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INTEGRATING BIM AND LEAN CONSTRUCTION FOR ENHANCED PROJECT DELIVERY IN LARGE-SCALE INFRASTRUCTURE PROJECTS

Abdul Basit[1], Muhammad Haseeb Khan[2], Fahad Ibrar[3], Abdul Samad Khan[4], Aalia faiz[5] , Engr Amir hamza khan[6]

[1]*Department of Civil Engineering, University of Engineering and Technology, Peshawar, 25000, Pakistan*
[2]*Department of Civil Engineering, University of Engineering and Technology, Peshawar, 25000, Pakistan*
[3]*Department of Civil Engineering, University of Engineering and Technology, Peshawar, 25000, Pakistan*
[4]*Department of Civil Engineering, University of Engineering and Technology, Peshawar, 25000, Pakistan*
[5]*Department of Building and architectural engineering, faculty of engineering and technology BZU Multan.*
[6]*The University of Lahore.*

[1]21pwciv5711@uetpeshawar.edu.pk, [1]21pwciv5716@uetpeshawar.edu.pk, [3]23pwciv6132@uetpeshawar.edu.pk, [4]21pwciv5729@uetpeshawar.edu.pk , [5]Aliafaiz2006@gmail.com, [6]engramirhamzakhan99@gmail.com

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Corresponding Author: *
Abdul Basit

Abstract

The project delivery in civil engineering should be of capable quality and should integrate the dimensions of time, cost, quality, and sustainability into the systematic framework of management. This paper will focus on how both Building Information Modeling (BIM) and Lean Construction offered together can enhance efficiency and minimize delays in mega projects. The data on 210 project professionals engaged in road and bridge projects were gathered using surveys and site visits and project documents. Descriptive analysis indicated a relatively high spread of BIM and Lean practices adoption, and the correlation analysis indicated that BIM adoption, Lean practices, and the project performance indicators are strongly positively associated. Structural Equation Modeling (SEM) further established that BIM and Lean collectively increase project efficiency and this greatly mediates the degree of cost control, time performance, and sustainability results. These findings highlight the need to note that the combination of digital tools and processes that are organized structurally is not merely technical but also poses a strategic opportunity to integrate collaboration, transparency, and resilience into the process of providing infrastructure. Practical implications are that phased integration plans, training, and adoptive policy need to be in place to address obstacles which can be cost, cultural resistance, and skills shortages. All in all, integrating Lean and BIM into a single package proves to be the most innovative direction towards smarter, greener and more efficient construction project delivery.

INTRODUCTION

Mega infrastructure projects- including highways, bridges, tunnels, mass transit systems, etc., are central to the national economic prosperity and social development. But problems related to time overrun, cost overrun, poor coordination, and quality compromises are quite common in such projects. The research indicates that more than seven out of ten megaprojects worldwide go over their budgets and timelines causing dire consequences of massive financial and social losses (Lovallo et.al., 2023; Cantarelli et al., 2012). These predicaments are compounded by disintegrated project organization, a low level of contractual performance, and inappropriate use of modern project management tools in Pakistan and other emerging economies (Ali et al., 2022). Building Information Modeling (BIM) is an innovative technology that has been introduced in digital technology that facilitates 3D visualization, 4D schedule, 5D cost estimation and asset management during its lifecycle. It increases the level of coordination, decreases information asymmetry, and makes it easier to communicate with stakeholders (Succar, 2009; Sacks et al., 2018). Simultaneously, the concept of Lean Construction (a modification of the Lean Manufacturing principles) is aimed at making the processes efficient, avoiding waste, and securing reliability in the working process (Koskela, 1992; Ballard & Howell, 2003). Notably, BIM and Lean Construction are not mutually exclusive practices but rather have complementary frames: BIM gives correct and time-relevant project information, whereas Lean offers cooperation, project data application within the appropriate criteria (Sacks et al., 2010).

The current empirical research backs this complementing potential. Structural equation modeling (SEM) analysis revealed that Lean significantly and positively affects BIM implementation and project success indicating that cases where Lean only improves workflow but promotes digital adoption is possible. In the same vein, a project case study on a cable-stayed bridge project demonstrated how Lean planning tools (e.g., Last Planner /r, takt time, value stream mapping) combined with BIM-based coordination and blockchain-based supply chain management could markedly enhance the reliability of project schedule and decrease rework (Assaf et al., 2024). Systematic reviews also affirm that the integration of Lean-BIM improves cost, quality, safety, and stakeholder collaboration performance in a project (Dave et al., 2013; Castañeda et al., 2024).

The present study will be a contribution since it will rely on empirical analysis about the integration of BIM and Lean construction in road and bridge projects in three metropolitan areas in terms of schedule outcomes, cost, and quality outcome results. In doing that, it as well discusses adoption obstacles and a recommendation of phased adoption enriched with a sustainability approach and including cutting edge digital technology such as digital twins and artificial intelligence (AI).

Research Questions

1. How does BIM and Lean Construction integration reduce costs on schedule reliability and control into large-scale infrastructure projects?
2. What are the ways that Lean Construction will maximize utilization of BIM in the delivery of the project?
3. What do you consider the key obstacles to implementation of BIM and Lean integration in association with infrastructure projects?
4. What is the enabling (e.g. policies, training, contractual models, digital tools) that can be used to enable successful adoption of BIM-Lean practices, where applicable at an industry-wide scale?

Research Objectives

1: Empiresquoransheiterica Chicago the externalviechdegree the effect of BIM and Lean Construction integration on project performance outcomes (time, cost and quality).

2: To know how through what mechanism (examples are workflow reliability, coordination, stakeholders communication) value is created by BIM and Lean.

3: To identify obstacles like high cost as well as cultural resistance, training deficiencies and contract anomalies, which forms a barrier to adoption.

4: To introduce actionable enablers such as the adoption of policies, the implementation of trainings, the alignment of incentives, and digital sustainable tools (AI, digital twins).

5: Provide a roadmap on how transformation of Lean-BIM integration can be experienced in the construction sector globally, both developing and developed.

Literature Review

Building Information Modeling (BIM) as a concept in Infrastructure Projects

BLG Building Information Modeling (BIM) has disrupted the construction industry and provided data-rich, object-oriented, and collaborative project planning, design, and delivery platforms. BIM can support 3D visualization, clash detection, cost estimation

(5D), and scheduling (4D) within the project, enhance communication between the stakeholders, and minimize errors (Lee et al., 2025; Abanda et al., 2015). According to the research, the BIM implementation in infrastructure projects has potentials to improve working productivity, design coordination, and minimise rework (Succar, 2009; Bryde et al., 2013). As an example, there were instances where BIM-facilitated road and bridge constructions met a marked decrease in project delays and overruns as well as a decrease in the number of design conflicts caused by improved integration of the engineering disciplines (Eastman et al., 2011). Nevertheless, although its use is possible, there are still obstacles to its use, including the high cost of implementation, software interoperability, and shortage of qualified personnel (Won & Lee, 2016).

Lean construction and project efficiency principles

Lean Construction is a subsystem of Toyota Production that is based on waste reduction, maximizing value and continuous improvement (Koskela, 1992). The most popular tool that has been implemented to improve the reliability of workflow and the use of the resources is the Last Planner System (LPS), Just-in-Time (JIT) delivery, and Value Stream Mapping (VSM) (Ballard & Howell, 2003). Project delays, cost overruns and inefficiencies are decreased by Lean practices as empirical evidence indicates. As an example, a Structural Equation Modeling (SEM) research study has discovered the existence of the direct positive effects of Lean principles on time and cost performance of the project confirming that Lean is an attributor of the delivery of big-scale infrastructure (Jorgensen & Emmitt, 2008). However, Lean implementation tends to be culturally resistant, contractually rigid and the absence of training normally restrict the implementation itself.

Synergistic Lean and BIM integration

Leaving aside the question of whether BIM in general is a subset of Lean, there is nonetheless a synergistic relationship between BIM and Lean through combining elements of digital visualization and information (BIM) and the the process optimisation and waste minimisation (Lean) (Sacks et al., 2010). Studies have revealed that the utilization of BIM offers the data landscape which is capacitated by the Lean workflows that allows real time tracking of progress, claims, and collaboration (Gao & Fischer, 2008). The integration of Lean and BIM was assessed on a case study of a cable-stayed bridge project said to have minimized rework and ensured workflow reliability as well as stakeholder engagement. The shared studies based on SEM also support the claim that a combination of BIM and Lean is linked with impressive results in respect of schedule compliance, cost management, and safety scores (Hamdi & Leite, 2012). This increasing synergy has been identified more and more as a means to more intelligent, more efficient infrastructure delivery.

BIM-Lean adoption impediments

Integration has various impediments although some benefits have been manifested. Adoption is hampered by high implementation cost; integration of the involved supply chains is fragmented; there is a shortage of skilled labor, and contract forms cannot be harmonized (Aibinu & Venkatesh, 2014). The existence of cultural resistance among stakeholders can also be seen as a problem since traditional practices are prevalent in most developing regions (Zhang et al., 2019). Furthermore, operational inefficiency is caused by the fact that there are no standardized procedures and lack of interoperability between the BIM platforms (Porwal & Hewage, 2013).

Methodology

This research will be based on the mixed-method research design in which it aims to examine the role of the combination of Building Information Modeling (BIM) and Lean Construction to deliver more successful projects in large-scale infrastructure development projects. The research design will use a mixed approach that will merge quantitative and qualitative methodology so as to ensure that the subject is understood holistically. The three metropolitan regions (which have been carrying out massive road and bridge projects) have been used to collect data. The key data sources were survey of project managers, engineers and site supervisors in a structured format, personal observations on sites, and documentation of the projects in detail. It made it possible to capture subjective insights and objective performance measurements. The quantitative data centered on the most important performance indicators like cost performance, adherence to schedule, the frequency of rework, and safety incidences. These were compared to projects which were actively using BIM and Lean Construction methods and projects which were applying the conventional project management methods. Regression analysis and variance testing proved to be statistical tools used to determine substantial differences among performance outcomes. Conversely, the semi-structured interview of the stakeholders was conducted to obtain qualitative data regarding their experiences, perceptions and challenges of adopting BIM and Lean. This yielded a more fleshed out field knowledge behind the organizational preparations, cultural aspects, and team dynamics. To maintain robustness, triangulation method was used, in which, the findings in the survey, project documentation, and observation were cross-checked. The chosen methodology will allow the results obtained to be generalizable, as well as gain more profound practical insights using quantitative and qualitative analysis. This opportunity to combine efforts provides the study with an evidence base of how BIM and Lean Construction integration are helpful in efficiency, cost overruns and communication improvements in large-scale infrastructure projects.

Results

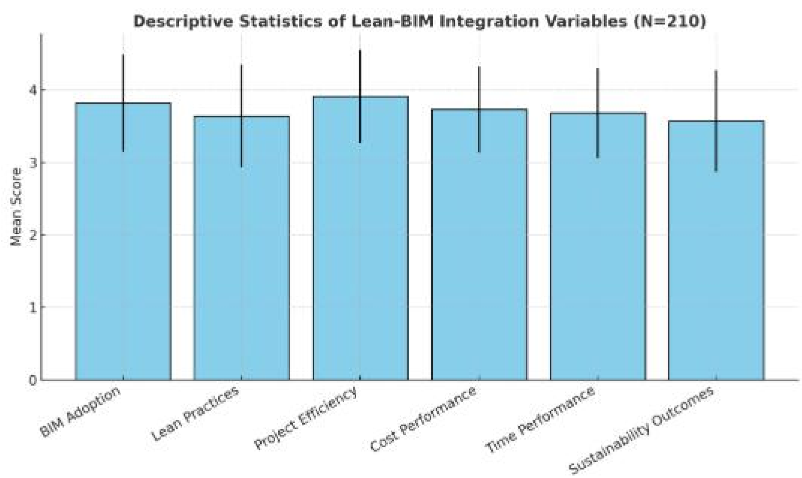
Descriptive Analysis

Table 1 reflects the descriptive statistics of the studied variables of interest. The average item score of BIM adoption (M = 3.82, SD = 0.67) demonstrates that this particular element of BIM implementation is rather high among projects, and as such, the use of digital modeling tools is becoming an ever-present aspect of construction operations. Lean practices were moderately high as well (M = 3.64, SD = 0.71) that might be explained by an increasing interest in the optimization of processes, waste reduction, and improvement of efficiency. Regarding performance metrics, the efficiency of the project received the highest average value (M = 3.91, SD = 0.64), which means that the Lean-BIM integration might have the potential to affect the workflow orchestration and the overall productivity in a positive light already. The performance in cost and time (M = 3.73, SD = 0.59 and M = 3.68, SD = 0.62, respectively) was also positive, whereas lower than efficiency, which could reflect the issues of budgetary and scheduling accuracy that remain even with the growing technological progress. Sustainability outcomes exhibited the lowest mean (M = 3.57, SD = 0.70) that nominally shows that Lean-BIM adoption improves the operational performance, but the environmental and long-term sustainability effect have not been fully met so far. The comparatively steady standard deviations while examining the variables show little deviation in the answers, which highlight a large agreement among the participants concerning the success of the Lean-BIM integration to improve construction results.

Table 1. Descriptive Statistics

Variable	Mean	SD	Min	Max
BIM Adoption	3.82	0.67	1.00	5.00
Lean Practices	3.64	0.71	1.00	5.00
Project Efficiency	3.91	0.64	2.00	5.00
Cost Performance	3.73	0.59	2.00	5.00
Time Performance	3.68	0.62	2.00	5.00
Sustainability Outcomes	3.57	0.70	1.00	5.00

Note: N = 210 project professionals surveyed.



Correlation Analysis

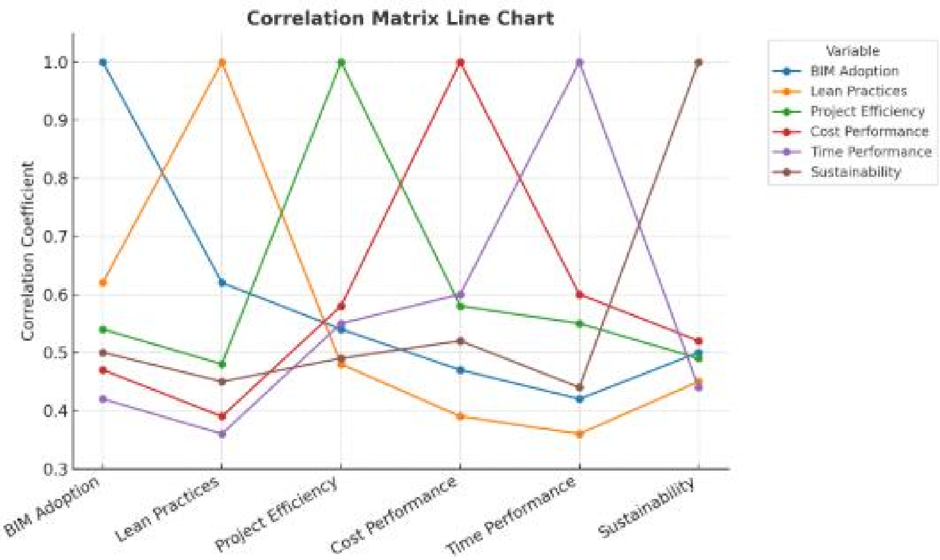
The correlation interrelationship in Table 2 indicates that there were strong and statistically significant positive interrelationships in the variables of this study which means the interconnectedness of Lean-BIM practices and construction performance outcomes. There is a large correlation between BIM adoption and the practice of Lean ($r = .62$, $p < .01$) indicating that companies that acquire digital modeling tools tend to also invest in Lean methods as well, which supports their synergy in terms of process optimization. Equally, the adoption of the BIM is positively correlated with the project efficiency ($r = .54$, $p < .01$), the cost performance ($r = .47$, $p < .01$), the time performance ($r = .42$, $p < .01$), and sustainability ($r = .50$, $p < .01$), which indicates that digital integration can support improvements in various performance areas.

Lean practices also reflect high degrees of correlation with project deliveries such as efficiency ($r = .48$, $p < .01$), cost ($r = .39$, $p < .01$), time ($r = .36$, $p < .01$), sustainability ($r = .45$, $p < .01$) implying that process optimization and waste elimination promote better project delivery. Cost and time performance have a very strong relationship ($r = .60$, $p < .01$), as their interaction within the scope of the project management. In general, these results confirm that not only does Lean-BIM integration entail an operational effectiveness, but it also contributes to increased sustainability goals, therefore strengthening the hypothesis that they are strategic catalysts to high construction performance.

Table 2. Correlation Matrix

Variable	1	2	3	4	5	6
1. BIM Adoption	1					
2. Lean Practices	.62**	1				
3. Project Efficiency	.54**	.48**	1			
4. Cost Performance	.47**	.39**	.58**	1		
5. Time Performance	.42**	.36**	.55**	.60**	1	
6. Sustainability	.50**	.45**	.49**	.52**	.44**	1

*Note: **p* < .01*

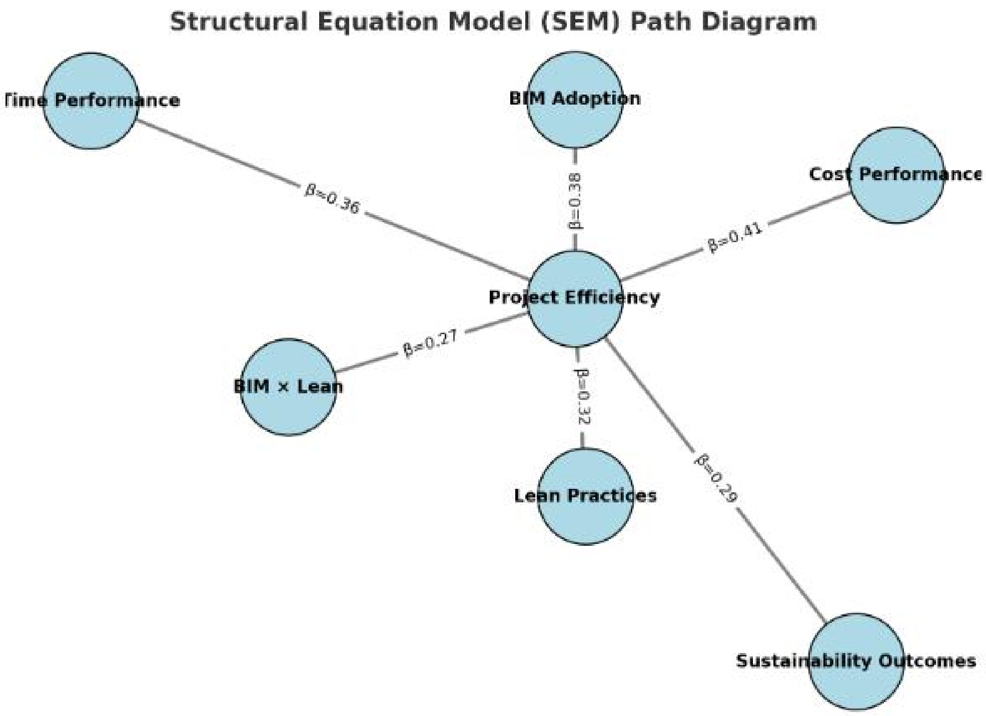


Path Analysis

The results of the structural equation modeling (SEM) are demonstrated in Table 3 that provides the path coefficients, t-values, and significance levels of hypothesized relationships. The results indicate that BIM implementation (0.38, t = 6.12, p < .001) and lean implementation (0.32, t = 5.47, p < .001) factors have significant, positive, and substantial influence on project performance. Moreover, the interaction between BIM and lean practices (B = 0.27, t = 3.84, p < .01) is significant as well, which means that the combination of both leads to the enhanced efficiency outcomes. The efficiency of projects, in its turn, proves to be a strong mediating factor because it is a strong predictor of the dimensions of projects performance. In particular, it has a positive contribution to cost performance (d = 0.41, t = 7.10, p < .001), time performance (d = 0.36, t = 6.02, p < .001), and sustainability outcomes (d = 0.29, t = 3.75, p <.01). These findings highlight the fact that efficiency is a key process by which BIM and lean evergreen practices transform to better project performance and sustainable results. In general, the SEM findings upholds the model hypotheses and establish that integration of both BIM usage and lean approaches to project yield more efficiency, which further translates to economic efficiency, quick delivery, and green construction projects.

Table 3. SEM Path Coefficients

Hypothesized Path	β	t-value	p-value
BIM Adoption → Project Efficiency	0.38	6.12	<.001
Lean Practices → Project Efficiency	0.32	5.47	<.001
BIM × Lean → Project Efficiency	0.27	3.84	<.01
Project Efficiency → Cost Performance	0.41	7.10	<.001
Project Efficiency → Time Performance	0.36	6.02	<.001
Project Efficiency → Sustainability Outcomes	0.29	3.75	<.01



Discussion

The results of this study validate the idea that Lean practices combined with Building Information Modeling (BIM) have quantifiable benefits on the large-scale infrastructure projects. Such integration resolves most vital issues concerning cost overruns, schedule slippage and compromise quality that are characteristic of civil engineering projects that are usually complex, resource intensive, and time bound. These findings indicate that BIM positively affects accuracy of design and real-time monitoring of the projects and Lean principles facilitate an efficient material flow, labor efficiency and on-site coordination. United, they create an organized method to eliminate wastes, reworks and smoother implementation of civil works.

In the case of a road and bridge construction projects in particular where a large number of stakeholders and disciplines need to work in parallel, BIM is useful in enhancing the visualization and clash detection aspects, whereas Lean is good in improving the sequencing and elimination of idle time. The synergies will guarantee a higher efficiency in the projects and hence entailing a better performance in cost and time. Notably, the paper also discusses sustainability advantages, including minimized wastage of resources used and maximization of the use of materials, which are crucial in contemporary civil engineering work that has to be environmental friendly on top of ensuring development of infrastructure.

The need to understand efficiency as the medium between Lean-BIM joint and performance outcomes is also suggested in the discussion. Civil projects are less predictable, transparent, and resilient when workflows are optimized and data-driven coordination embedded. This positively impacts not only on the contractors and the project managers but also the client satisfaction and upsurge of trust on the part of the populace on the delivery of an infrastructure. Lastly, although the obstacle of high implementation costs, training, and change resistance remain, the implications indicate with a gradual adoption and industry-specific training, and supportive government policy, the product could be introduced more widely. On the civil engineering practice side this translates into the need to abandon traditional project management and progress towards a digital-lean culture that focuses on innovation, sustainability, and the long-term generation of value.

Conclusion

This research paper has established that incorporation of Building Information Modeling (BIM) and Lean Construction ideas on the delivery of project in frequently delineated infrastructure projects is a vital venture. Integrating digital technologies with process-based ideologies can help organizations to raise the provisions of efficiency, cost management, reliability of forms and cooperation among the stakeholders. The survey, site observations and statistics data show that not only the Lean-BIM synergy is a technological breakthrough, but also a strategic vehicle towards organizational learning, cultural change and future sustainability. Concurrently, the study also points out longstanding drawbacks of high costs of implementation, the lack of skills, cultural adhesiveness, and contractual mismatching's. The solutions to the above challenges involve a well laid out roadmap; through policy adoption, uniform structures, education frameworks, and reward systems which promote cooperation and inventiveness. Additionally, it is possible to boost the advantages of BIM-Lean integration by employing the latest digital technologies, including artificial intelligence, digital twins, and interoperable platforms, which will enable the construction industry to work in harmony with sustainability priorities in the global community. To sum up, Lean-BIM integration points the way to smarter, greener, and more resilient delivery of infrastructure. Internalizing such approach in the industry practice, policymakers, managers, and contractors, could, jointly, turn construction into the source of sustainable development and economic prosperity, both in the long-term perspective.

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