventing more thorough investigation of stakeholder perceptions. Purposeful case selection across several areas and project kinds increases the transferability of ideas, and convergent triangulation reduces single-source prejudice.

Future studies should include carbon-footprint or circular-economy measures to match supply- chain optimization with sustainability requirements, test interoperability standards for common- data environments, and pursue longitudinal, multi-stakeholder research quantifying how each framework layer matures over time.

All things considered, the data supports the idea that no one paradigm lean, digital, agile, or systems-oriented suffices in isolation. The efficiency and resilience required by twenty-first- century infrastructure projects can be delivered only by a context-sensitive hybrid that synchronizes strategic intent, collaborative culture, digital transparency, and unrelenting learning.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of 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
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- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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