

ENHANCING COST RELIABILITY IN CONSTRUCTION: THE SYNERGISTIC IMPACT OF BIM AND LEAN PRINCIPLES

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ABSTRACT

Effective cost management is critical in construction projects, where budget variability often threatens cost reliability and financial performance. Building Information Modeling (BIM) and Lean Construction Principles (LCP) offer complementary approaches to enhance decision-making, optimize resource allocation, and mitigate financial risks. Despite their proven potential, the integration of BIM and LCP remains underutilized, limiting their impact on cost predictability and reliability. Existing research highlights the synergies between BIM and LCP for reducing variability and waste; however, applications in real-world projects often lack comprehensive probabilistic analysis. This paper explores the impact of BIM-LCP integration on cost management and cost reliability using advanced probabilistic methods—Monte Carlo, Importance Sampling, and Latin Hypercube. These techniques provide robust insights into the effects of variability, process standardization, and waste reduction on cost outcomes. Findings underscore the importance of standardizing processes, coordinating disciplines, and minimizing waste to achieve cost reliability. This study offers actionable strategies for construction professionals to enhance financial predictability, optimize contract management, and reduce risks across project lifecycles, aligning with industry demands for improved cost management practices.

KEYWORDS

BIM, Lean Principles, Cost Reliability, Numerical Simulation Model, Cost Management, Budget Variability.

INTRODUCTION

Variability in activity execution costs is a critical factor impacting cost reliability and overall project performance in construction (Tommelein et al., 2001). Despite advancements in project management, the construction industry struggles to address variability effectively, hindering its ability to deliver projects on time and within budget (Fischer et al., 2021). Strategies such as Building Information Modeling (BIM) and Lean Construction Principles (LCP) have shown potential to enhance cost reliability by minimizing waste, standardizing workflows, and

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reducing uncertainty (Koskela et al., 2002). However, their combined impact remains underexplored, particularly in the context of advanced probabilistic methods (Li et al., 2020).

This study addresses these gaps by analysing how variability, process standardization, and waste reduction influence financial outcomes in construction projects (León et al., 2024b). Using Monte Carlo, Importance Sampling, and Latin Hypercube simulations, it evaluates the impact of BIM-LCP integration on cost reliability, compared to traditional management practices (Rubinstein & Kroese, 2016). These methods provide robust insights into cost variability and financial risks, enabling a deeper understanding of their influence on project performance (Koskela & Ballard, 2021). By bridging theoretical and practical gaps, this research offers actionable strategies for reducing cost variability, improving budget predictability, and promoting data-driven decision-making (Keorapetse et al., 2024). The findings contribute to the broader adoption of BIM-LCP integration as a best practice in the construction industry, setting a foundation for more resilient and efficient project management frameworks (Koskela et al., 2019).

POINTS OF DEPARTURE

COST RELIABILITY

Cost reliability is a critical metric in construction, reflecting the likelihood that a project adheres to its planned budget (Chen & Bao, 2013). Managing cost reliability requires addressing its primary driver: cost variability, which arises from uncertainties in resource allocation, execution times, and unforeseen risks (Poshdar et al., 2014). While variability is inherent to construction systems and cannot be eliminated, its impact on cost predictability can be mitigated through strategic management approaches such as Building Information Modelling (BIM) and Lean Construction Principles (LCP), which provide structured methodologies to enhance process control and decision-making (Ballesteros-Pérez et al., 2020).

Cost variability stems from both internal inefficiencies, such as workflow interruptions, and external factors, including material price volatility and environmental conditions (Heigermoser et al., 2019). Rather than attempting to eliminate variability, the focus must be on controlling its effects. BIM and LCP play a crucial role in this process by enabling more accurate cost estimation, proactive risk identification, and enhanced collaboration among stakeholders. By integrating digital modeling and lean management principles, these methodologies significantly reduce cost variability, improving cost reliability (Gonzalez et al., 2008). Unlike variability, cost reliability emphasizes financial predictability, offering a probabilistic measure of a project's ability to remain within budget (Hu & Du, 2014). This metric is essential for accurate cash flow projections, informed financial planning, and long-term economic sustainability (Andújar-Montoya et al., 2020). By quantifying the probability of actual costs aligning with planned budgets, cost reliability provides stakeholders with actionable insights to anticipate and manage financial risks effectively (Keorapetse et al., 2024).

In this study, cost reliability is analyzed using advanced probabilistic tools—Monte Carlo, Importance Sampling, and Latin Hypercube simulations (Abdel-Jaber et al., 2022). These methodologies capture variability and interdependencies, allowing for a detailed evaluation of financial outcomes under uncertainty (Arashpour & Arashpour, 2015). The integration of BIM and LCP further enhances reliability by not only reducing waste and improving coordination but also establishing a systematic approach to managing variability. Through workflow standardization, real-time data analysis, and lean cost management strategies, these methodologies reinforce financial predictability and mitigate risks associated with budget deviations (Li et al., 2017). This study demonstrates that the synergy between BIM and LCP is not merely complementary but a fundamental mechanism for achieving cost reliability,

positioning their integration as a central strategy for financial predictability in construction (Jaśkowski, 2015).

LEAN PRINCIPLES AND BIM: A SYNERGISTIC APPROACH

Lean Principles and Building Information Modeling (BIM) offer complementary strategies to improve construction performance by reducing cost variability (Ballesteros-Pérez et al., 2020). Lean focuses on maximizing value through waste minimization, process standardization, and variability reduction, fostering predictable outcomes and efficient cost management (Koskela et al., 2002). BIM, in turn, integrates data and processes through digital technologies, enabling accurate cost estimation, real-time collaboration, and scenario simulations (Jaśkowski, 2015). By visualizing workflows and identifying risks before execution, BIM enhances transparency, reduces uncertainty, and aligns planned and actual outcomes (Moon et al., 2015).

Together, Lean and BIM create a synergistic framework for modern construction management (Landim et al., 2022). Lean provides the foundation for waste reduction, while BIM delivers the technological tools to operationalize these goals (Koskela et al., 2002). This integration enables construction professionals to reduce risks, improve predictability, and achieve consistent project performance (Ekanayake et al., 2021). Although there are studies linking Lean and BIM with cost variability, there are few studies providing a quantitative approach to the problem. Furthermore, a link between Lean and BIM with cost reliability has not been established. By addressing variability and strengthening cost reliability, this approach transforms traditional construction practices and promotes more resilient and efficient workflows (Landim et al., 2022).

RESEARCH METHODOLOGY

To address the increasing need for financial predictability in construction, this study examines how Building Information Modelling (BIM) and Lean Construction Principles (LCP) influence cost reliability through advanced probabilistic simulation methods (Engebø et al., 2021). Two comparable residential construction projects in Colombia were analyzed: one implementing BIM-LCP and the other using traditional methodologies (León et al., 2024a). Both projects share similar levels of industrialization, resources, and standardization, differing primarily in their management approaches (Lessing et al., 2005). Data from 4,800 residential units, covering three apartment towers per project, were collected at the chapter level (e.g., foundations, structure, finishes), incorporating planned and executed costs for each activity. From this data, key statistical metrics—including cost averages, standard deviations, and covariances—were computed to quantify variability and interdependencies (Janssen, 2013).

These metrics served as inputs for Monte Carlo, Importance Sampling, and Latin Hypercube simulations, which generated thousands of simulated cost scenarios. The selection of these probabilistic methods is based on their well-established applicability in financial risk assessment and construction cost estimation (Rubinstein & Kroese, 2016; Abdel-Jaber et al., 2022). Monte Carlo simulations evaluate cost variability by generating probabilistic distributions of possible outcomes, capturing the randomness inherent in project execution. Importance Sampling enhances computational efficiency by focusing on high-impact probability regions, providing a refined estimation of financial risks. Latin Hypercube Sampling improves the representation of cost dependencies across different project components, ensuring a more systematic distribution of input variables. These methods collectively provide a robust probabilistic framework for analyzing cost reliability under uncertainty.

The failure function, defined as the sum of planned costs across chapters, served as a benchmark to assess deviations. A project was considered financially reliable when the probability of exceeding this threshold was low, ensuring greater cost predictability. The models quantified cost overruns (failure probability, FP) and budget adherence (cost reliability,

CR), demonstrating that BIM-LCP reduced variability and improved cost predictability (Hosseinian et al., 2022). To enhance the robustness of the cost reliability estimates, 95% confidence intervals (CI) were computed using percentiles (2.5% and 97.5%), providing a precise range within which cost reliability values are expected to fall. The CI values were derived from 10,000 iterations, ensuring stability in the estimated metrics. The combination of Monte Carlo, Importance Sampling, and Latin Hypercube simulations captured cost fluctuations and interdependencies, reinforcing the statistical reliability of the results. This methodology establishes a scalable framework for integrating probabilistic analysis into construction management, offering data-driven insights to optimize financial planning and risk mitigation (Aven, 2016).

FIRST STEP – CASE STUDIES

To evaluate the impact of BIM and Lean Construction Principles (LCP) on cost reliability, two residential construction projects in Colombia were selected from a database of over 40 projects. Both projects share comparable levels of industrialization, standardization, technology, equipment, and workforce, differing only in their adoption of BIM-LCP practices. The project implementing BIM-LCP systematically integrated Building Information Modeling (BIM) and Lean Construction Principles (LCP) throughout its lifecycle. BIM was applied through 4D modeling for construction sequencing and 5D modeling for financial tracking, enabling improved cost predictability, enhanced coordination among stakeholders, and real-time project monitoring. Lean principles were embedded via the Last Planner System (LPS) to enhance workflow reliability and Just-in-Time (JIT) strategies to optimize material use and reduce waste. In contrast, the traditional project followed Critical Path Method (CPM) scheduling, conventional cost estimation, and reactive decision-making, without leveraging digital modeling or lean workflow management. This distinction allowed for a comparative analysis of how BIM-LCP influences cost reliability and project performance.

Residential projects, with activities ranging from foundation work to interior finishes, were chosen for their complexity and interdisciplinary demands, which require precise cost management and close coordination among subcontractors. By analysing variability in activity execution costs, this approach provides insights into how management practices influence financial predictability. These findings establish a robust foundation for the probabilistic simulations, offering a detailed assessment of the financial outcomes of BIM-LCP integration.

SECOND STEP – DEFINITION OF VARIABLES AND STATISTICAL METRICS

This step defined key metrics to quantify variability and assess cost reliability, addressing the challenges of financial predictability in construction projects. The analysis used the mean and standard deviation of activity costs to measure variability, cost covariance to capture interdependencies, and a failure function to quantify the probability of budget deviations as a financial risk indicator.

THIRD STEP – DEVELOPMENT OF NUMERICAL SIMULATION MODELS

To address cost variability in construction, this study applied three advanced probabilistic simulation models—Monte Carlo (Janssen, 2013), Importance Sampling (Janssen, 2013), and Latin Hypercube (Shields & Zhang, 2016)—to evaluate the influence of BIM and Lean Construction Principles (LCP) on cost reliability and budget variability. Each model ran 10,000 simulations to analyse how varying levels of BIM-LCP implementation impact financial outcomes. Montecarlo generated activity costs based on probability distributions derived from statistical measures calculated in Step 2, exploring broad variability scenarios. Importance Sampling focused on high-probability regions to provide refined predictions, while Latin Hypercube stratified input data to ensure comprehensive variability coverage. A project was

considered reliable when few simulations exceeded the failure function, defined as the sum of baseline planned costs.

FOURTH STEP – RESULTS

This step focuses on developing the probabilistic simulation models necessary to evaluate the impact of BIM and Lean Construction implementation on cost reliability and budget variability. Monte Carlo, Importance Sampling, and Latin Hypercube methods were employed to construct these models, using statistical inputs derived from the data collected in previous steps. These models simulate financial outcomes under varying conditions of variability and uncertainty, providing a robust foundation for analysing how management practices influence project performance. A critical parameter, the failure function (FF), was defined as the sum of mean activity costs for the different budget chapters of the project:

$$FF = \sum_{i=1}^n C_i \quad \text{Equation 1, } FP = \frac{if}{s} \quad \text{Equation 2, } CP = 1 - PF \quad \text{Equation 3}$$

Here, n represents the number of activities corresponding to the budget chapters of the project, C_i is the average cost of each activity, if is the number of iterations exceeding the failure function, and s is the total number of simulations. FP represents the failure probability, or the likelihood of exceeding the planned budget, while CR reflects the project's adherence to planned costs. The simulations were developed to evaluate the correlation between the level of BIM and Lean Construction implementation and its impact on cost reliability and budget variability. Using inputs derived from statistical measures calculated in previous steps, these models provide a robust framework to analyze how management practices influence financial outcomes under varying conditions of variability and uncertainty. A normal probability distribution was applied to model activity costs, as justified by the central limit theorem, which establishes that the sum of independent random variables tends to follow a normal distribution, even if the original variables are not normally distributed. This assumption is particularly valid in construction projects, where aggregated costs across numerous activities exhibit characteristics aligned with a normal distribution due to the inherent averaging effect.

FIFTH STEP – VALIDATION

To ensure robust financial planning, this study rigorously validated the numerical simulation models used to assess the impact of BIM and Lean Construction Principles (LCP) on cost reliability. Validation was conducted by comparing simulation results with existing literature on probabilistic cost modeling and incorporating peer feedback from industry experts to ensure alignment with theoretical frameworks and real-world conditions. To enhance replicability, the study followed a structured methodology that clearly defines project selection criteria, data collection protocols, and statistical modeling techniques. The two analyzed projects were selected based on comparable industrialization levels and resource availability, ensuring that the primary differentiating factor was the management approach (BIM-LCP vs. traditional methods). Data collection focused on planned and executed costs, while cost variability was assessed using confidence intervals and probabilistic simulations to quantify financial uncertainty.

Monte Carlo, Importance Sampling, and Latin Hypercube simulations were executed with 10,000 iterations, ensuring stable convergence and a robust assessment of financial predictability. The computational analysis was performed using Python and Excel, maintaining standardized metrics and controlled variability to enhance the reproducibility of the findings. This structured framework allows the methodology to be adapted to different construction

contexts, offering a scalable approach to cost reliability assessment and financial risk mitigation.

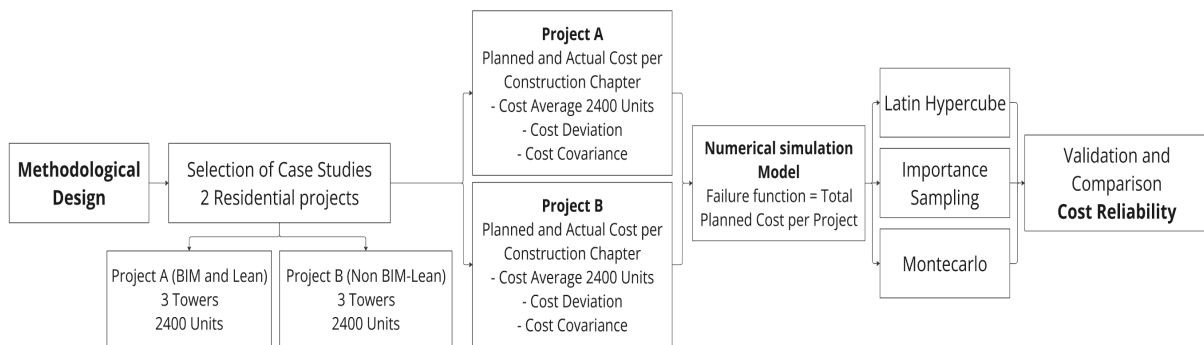


Figure 1: Methodology

RESULTS

CASE STUDY DESCRIPTION

The general information collected from the two case studies is summarized in Table 1. Based on this, Table 2 provides a detailed comparison of activity costs at both the initial baseline schedule and project completion. The data includes information for 4,800 residential units across Projects A and B, highlighting key differences in cost performance under varying levels of BIM and Lean Construction Principles (LCP) implementation.

Table 1: Case Study Characteristics

Project	Type	Units	Area (m2)	Construction Management tools	Planning
"A"	Apartment	2400	45	BIM-LEAN	Last Planner System
"B"	Apartment	2400	45	NON-BIM-LEAN	CPM

Also, Table 2 presents the key statistical metrics derived from construction activity costs in Projects A and B. These metrics provide critical insights into cost variability and its influence on cost reliability, offering a foundation for assessing financial predictability in construction projects. The table enables a comparative analysis between the projected costs at the beginning of construction and the actual costs observed upon project completion. Additionally, each activity is assigned a probability distribution, modelled as Normal. These distributions enable accurate input modelling for probabilistic simulations, ensuring a comprehensive analysis of cost variability and its impact on project outcomes. While Projects A and B share similarities in architectural design, their differing levels of BIM and Lean Construction Principles (LCP) implementation highlight the influence of these practices on cost reliability and budget variability.

Table 2: Statistical Metrics

Project A					
Chapter	Projected Average Cost \$USD	Executed Average Cost \$USD	Variation \$USD	Percentage	Standard deviation \$USD
<i>Foundations</i>	\$ 2.011.974,09	\$ 2.011.907,25	\$ 66,84	0,00%	\$ 47,27
<i>Structure</i>	\$ 2.031.648,80	\$ 2.011.399,14	\$ 20.249,66	1,00%	\$ 14.318,67
<i>Metal Formwork</i>	\$ 261.203,82	\$ 262.936,47	\$ 1.732,66	0,66%	\$ 1.225,17
<i>Steel</i>	\$ 1.117.471,23	\$ 1.124.521,04	\$ 7.049,82	0,63%	\$ 4.984,97
<i>Roof</i>	\$ 277.620,69	\$ 278.452,63	\$ 831,94	0,30%	\$ 588,27
<i>Waterproofing</i>	\$ 120.364,49	\$ 121.143,08	\$ 778,59	0,65%	\$ 550,54
<i>Brick</i>	\$ 238.226,04	\$ 237.503,42	\$ 722,62	0,30%	\$ 510,97
<i>Floors</i>	\$ 133.794,71	\$ 134.263,44	\$ 468,73	0,35%	\$ 331,44
<i>Sanitary Installations</i>	\$ 916.924,83	\$ 895.509,60	\$ 21.415,22	2,34%	\$ 15.142,85
<i>Sanitary Fixtures</i>	\$ 112.496,39	\$ 113.606,41	\$ 1.110,02	0,99%	\$ 784,90
<i>Electrical Installations</i>	\$ 1.299.750,32	\$ 1.290.942,81	\$ 8.807,52	0,68%	\$ 6.227,85
<i>Wood Carpentry</i>	\$ 85.875,84	\$ 84.440,73	\$ 1.435,11	1,67%	\$ 1.014,77
<i>Metal Carpentry</i>	\$ 876.711,96	\$ 888.303,38	\$ 11.591,42	1,32%	\$ 8.196,37
<i>Paint</i>	\$ 87.019,66	\$ 89.630,26	\$ 2.610,59	3,00%	\$ 1.845,97
<i>Locks and Mirrors</i>	\$ 22.317,93	\$ 22.322,45	\$ 4,53	0,02%	\$ 3,20
<i>Cleaning</i>	\$ 76.410,59	\$ 75.407,06	\$ 1.003,53	1,31%	\$ 709,60
<i>Internal Urban Planning</i>	\$ 254.366,56	\$ 254.400,48	\$ 33,92	0,01%	\$ 23,98
<i>Internal Urban - Sanitary</i>	\$ 431.088,80	\$ 429.642,19	\$ 1.446,61	0,34%	\$ 1.022,90
<i>Internal Urban - electrical</i>	\$ 754.760,76	\$ 747.059,11	\$ 7.701,65	1,02%	\$ 5.445,89
<i>Common Areas</i>	\$ 197.676,73	\$ 196.308,20	\$ 1.368,53	0,69%	\$ 967,70
<i>Community Hall</i>	\$ 519.063,57	\$ 525.754,49	\$ 6.690,91	1,29%	\$ 4.731,19
<i>Platform 1</i>	\$ 381.858,44	\$ 369.239,41	\$ 12.619,03	3,30%	\$ 8.923,00
<i>Excavations and Backfills</i>	\$ 242.604,02	\$ 250.071,94	\$ 7.467,91	3,08%	\$ 5.280,61
Project B					
Chapter	Projected Average Cost \$USD	Executed Average Cost \$USD	Variation \$USD	Percentage	Standard deviation \$USD
<i>Foundations</i>	\$ 1.792.729,08	\$ 1.733.773,56	\$ 58.955,53	3,29%	\$ 41.687,85
<i>Structure</i>	\$ 1.792.395,42	\$ 1.757.389,58	\$ 35.005,85	1,95%	\$ 24.752,87
<i>Metal Formwork</i>	\$ 239.785,11	\$ 250.959,41	\$ 11.174,30	4,66%	\$ 7.901,42
<i>Steel</i>	\$ 1.032.723,41	\$ 1.042.848,15	\$ 10.124,74	0,98%	\$ 7.159,27
<i>Roof</i>	\$ 257.430,10	\$ 249.824,98	\$ 7.605,12	2,95%	\$ 5.377,63
<i>Waterproofing</i>	\$ 108.685,55	\$ 113.025,83	\$ 4.340,28	3,99%	\$ 3.069,04
<i>Brick</i>	\$ 215.118,11	\$ 206.577,70	\$ 8.540,41	3,97%	\$ 6.038,98
<i>Floors</i>	\$ 122.053,53	\$ 121.218,01	\$ 835,53	0,68%	\$ 590,81
<i>Sanitary Installations</i>	\$ 819.749,08	\$ 773.662,18	\$ 46.086,90	5,62%	\$ 32.588,36
<i>Sanitary Fixtures</i>	\$ 100.910,39	\$ 99.490,91	\$ 1.419,47	1,41%	\$ 1.003,72
<i>Electrical Installations</i>	\$ 1.154.383,51	\$ 1.161.848,52	\$ 7.465,01	0,65%	\$ 5.278,56
<i>Wood Carpentry</i>	\$ 78.066,32	\$ 80.597,64	\$ 2.531,32	3,24%	\$ 1.789,91
<i>Metal Carpentry</i>	\$ 794.336,33	\$ 754.301,78	\$ 40.034,55	5,04%	\$ 28.308,70
<i>Paint</i>	\$ 77.534,52	\$ 77.811,25	\$ 276,73	0,36%	\$ 195,68
<i>Locks and Mirrors</i>	\$ 20.629,00	\$ 21.733,06	\$ 1.104,05	5,35%	\$ 780,68
<i>Cleaning</i>	\$ 67.394,15	\$ 68.304,19	\$ 910,05	1,35%	\$ 643,50
<i>Internal Urban Planning</i>	\$ 233.508,50	\$ 222.222,26	\$ 11.286,24	4,83%	\$ 7.980,58
<i>Internal Urban - Sanitary</i>	\$ 397.093,54	\$ 394.606,82	\$ 2.486,71	0,63%	\$ 1.758,37
<i>Internal Urban - electrical</i>	\$ 697.768,62	\$ 690.513,67	\$ 7.254,94	1,04%	\$ 5.130,02
<i>Common Areas</i>	\$ 176.719,03	\$ 179.586,99	\$ 2.867,96	1,62%	\$ 2.027,95
<i>Community Hall</i>	\$ 462.501,15	\$ 454.741,08	\$ 7.760,08	1,68%	\$ 5.487,20
<i>Platform 1</i>	\$ 335.706,67	\$ 334.397,98	\$ 1.308,69	0,39%	\$ 925,38
<i>Excavations and Backfills</i>	\$ 220.571,62	\$ 214.622,87	\$ 5.948,75	2,70%	\$ 4.206,40

To address the challenge of improving financial predictability in construction, this study evaluates the impact of BIM and Lean Construction Principles (LCP) on cost reliability and budget variability through advanced probabilistic simulations. Figure 2 illustrates the results, highlighting differences in financial performance between the two projects. In Project A, a failure function of \$13,047,855.29 USD was defined as the maximum allowable budget according to the initial baseline. Scenarios exceeding this threshold were classified as failures. The analysis revealed an average failure probability of 21.5%, corresponding to a cost reliability of 78.5%, meaning costs remained within budget in 78.5% of the simulations. In contrast, Project B had a failure function of \$11,731,875.61 USD and an average failure probability of 59.9%, resulting in a significantly lower cost reliability of 40.1%. Project A, with BIM and Lean practices, outperformed Project B by a margin of 38.4%, demonstrating the effectiveness of advanced management strategies in enhancing financial predictability.

The failure function and cost reliability metrics provide measurable benchmarks that enable construction managers to assess financial risks and make informed decisions during the project lifecycle. While cost variability captures deviations from planned budgets, financial risk emerges when these deviations introduce uncertainty into cash flow projections and resource allocation. The proposed failure probability (FP) and cost reliability (CR) metrics enable construction managers to anticipate the likelihood and magnitude of budget overruns, providing actionable insights for financial risk management and contingency planning. The models quantified the frequency of cost overruns (failure probability, FP) and the likelihood of staying within budget (cost reliability, CR), demonstrating that BIM-LCP practices significantly enhanced financial outcomes by reducing variability and improving predictability (Hosseinian et al., 2022).

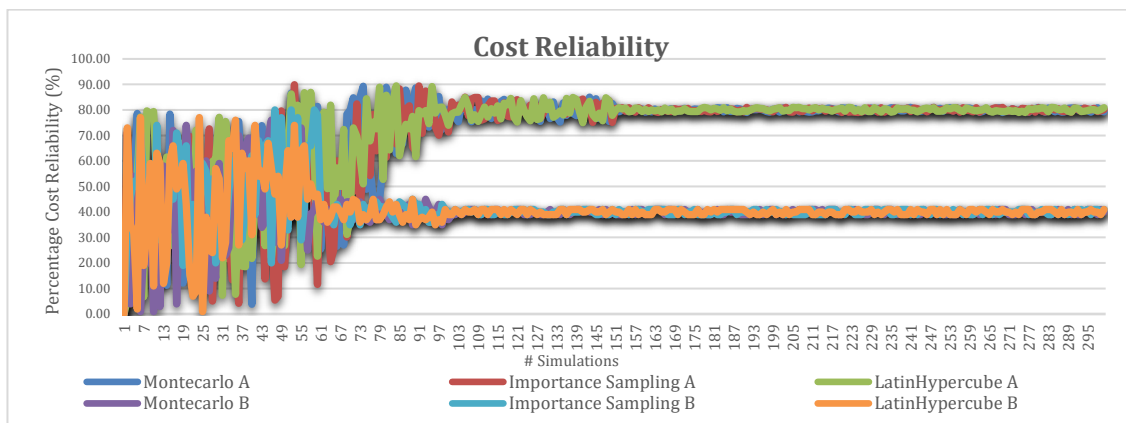


Figure 2: Failure Probability by three Simulation Methods

In an industry characterized by high variability and financial uncertainty, these findings demonstrate the critical role of BIM and Lean Construction Principles (LCP) in enhancing cost reliability and budget variability management. Table 3 summarizes failure probabilities for each project type, highlighting Project A’s superior performance with significantly lower failure probabilities compared to Project B.

The simulation results align with expectations from the literature, demonstrating how BIM and Lean practices reduce process variability and enhance financial predictability. In contrast, traditional methods reliant on CPM, without the collaboration and standardization enabled by BIM and Lean, exhibit higher variability and lower reliability. The failure probabilities presented in Table 3 provide project-specific references for assessing cost reliability rather than universal benchmarks. These values allow construction managers to compare performance across similar projects, facilitating risk anticipation and data-driven decision-making to optimize planning strategies.

By leveraging BIM and Lean practices, construction managers can adopt proactive strategies to mitigate risks, improve financial stability, and deliver more predictable project outcomes. These results establish a foundation for future research into the scalability and adaptation of BIM and Lean practices across diverse project types, setting a precedent for more resilient, efficient, and predictable construction management practices.

Table 3: Cost Reliability Summary

	Project A (BIM-LEAN)	Project B
Average	78,50%	40,10%
Montecarlo	78,5%	39,7%
Importance Sampling	75,9%	37,2%
Latin Hypercube	81,1%	43,4%

DISCUSSION

Variability in construction activity execution is a critical factor in project performance, particularly in cost reliability (Garcia-Lopez & Fischer, 2024; Salhab et al., 2022). Controlling this variability and reducing cost deviations directly enhance financial predictability (Santos & Famá, 2023). The results confirm a quantifiable relationship between adopting BIM and Lean Construction Principles (LCP) and reducing cost variability, demonstrating how advanced management strategies improve financial performance.

Beyond cost predictability, variability also influences risk assessment and financial sustainability (Aven, 2016). Numerical simulations identify critical variables, predict uncertainty sources, and assess financial risks in construction planning (Sami Ur Rehman et al., 2022). This study confirms that excessive execution cost variability significantly increases the likelihood of cost overruns (Gonzalez et al., 2008), particularly in high-risk activities such as foundation work and plumbing systems (Succar & Kassem, 2015). Recognizing these risk-prone areas enables targeted mitigation strategies and informed financial decision-making (Succar & Kassem, 2015).

The comparison between the two case studies highlights the impact of BIM and LCP on cost reliability, isolating management practices as the key differentiating factor. Despite having the same resources, labor, and design expertise, Project A, with BIM-LCP integration, exhibited superior cost stability, while the traditionally managed project showed greater variability (Ekanayake et al., 2021). These findings align with previous research linking modern construction methodologies to improved planning reliability and financial performance (Chen & Bao, 2013). While the study confirms that BIM-LCP integration significantly enhances cost reliability, it is important to acknowledge the influence of external factors such as market volatility, resource constraints, and contractual risks. These elements can contribute to cost deviations beyond those captured in the model. Future research should explore how BIM-LCP strategies can be adapted to different economic and regulatory environments to mitigate these uncertainties (León et al., 2025).

The three simulation methods (Monte Carlo, Importance Sampling, and Latin Hypercube) produced consistent results, validating their reliability in cost modelling. While all methods converged to similar outcomes, Importance Sampling and Latin Hypercube achieved faster convergence due to their refined sampling approaches, whereas Monte Carlo required more iterations (Janssen, 2013). This methodological consistency strengthens confidence in the failure probability (FP) and cost reliability (CR) metrics, reinforcing their applicability in construction financial planning.

Despite the robustness of the probabilistic analysis, certain statistical limitations should be considered. The analysis is based on two case studies, which, while methodologically sound, may limit broader generalizability. Additionally, the models assume stable cost distributions,

which may not fully capture extreme market fluctuations or unprecedented events. Future studies should explore how cost reliability metrics behave under varying economic conditions and across diverse construction typologies.

These findings underscore the practical benefits of BIM and Lean methodologies in managing complex or high-risk projects, such as large-scale infrastructure developments. Future research could expand this framework to validate its scalability across diverse construction environments, considering regional practices and technological adoption levels.

CONCLUSION

This study advances the understanding of how Building Information Modeling (BIM) and Lean Construction Principles (LCP) enhance cost reliability by minimizing variability and improving financial predictability in construction projects. The analysis of two comparable case studies demonstrates that BIM-LCP integration significantly improves budget adherence, particularly in high-risk activities such as foundation work and plumbing systems. The findings validate the effectiveness of advanced probabilistic methods—Monte Carlo, Importance Sampling, and Latin Hypercube—in modeling cost variability and quantifying financial risks. While all methods produced consistent results, the faster convergence of Importance Sampling and Latin Hypercube underscores their practicality for time-sensitive construction planning. The methodological consistency across simulations further reinforces the reliability of these models in representing real-world cost dynamics.

From a practical standpoint, this study provides actionable strategies to reduce cost variability, enhance risk management, and promote financial stability in construction projects. By demonstrating the benefits of BIM and LCP integration, it establishes a foundation for broader adoption of these methodologies as best practices in project planning and execution.

Although limited to two case studies, the findings align with existing literature, supporting the scalability of BIM and LCP across diverse construction markets. Future research should explore their implementation in larger and more complex projects, considering regional variations in practices and technology adoption. By improving cost reliability, this study contributes to better project outcomes and long-term financial resilience in the construction industry. The proposed methodological framework offers a replicable and scalable approach for leveraging advanced probabilistic tools to drive innovation and best practices in construction management.

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