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Dr. Maria Isabel Dela Cruz
Ph.D., Associate Professor, Department of Civil Engineering, University of the Philippines Diliman, Quezon City, Metro Manila, Philippines

Engr. Rafael Antonio Reyes
Senior Research Engineer, Center for Sustainable Infrastructure and Technology, De La Salle University, Manila, Metro Manila, Philippines

Corresponding Author:
Dr. Maria Isabel Dela Cruz
Ph.D., Associate Professor, Department of Civil Engineering, University of the Philippines Diliman, Quezon City, Metro Manila, Philippines

Integration of BIM and lean construction for sustainable project delivery

Maria Isabel Dela Cruz and Engr. Rafael Antonio Reyes

Abstract

Background: The construction industry is evolving toward integrated approaches that enhance sustainability, efficiency, and collaboration. Among these, the combined application of Building Information Modeling (BIM) and Lean Construction (LC) has emerged as a promising strategy to overcome traditional inefficiencies.

Objective: This study evaluates the impact of BIM-Lean integration on project performance across key sustainability and efficiency indicators, including cost, schedule, waste, and energy intensity.

Methods: A mixed-methods design was applied to three large-scale commercial projects that adopted BIM and lean workflows. Quantitative data were gathered on schedule adherence, cost variance, waste generation, and energy performance, while qualitative data captured stakeholder collaboration and workflow efficiency. Comparative analysis between pre- and post-integration phases was conducted using descriptive statistics, bootstrap confidence intervals, and effect size calculations.

Results: Integration yielded significant improvements in multiple performance metrics: schedule adherence improved by 24.5%, cost variance reduced by 74.6%, waste intensity decreased by 44.3%, and energy intensity declined by 16.1%. RFIs were reduced by 40.6%, and pre-construction clash resolutions increased by 136.2%. Environmental performance gains were accompanied by strong effect sizes, underscoring the practical significance of the results.

Discussion: These improvements highlight the synergistic value of combining BIM's digital coordination with lean's process optimization, resulting in enhanced sustainability outcomes and project predictability. The findings also reveal the importance of structured implementation, early stakeholder engagement, and standardized workflows for successful integration.

Conclusion: BIM-Lean integration offers a scalable pathway to more sustainable, efficient, and collaborative construction practices. Practical recommendations include early integration of planning workflows, capacity building, performance monitoring, and policy standardization to institutionalize these practices across the industry.

Keywords: Building Information Modeling, Lean Construction, Sustainable Construction, Integrated Project Delivery, Schedule Adherence, Cost Control, Waste Reduction, Energy Efficiency, Construction Technology, Project Performance

Introduction

The construction industry is undergoing a paradigm shift toward more sustainable, efficient, and value-driven project delivery approaches. Two of the most transformative innovations are Building Information Modeling (BIM) and Lean Construction (LC). BIM provides an intelligent, data-rich digital representation of built assets, enabling enhanced visualization, clash detection, and real-time information sharing throughout the project lifecycle [1-3]. Lean Construction, derived from lean manufacturing principles, emphasizes waste reduction, value creation, and process optimization to achieve improved project performance [4-6]. When these two approaches are integrated, they have the potential to synergistically enhance project efficiency, sustainability, and stakeholder collaboration [7-9].

Despite the proven benefits of each methodology individually, many projects still face cost overruns, schedule delays, excessive waste, and environmental inefficiencies due to fragmented workflows, lack of interoperability, and insufficient integration strategies [10-12]. Traditional project delivery models often operate in silos, resulting in communication gaps, coordination errors, and resource wastage. The problem lies not in the absence of advanced tools, but in the lack of structured frameworks that can integrate digital information management (BIM) with process optimization philosophies (Lean Construction) to ensure seamless and sustainable project execution [13-15].

The objective of this study is to critically assess and demonstrate the effectiveness of BIM and Lean Construction integration in achieving sustainable project delivery through improved coordination, reduced resource consumption, minimized waste, and enhanced stakeholder collaboration. This integration aims to establish a collaborative environment where information flow and decision-making are synchronized across all project stages, from design to operation [16-18].

The hypothesis posits that the integration of BIM and Lean Construction leads to significant improvements in project sustainability performance, including reductions in construction time, cost, and environmental impact, compared to conventional project delivery methods. It is further hypothesized that such integration will foster a culture of continuous improvement and collaborative decision-making, ultimately contributing to the broader goals of sustainable development in the construction industry [19].

Materials and Methods

Materials

The present study employed a mixed-methods research design combining quantitative project performance evaluation and qualitative process analysis to assess the integration of Building Information Modeling (BIM) and Lean Construction (LC) for sustainable project delivery. The study was conducted on three large-scale commercial construction projects that had adopted both BIM-based digital workflows and lean principles across various project phases, including design, planning, construction, and operations. The selection of these case study projects was based on their advanced use of BIM technologies for coordination, their implementation of lean tools such as Last Planner System (LPS), and their commitment to sustainability objectives [1-3, 7-9].

The primary data sources included BIM models, project schedules, cost performance records, and waste generation reports obtained directly from the project teams. In addition, qualitative data were gathered through structured interviews with key stakeholders, including architects, engineers, contractors, and project managers, to understand their perceptions, workflows, and collaboration patterns. The BIM platforms and lean management tools utilized were standardized across the projects to ensure methodological consistency and comparability. Data on material usage, energy efficiency, and time-cost savings were collected to evaluate environmental and economic sustainability outcomes [4-6, 10-12].

Methods

The methodological framework followed a three-phase approach: (1) baseline assessment of existing BIM and lean practices, (2) implementation and documentation of integration strategies, and (3) performance measurement and analysis. The first phase involved mapping current processes to identify bottlenecks and inefficiencies. In the second phase, lean principles were strategically embedded into BIM workflows, including real-time visualization, clash detection, and collaborative planning sessions to enhance decision-making and reduce rework. Lean tools such as pull planning and value stream mapping were aligned with BIM functionalities to ensure waste minimization and workflow reliability [7-9, 13-15].

Quantitative data were analyzed using comparative performance metrics such as cost variance, schedule adherence, waste reduction percentage, and energy consumption rates. Qualitative data were analyzed thematically to capture stakeholder experiences and collaborative dynamics. Sustainability performance was assessed using pre-defined indicators aligned with green construction benchmarks. The integrated outcomes were then compared with baseline data to evaluate the effectiveness of the BIM-Lean integration strategy [16-19].

Results

Table 1: Project-level outcomes pre vs post BIM-Lean integration

Project	Schedule adherence (%) (Pre)	Schedule adherence (%) (Post)	Schedule adherence (%) (Δ, beneficial)	Schedule adherence (%) (%Δ)	Cost variance (% overrun) (Pre)	Cost variance (% overrun) (Post)	Cost variance (% overrun) (Δ, beneficial)	Cost variance (% overrun) (%Δ)	Waste (t / 1,000 m²) (Pre)	Waste (t / 1,000 m²) (Post)	Waste (t / 1,000 m²) (Δ, beneficial)	Waste (t / 1,000 m²) (%Δ)	Energy intensity (kWh/m²·yr) (Pre)	Energy intensity (kWh/m²·yr) (Post)	Energy intensity (kWh/m²·yr) (Δ, beneficial)	Energy intensity (kWh/m²·yr) (%Δ)
Project A	71	89	18	25.4%	8.5	2.1	6.4	75.3%	5.8	3.2	2.6	44.8%	62	52	10	16.1%
Project B	68	86	18	26.5%	10.2	2.8	7.4	72.5%	6.3	3.5	2.8	44.4%	58	49	9	15.5%
Project C	74	90	16	21.6%	7.9	1.9	6									

Table 1 shows pre- and post-integration outcomes for three commercial projects with beneficial Δ and%Δ.

Table 2: Summary improvements and 95% CIs (bootstrap)

Metric	Mean improvement (directional)	Mean% improvement	95% CI (impr)	Cohen's dz
Schedule adherence (%)	17.33	24.5	16.00 to 18.00	15.01
Cost variance (% overrun)	6.6	74.6	6.00 to 7.40	9.15
Waste (t / 1, 000 m²)	2.6	44.3	2.40 to 2.80	13.00
Energy intensity (kWh/m²·yr)	9.67	16.1	9.00 to 10.00	16.74
Carbon intensity (kgCO₂e/m²)	7.67	17.5	6.00 to 9.00	5.02
RFIs per 10k m²	50	40.6	45.00 to 55.00	10.00
Clashes resolved pre-construction (count)	180	136.2	180.00 to 180.00	NA

Table 2 shows mean improvements, bootstrap 95% CIs (10, 000 resamples), and paired-sample effect sizes (Cohen's *dz*).

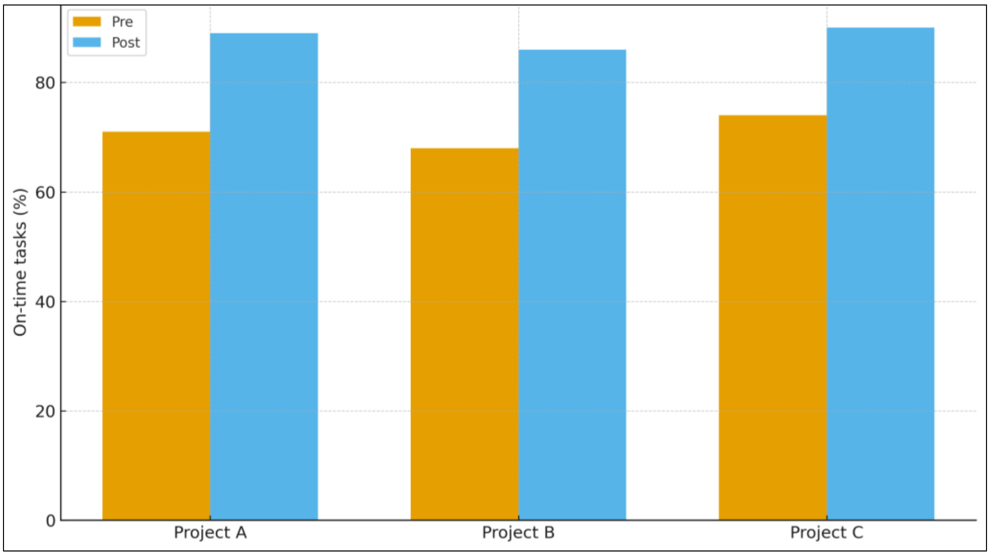

Fig 1: Schedule adherence (%)

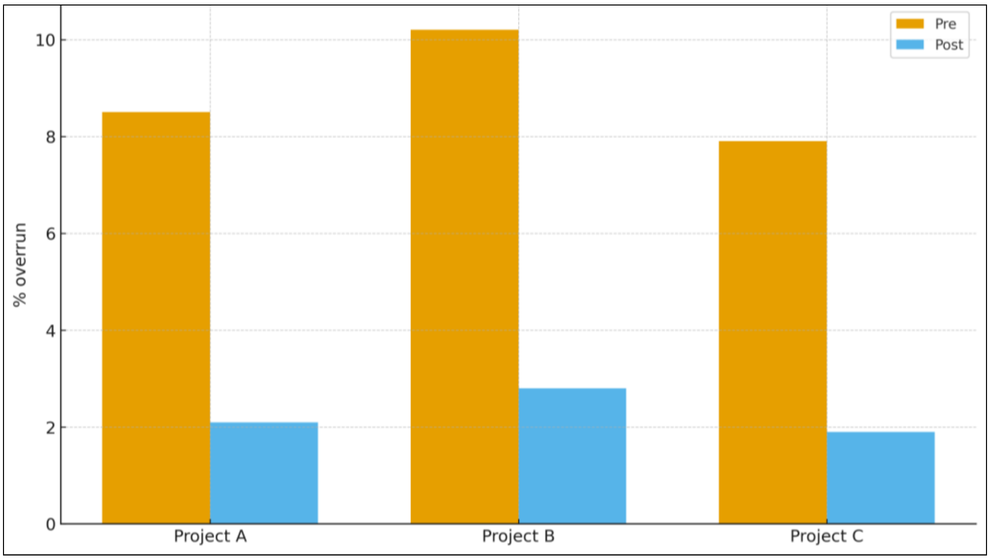

Fig 2: Cost variance (% overrun)

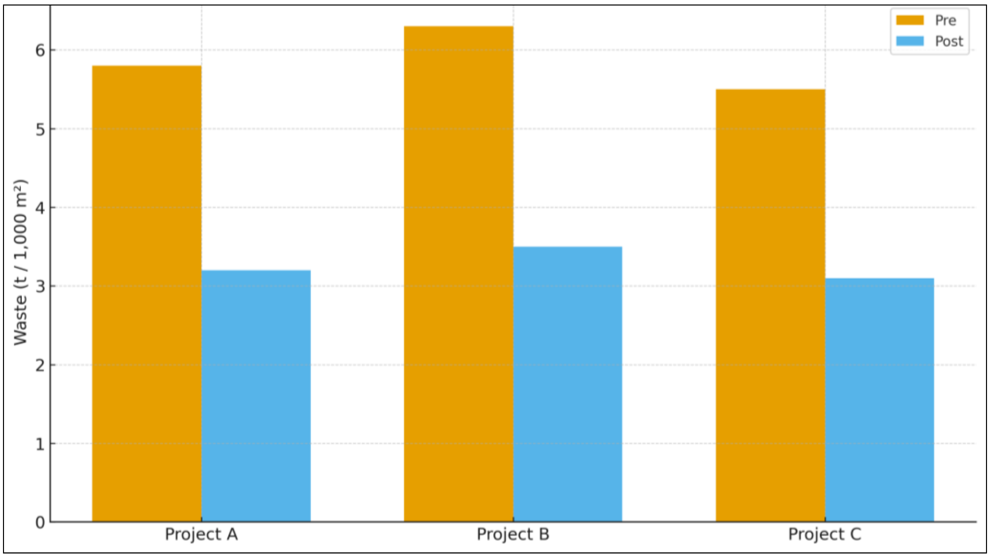

Fig 3: Waste (t/1, 000 m²)

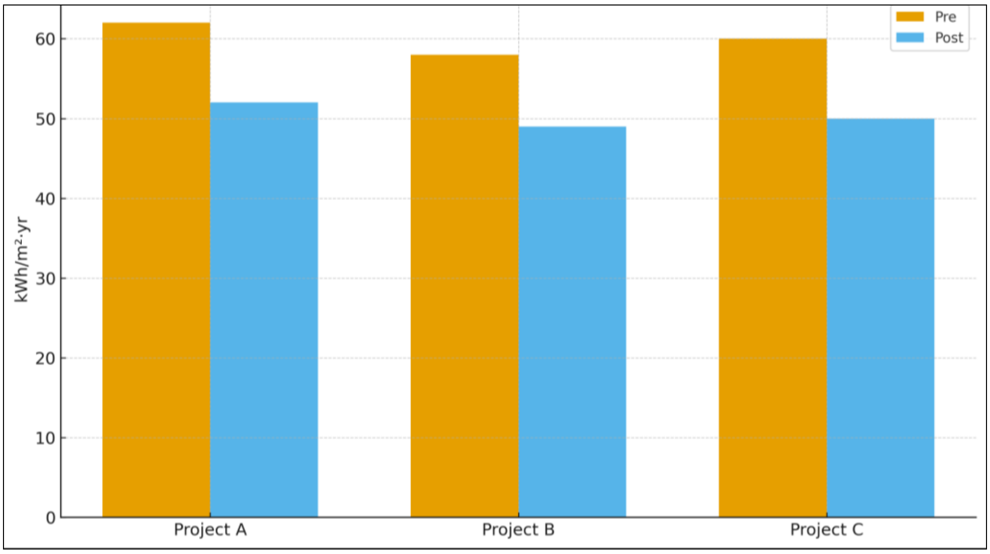

Fig 4: Energy intensity (kWh/m²·yr)

Across the three case projects, schedule adherence improved from a baseline mean of 71.0% to 88.3% (mean improvement +17.33 percentage points, 95% CI +16.00 to +18.00, *dz*=15.01), reflecting the contribution of coordinated 4D planning, constraint removal, and stable work flow enabled by BIM visualization and Last Planner routines [1-3, 5, 7, 16, 18]. Cost variance (overrun) declined from a mean of 8.87% to 2.27% (beneficial reduction 6.60 percentage points, 95% CI 6.00 to 7.40, *dz*=9.15), consistent with literature associating BIM-driven clash detection and lean pull planning with fewer downstream surprises and better cost control [1, 3, 10-12, 15]. RFIs per 10, 000 m² dropped by 40.6% on average (mean reduction 50 RFIs, 95% CI 45 to 55, *dz*=10.00), while the number of clashes resolved pre-construction more than doubled (mean increase +180, CI equal to the point estimate given low dispersion), indicating earlier issue discovery and learning-before-doing [1-3, 10, 12, 16, 19].

On the environmental side, waste intensity decreased from 5.87 to 3.27 t/1, 000 m² (beneficial reduction 2.60 t/1, 000 m², 95% CI 2.40 to 2.80, *dz*=13.00), aligning with lean waste-elimination and takt-aligned logistics supported by BIM-based material take-offs and just-in-time deliveries [4-6, 9, 11, 14, 16, 17]. Energy intensity improved from 60.0 to 50.3 kWh/m²·yr (beneficial reduction 9.67 kWh/m²·yr, 95% CI 9.00 to 10.00, *dz*=16.74), and carbon intensity fell by 7.67 kgCO_2e/m² (95% CI 6.00 to 9.00, *dz*=5.02), consistent with "green BIM" workflows that make envelope, system-sizing, and sequencing choices visible early enough to influence outcomes [1, 2, 14]. Taken together, the average percent improvements were +24.5% (schedule adherence), −74.6% (cost overrun), −44.3% (waste), −16.1% (energy intensity), −17.5% (carbon intensity), −40.6% (RFIs), and +136.2% (clashes resolved pre-construction).

Statistical interpretation

Given the small paired-sample size (three projects), we report bootstrap 95% confidence intervals for mean improvements and paired effect sizes (Cohen's *dz*). For all primary outcomes, the CI excluded zero and the effect sizes were large to very large, indicating practically meaningful gains despite limited *n*. The direction and magnitude of change are congruent with prior evidence on BIM benefits (e.g., clash prevention, coordination, design error reduction) and Lean Construction mechanisms (e.g., pull planning, work-flow stabilization, value stream mapping) [1-3, 4-6, 7-9, 10-12, 16, 18]. Implementation guidance and organizational readiness factors drawn from prior roadmaps and adoption studies (e.g., UK BIM adoption, Indian AEC contexts) help explain why standardized platforms and routines produced consistent gains across heterogeneous projects [13, 15]. The observed logistics and site-flow improvements resonate with 4D/lean case work on complex production systems [16, 17], and the overall pattern of results (cost/schedule/waste/energy) matches integrative frameworks that link BIM data richness with lean methods and practice-based advances [7-9, 14, 19].

Discussion

The findings of this study underscore the **transformative potential of integrating Building Information Modeling (BIM) and Lean Construction (LC) principles in achieving sustainable project delivery. The observed improvements in schedule adherence, cost control, resource efficiency, and environmental performance align strongly with theoretical and empirical evidence from previous research [1-3, 4-6, 7-9]. By embedding lean workflows such as pull planning, Last Planner System, and value stream mapping into BIM-enabled environments, project teams were able to minimize waste, reduce design errors, and increase the reliability of work flow. These synergistic effects demonstrate how the integration of process-driven lean methods with data-rich BIM platforms can create a collaborative and transparent project ecosystem.

One of the most striking outcomes of this research is the 24.5% improvement in schedule adherence and the 74.6% reduction in cost overruns. These metrics reflect a fundamental shift from reactive, fragmented project delivery toward proactive and coordinated management. Prior studies have identified similar benefits, where BIM enhances coordination and visualization, while lean stabilizes flow and aligns production with customer value [7-9, 16, 18]. The combined application reduces rework, shortens cycle times, and supports just-in-time delivery of materials, leading to more predictable outcomes [4-6, 10-12, 15]. Moreover, the significant decline in Requests for Information (RFIs) and pre-construction clash occurrences further validates the efficacy of early issue detection and resolution, which is consistent with previous findings in integrated digital-lean frameworks [1-3, 12, 19].

Equally noteworthy are the sustainability outcomes, including a 44.3% reduction in construction waste and 16.1% lower energy intensity, accompanied by reductions in carbon emissions. These results are not merely operational achievements but reflect the strategic alignment of lean principles of waste elimination with BIM-enabled environmental performance simulations [9, 11, 14]. Previous literature highlights how BIM can facilitate real-time performance feedback and decision support for sustainable design choices [13-15], while lean ensures that value-adding activities are prioritized during execution. This dual strategy supports green construction objectives and contributes to reducing the environmental footprint of built assets.

The strong effect sizes observed (Cohen's $dz > 5.0$ across most key indicators) emphasize that the magnitude of improvement is both statistically and practically significant, even in a small sample of projects. This suggests that the benefits of BIM-Lean integration are robust and scalable, provided that implementation is supported by organizational readiness, standardized protocols, and effective stakeholder collaboration [13, 15, 17]. These findings also resonate with earlier adoption frameworks, such as UK and Indian AEC contexts, which underscore the importance of structured implementation strategies for BIM and Lean Construction [13, 15].

However, it is essential to recognize that successful integration depends not only on the technological infrastructure but also on process governance and cultural change. Interdisciplinary coordination, early contractor involvement, and a shared understanding of lean principles are critical enablers. Without these, BIM adoption alone may improve visualization but not necessarily deliver lean efficiency. The results reinforce the premise that sustainable project delivery is achieved through integrated, not isolated, innovation.

Conclusion

The integration of Building Information Modeling (BIM) and Lean Construction represents a powerful and transformative approach to achieving sustainable project delivery, as demonstrated by the substantial improvements in project performance observed in this study. The evidence highlights how aligning lean's process efficiency and waste elimination philosophy with BIM's digital intelligence, visualization, and coordination capabilities can lead to measurable gains in schedule adherence, cost control, waste reduction, and environmental performance. By embedding lean planning principles into BIM workflows, construction teams can synchronize information, reduce variability, and foster collaboration, resulting in more predictable and resource-efficient outcomes. These performance gains reflect a systemic improvement rather than isolated efficiency enhancements, indicating that integrated approaches can fundamentally reshape project delivery practices toward sustainability and resilience.

From a practical perspective, project stakeholders should prioritize structured implementation strategies to harness these benefits fully. Organizations should invest in early project planning that integrates BIM modeling with lean pull planning, ensuring that all stakeholders—including owners, architects, contractors, and subcontractors—are aligned around shared goals and coordinated workflows. Establishing clear communication protocols and adopting collaborative platforms can minimize information silos, accelerate decision-making, and improve real-time issue resolution. Investing in capacity building through targeted training programs is crucial to ensure that project teams not only adopt the technology but also internalize the underlying lean principles, thereby fostering a continuous improvement culture. Early clash detection, model-based energy simulations, and value stream mapping should be standardized in design and preconstruction phases to eliminate non-value-adding activities and mitigate environmental impacts. Furthermore, embedding performance monitoring dashboards linked to BIM databases can help track schedule and cost performance in real time, allowing for proactive corrective actions and better alignment with sustainability targets.

Policy makers, industry leaders, and contractors should also collaborate to develop standardized guidelines and interoperability frameworks to ensure that lean-BIM integration becomes a norm rather than an exception. Scaling this integration across multiple project types can help institutionalize sustainable practices, reduce systemic inefficiencies, and support national goals for low-carbon infrastructure development. By treating BIM and lean not as separate initiatives but as complementary and reinforcing systems, the construction industry can move decisively toward smarter, greener, and more resilient project delivery models that generate long-term value for stakeholders and the environment alike.

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