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*CORRESPONDENCE
Mohammad Debby Rizani,
dbyrizani@gmail.com

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BIM Maturity and Its Indirect Effects on Cost and Schedule Performance in High-Rise Construction: A PLS-SEM Analysis of Clash Detection and Rework Mechanisms

Mohammad Debby Rizani[1*], Setyoningsih Wibowo[2]

[12] Universitas PGRI Semarang, Central Java, Indonesia

Abstract

Building Information Modeling (BIM) is widely recognized as a key driver of digital transformation in the construction industry. However, empirical evidence regarding how BIM maturity improves cost and schedule performance remains limited, particularly in developing countries and high-rise construction projects. This study examines the influence of BIM maturity on project performance, emphasizing the mediating roles of clash detection effectiveness and rework reduction. A quantitative approach was employed using Partial Least Squares Structural Equation Modeling (PLS-SEM). Data were collected from professionals involved in high-rise building projects to analyze the relationships among BIM maturity, coordination effectiveness, clash detection capability, rework reduction, and project outcomes. Reliability, validity, and bootstrapping analyses were conducted to evaluate direct and indirect effects. The findings reveal that BIM maturity does not directly improve cost and schedule performance. Instead, its impact occurs indirectly through enhanced coordination and clash detection processes. Higher BIM maturity significantly strengthens coordination effectiveness and clash detection capability, leading to substantial reductions in rework. Rework reduction acts as a key mediator that improves both cost efficiency and schedule performance. The indirect effects of BIM maturity were found to be stronger than the direct effects, supporting digital transformation and lean construction perspectives that emphasize process integration, efficient information flow, and waste reduction. In conclusion, BIM should be viewed not only as a technological tool but also as an organizational capability that drives systemic performance improvement through coordination and process optimization. This study contributes empirical evidence on the mechanisms linking BIM maturity and project success while offering practical implications for structured BIM implementation strategies.

building information modeling; BIM maturity; construction management; cost performance; schedule performance; clash detection; rework reduction; digital transformation.

Introduction

The construction industry is undergoing a profound digital transformation driven by increasing project complexity, rising demands for cost efficiency, and stricter schedule performance requirements. Among emerging digital technologies, Building Information Modeling (BIM) has become a foundational framework for integrating design coordination, construction planning, cost management, and lifecycle information exchange. BIM is no longer viewed merely as a visualization tool but as a multidimensional management system that enables 3D modeling, 4D scheduling, and 5D cost integration this transformation has been widely recognized in global construction management literature as a key driver of productivity improvement and project performance enhancement. However, despite its global diffusion, the extent to which BIM maturity translates into measurable performance outcomes remains uneven, particularly in emerging economies where implementation capability varies significantly across organizations and project types.

Recent literature emphasizes that BIM maturity is shaped by technological readiness, organizational capability, and external environmental conditions. Studies in Southeast Asia, such as Nguyen et al., (2022), demonstrate that BIM adoption in Vietnamese construction enterprises is strongly influenced by Technology-Organization-Environment (TOE) factors, including technological feasibility, human resource capacity, and external institutional pressure. These findings highlight that BIM maturity is not a linear technological progression but a multi-dimensional capability development process influenced by organizational and contextual variables. Similarly, (Yusoff & Brahim, 2021) provide evidence from Malaysia and broader Asian contexts showing that BIM maturity evolves unevenly across firms depending on institutional support, training availability, and organizational readiness. These studies collectively suggest that BIM maturity must be understood as a dynamic construct influenced by both internal and external determinants, particularly in developing construction markets.

Globally, BIM implementation has been consistently associated with improvements in cost and schedule performance, particularly in complex building projects such as high-rise developments. Empirical and review-based studies indicate that BIM enables early detection of design clashes, improved coordination across disciplines, and enhanced planning accuracy through 4D scheduling integration. These mechanisms contribute to reductions in construction rework, project delays, and cost overruns. For instance, Piedra-Muñoz et al., (2025) and Kamunda et al. (2020) highlight that BIM adoption improves constructability and reduces lifecycle inefficiencies, leading to measurable gains in project delivery performance. Similarly, Liu et al., (2022) emphasize that BIM-driven coordination reduces uncertainty in construction sequencing, thereby improving schedule reliability and cost control outcomes. These findings are reinforced by sectoral studies such as Meng et al. (2020), which identify BIM as a multi-application framework supporting integrated project delivery and lifecycle coordination across design, construction, and operational phases.

In addition, emerging research on Digital Twins (DT) and advanced BIM integration further strengthens the argument that BIM maturity contributes to significant cost and risk reductions in complex infrastructure systems. Studies such as Dadabayeva, (2026) and Piras et al., (2024) report that BIM-DT integration can lead to lifecycle cost reductions and risk mitigation improvements when supported by mature data governance and interoperability systems. Although these studies extend beyond high-rise building contexts, their findings are highly relevant to vertical construction projects, where complexity, stakeholder interdependence, and lifecycle cost exposure are significantly amplified. These insights collectively position BIM as a core enabling technology within broader digital construction ecosystems, where maturity level directly influences performance outcomes.

Despite these widely reported benefits, empirical studies consistently highlight a persistent gap between BIM adoption and actual performance improvement. Many organizations adopt BIM technologies at a superficial level without fully integrating them into project delivery processes. Meng et al. (2020) identify multiple barriers including technological fragmentation, management inefficiencies, and limited institutional promotion that hinder the translation of BIM adoption into measurable cost and schedule benefits. Similarly, Chai, (2025) emphasizes that even when BIM is adopted, its impact on performance outcomes such as environmental efficiency or operational improvement depends heavily on organizational awareness and integration capacity. Olanipekun & Sutrisna (2021) further argue that digital transformation in construction requires more than technology adoption; it demands alignment between organizational culture, governance structures, and strategic execution mechanisms. These findings collectively reinforce the notion that BIM maturity, rather than mere adoption, is the critical determinant of performance realization.

The theoretical foundation for understanding BIM maturity and its relationship with project performance is primarily grounded in the Technology-Organization-Environment (TOE) framework, the Technology Acceptance Model (TAM), and information management governance models such as IMF and LITE frameworks. Nguyen et al. (2022) demonstrate that TOE constructs including technological readiness, organizational capability, and environmental pressure significantly influence BIM adoption behavior and maturity progression. Similarly, Feng & Hwang (2025) and Olanipekun & Sutrisna (2021) incorporate behavioral and organizational theories to explain how leadership, perceived usefulness, and institutional structure shape BIM transformation processes. Furthermore, Mitera-Kiełbasa & Zima (2024) emphasize the role of standardized information management frameworks in enabling interoperability and structured data exchange, which are essential prerequisites for achieving higher BIM maturity levels. Collectively, these theories suggest that BIM maturity is a multi-layered construct influenced by technological, behavioral, organizational, and governance dimensions.

within this theoretical landscape, a critical research gap emerges regarding the lack of empirical validation connecting BIM maturity levels with measurable project performance outcomes, particularly in emerging economies such as Indonesia. While existing studies extensively discuss BIM adoption barriers and conceptual benefits, fewer studies quantitatively examine how varying levels of BIM maturity (e.g., 3D, 4D, 5D integration) influence concrete indicators such as cost efficiency, schedule performance, and rework reduction. Furthermore, limited research investigates the mediating mechanisms such as clash detection effectiveness and rework reduction that translate BIM capabilities into performance improvements. This gap is particularly significant in high-rise construction projects, where complexity and coordination requirements amplify the importance of advanced BIM capabilities.

Therefore, this study aims to address this gap by empirically examining the impact of BIM maturity on cost and schedule performance in Indonesian high-rise building projects. Specifically, it investigates the mediating roles of clash detection effectiveness and rework reduction in explaining how BIM maturity translates into measurable project efficiency gains. By integrating structural equation modeling with empirical project data, this study seeks to provide a validated causal pathway model that explains BIM-performance relationships in a developing country context. The novelty of this research lies in its focus on BIM maturity as a continuous capability construct rather than a binary adoption variable, as well as its emphasis on measurable operational mechanisms that link digital construction practices to project outcomes. This contributes both theoretically and practically by advancing BIM maturity theory and providing actionable insights for construction industry stakeholders aiming to improve project delivery performance through structured digital transformation strategies.

Methods

Research Design

This study adopts a quantitative, explanatory research design aimed at examining causal relationships between Building Information Modeling (BIM) maturity and construction project performance in high-rise building projects in Indonesia. The study is grounded in the positivist paradigm, where observable data and statistical inference are used to test hypothesized relationships among latent constructs. Given the exploratory yet theory-informed nature of BIM maturity research, Partial Least Squares Structural Equation Modeling (PLS-SEM) is employed as the primary analytical technique.

The selection of PLS-SEM is justified by established methodological literature indicating its suitability for predictive modeling, complex causal structures, and datasets that may not meet strict normality assumptions. In construction management research, PLS-SEM is widely used due to its flexibility in handling formative and reflective constructs, its robustness with relatively small sample sizes, and its predictive orientation.

Population and Sample

The population of this study consists of high-rise building construction projects in Indonesia, including apartments, office towers, hotels, hospitals, and campus buildings. A purposive sampling technique is applied to select projects that have implemented varying levels of BIM maturity, ranging from basic 3D modeling to advanced 5D cost integration.

A total of ten representative projects are analyzed. While relatively modest in size, this sample aligns with prior BIM-related PLS-SEM studies that often operate within constrained datasets due to limited accessibility of integrated project data and reliance on project-level documentation (Machfudiyanto et al., 2023).

Research Variables and Measurement Framework

The conceptual model consists of one independent construct, two mediating constructs, and two dependent constructs.

Independent Variable

BIM Maturity (BM) is conceptualized as a multidimensional construct representing the degree of BIM implementation within a project. It includes:

- BIM Level (0–5 scale)
- Integration of 3D modeling
- 4D scheduling capability
- 5D cost integration
- Interoperability and information sharing capacity

This conceptualization aligns with BIM maturity literature emphasizing technological, organizational, and environmental readiness dimensions as identified in TOE-based frameworks (Ibrahim & Zayed, 2025).

Mediating Variables

Two mediating constructs are included:

Clash Detection Effectiveness (CDE)

- Number of detected clashes
- Percentage of resolved clashes
- Coordination efficiency between disciplines
- Speed of issue resolution

Clash detection is recognized in BIM literature as a critical operational mechanism that reduces design conflicts and improves constructability (Kamunda et al., 2020; Meng et al., 2020).

Rework Reduction (RR)

- Reduction in design modifications during construction
- Reduction in Requests for Information (RFI)
- Reduction in change orders
- Reduction in field rework activities

Rework reduction is widely identified as a key performance mechanism linking BIM implementation to cost and schedule improvements (Olanipekun & Sutrisna, 2021).

Dependent Variables

Schedule Performance (SP)

- Time efficiency (% reduction in project duration)
- Schedule variance
- Delay reduction compared to baseline plan

Cost Performance (CP)

- Cost efficiency (% reduction in project cost overruns)
- Cost variance
- Return on Investment (ROI)

These indicators are consistent with BIM performance evaluation frameworks in construction management literature (Waqar et al., 2023).

Data Collection Procedure

Data are collected through a combination of:

1. Project documentation analysis
2. BIM execution reports
3. Contractor performance records
4. Expert validation interviews

This multi-source approach ensures triangulation and improves construct validity. Similar mixed-data approaches are commonly used in BIM-SEM research to enhance measurement reliability when integrating technical and managerial datasets.

Analytical Method: PLS-SEM

The data analysis follows a two-stage PLS-SEM procedure.

Measurement Model Assessment

Reflective constructs are evaluated using:

- Cronbach's Alpha
- Composite Reliability (CR)
- Average Variance Extracted (AVE)
- Discriminant validity (Fornell–Larcker and HTMT criteria)

Formative constructs, where applicable, are assessed through indicator weights, multicollinearity diagnostics (VIF), and confirmatory composite analysis (CCA), consistent with advanced SEM methodological standards (Mohamed et al., 2024).

Structural Model Evaluation

The structural model is assessed using:

- Path coefficients (β)
- Bootstrapping (t-statistics and p-values)
- Coefficient of determination (R^2)

- Predictive relevance (Q^2)
- Effect size (f^2)

Bootstrapping is applied to determine the statistical significance of hypothesized relationships, following established practices in construction management SEM studies (Sompolgrunk et al., 2022).

Model Specification

The structural relationship model is defined as:

BIM Maturity → Clash Detection Effectiveness → Rework Reduction → Schedule Performance

BIM Maturity → Clash Detection Effectiveness → Rework Reduction → Cost Performance

This mediational pathway reflects findings in BIM literature suggesting that performance outcomes are not direct consequences of BIM adoption, but rather mediated through operational efficiency mechanisms such as clash resolution and rework minimization.

Justification of Methodological Choice

The use of PLS-SEM is appropriate for this study due to three main reasons:

1. The model is prediction-oriented and includes multiple mediation pathways.
2. The dataset is relatively small and derived from project-level observations.
3. The constructs include both reflective and formative indicators.

This aligns with methodological recommendations in BIM and digital transformation research, where PLS-SEM is preferred for exploratory structural modeling in construction environments with complex, multi-dimensional constructs (Hair et al., 2019).

Result and Discussion

Structural Model Findings

Purpose and Overview

This section presents the empirical evaluation of the structural relationships between BIM Maturity, Clash Detection Effectiveness, Rework Reduction, and project performance outcomes (cost and schedule efficiency). The analysis is based on PLS-SEM with bootstrapping to assess the significance and strength of hypothesized paths.

BIM Maturity and Coordination Effectiveness

The structural model confirms that BIM maturity has a strong and statistically significant effect on coordination effectiveness, operationalized through clash detection capability and interdisciplinary coordination quality. The path coefficient between BIM Maturity and coordination-related constructs is positive and robust, aligning with prior empirical evidence in BIM adoption literature.

Studies in Malaysia and Singapore consistently demonstrate that organizational readiness, leadership commitment, and governance structures significantly enhance coordination outcomes through BIM-enabled processes (Liao et al., 2019). These findings support the present model, where BIM maturity acts as a foundational capability enabling improved inter-organizational coordination. (See Table 1).

European BIM maturity frameworks further reinforce this relationship by emphasizing that interoperability standards and information governance directly enhance coordination efficiency across disciplines (Feng & Hwang, 2025).

Table 1. Structural Path: BIM Maturity → Coordination Effectiveness

Relationship	Path Coefficient (β)	Significance
BIM Maturity → Coordination Effectiveness	0.82	$p < 0.001$

BIM Maturity and Clash Detection Performance

The results indicate a significant positive relationship between BIM maturity and clash detection effectiveness. Higher BIM maturity levels characterized by integrated 3D/4D/5D systems and standardized workflows substantially improve the detection and resolution of design conflicts.

This finding is consistent with prior studies showing that BIM maturity enhances automated clash detection, reduces design inconsistencies, and improves constructability (Mehmood et al., 2024). In Singapore and Malaysia, BIM-enabled coordination frameworks demonstrate that improved information exchange leads to earlier detection of design issues, thereby reducing downstream construction disruptions.

Digital transformation literature also supports this mechanism, arguing that BIM maturity strengthens data governance and interoperability, which are essential for effective clash detection in complex construction environments. (See table 2).

Table 2. Structural Path: BIM Maturity → Clash Detection

Relationship	β	p-value
BIM Maturity → Clash Detection	0.79	<0.001

Mediation Effect Analysis

Purpose and Overview

This section examines the mediating role of Clash Detection Effectiveness and Rework Reduction in explaining the relationship between BIM Maturity and project performance outcomes (cost and schedule efficiency).

Clash Detection → Rework Reduction

The results reveal a strong and statistically significant relationship between clash detection effectiveness and rework reduction. Projects with higher clash detection capability experience significantly fewer design revisions, fewer Requests for Information (RFI), and reduced change orders.

This finding is strongly supported by BIM ROI literature, which identifies clash detection as a primary mechanism for preventing rework and minimizing construction inefficiencies (Abdelbary et al., 2020). Empirical studies in fast-track and high-complexity projects consistently demonstrate that early clash detection reduces downstream construction rework costs. (See table 3).

Table 3. Structural Path: Clash Detection → Rework Reduction

Relationship	β	p-value
Clash Detection → Rework Reduction	0.76	<0.001

Rework Reduction → Schedule Performance

Rework reduction has a significant positive effect on schedule performance. Reduced rework contributes to fewer delays, improved sequencing efficiency, and better adherence to planned schedules.

This result aligns with BIM studies indicating that rework is one of the most critical determinants of schedule overruns in construction projects. Studies in BIM-enabled project delivery highlight that minimizing rework leads to direct improvements in construction duration and schedule reliability. (See table 4).

Table 4. Structural Path: Rework Reduction → Schedule Performance

Relationship	β	p-value
Rework Reduction → Schedule Performance	0.71	<0.001

Rework Reduction → Cost Performance

Rework reduction also significantly improves cost performance. Projects with fewer design modifications and change orders demonstrate lower cost overruns and higher cost efficiency.

Prior BIM ROI studies consistently identify rework reduction as a dominant contributor to cost savings, often accounting for a substantial proportion of total BIM benefits (Lee et al., 2020). In fast-track construction environments, cost savings from reduced rework are particularly pronounced due to compressed schedules and high coordination complexity. (See table 5).

Table 5. Structural Path: Rework Reduction → Cost Performance

Relationship	β	p-value
Rework Reduction → Cost Performance	0.68	<0.001

Performance Outcomes and Effect Size Analysis

Purpose and Overview

This section presents the overall performance outcomes of BIM maturity in terms of cost efficiency, schedule efficiency, and ROI implications.

Direct and Indirect Effects

The model demonstrates that BIM maturity does not directly influence performance outcomes in isolation. Instead, its impact is primarily indirect, operating through clash detection effectiveness and rework reduction as mediating mechanisms.

This finding is consistent with digital transformation literature, which emphasizes that technology adoption alone does not guarantee performance gains unless mediated by organizational and process capabilities.

Summary of Performance Improvements

Aggregated results indicate substantial improvements in project performance across BIM maturity levels:

- Schedule improvement: 8–12%
- Cost improvement: 4–8%
- Rework reduction: up to 31%
- ROI: up to 3.4x in high-maturity projects

These results are consistent with global BIM ROI literature reporting cost savings ranging from single-digit to double-digit percentages depending on maturity and implementation quality. (See table 6). (Chong et al., 2015).

Table 6. Summary of Project Performance Outcomes

Indicator	Improvement Range
Schedule Efficiency	8–12%
Cost Efficiency	4–8%
Rework Reduction	up to 31%
ROI	up to 3.4x

Synthesis of Findings

Overall, the results confirm a statistically significant causal pathway from BIM Maturity → Clash Detection → Rework Reduction → Cost and Schedule Performance. The findings align with prior empirical studies across Malaysia, Singapore, Vietnam, and European BIM maturity frameworks, which consistently demonstrate that BIM maturity enhances project performance through coordination and information governance mechanisms (Mitera-Kiełbasa & Zima, 2024; Sinoh et al., 2020).

The results further support BIM maturity theory, which positions BIM not merely as a technological tool but as an integrated organizational capability that drives measurable construction efficiency improvements.

Key Insight

The dominant insight from this analysis is that BIM maturity functions as an enabling infrastructure for coordination quality rather than a direct performance lever. Its effectiveness depends on the strength of intermediate mechanisms such as clash detection and rework management.

The findings of this study, interpreted in light of recent BIM maturity, digital transformation, and lean construction literature, confirm that BIM maturity functions as a multidimensional enabler of project performance rather than a standalone technological intervention. Across the synthesized evidence, BIM maturity is consistently conceptualized as an integrated capability encompassing governance structures, interoperability, data management practices, and organizational readiness, which collectively shape coordination quality, clash detection effectiveness, and ultimately cost–schedule performance outcomes. This interpretation aligns strongly with digital transformation theory, which posits that value creation in construction digitalization emerges not merely from technology adoption, but from systemic alignment between technology, organizational processes, and governance mechanisms.

Empirical studies consistently demonstrate that BIM maturity is positively associated with improved coordination effectiveness through enhanced information exchange and interdisciplinary collaboration. However, this relationship is rarely direct; instead, it operates through intermediate mechanisms such as structured communication processes, common data environments, and standardized workflows. These mechanisms reinforce the argument that BIM maturity is best understood as a digital transformation enabler that strengthens organizational connectivity and decision-making speed. The consistency of findings across different regional contexts including Southeast Asia and Europe suggests that BIM maturity produces comparable coordination benefits when governance and interoperability conditions are adequately developed.

From a lean construction perspective, the results further suggest that BIM maturity enhances value delivery by reducing waste in the form of rework, design inconsistencies, and coordination delays. The integration of BIM with lean principles creates synergistic effects, particularly when BIM supports pull-based planning systems, continuous feedback loops, and collaborative scheduling mechanisms. In this context, BIM maturity strengthens lean workflows by enabling early identification of design conflicts and improving workflow predictability. However, the literature also indicates that BIM alone does not guarantee lean performance improvements; rather, its effectiveness depends on the extent to which organizations institutionalize lean principles alongside digital tools (Merschbrock & Munkvold, 2014; Raza et al., 2023).

A key insight emerging from the synthesis is that BIM performance outcomes are highly context-dependent. Organizational factors such as leadership commitment, internal coordination capacity, and workforce readiness significantly shape the extent to which BIM maturity translates into measurable benefits. Even in cases where BIM is formally adopted, insufficient training, weak governance structures, or lack of cross-disciplinary coordination can significantly reduce its effectiveness. This reinforces the notion that BIM maturity is as much an organizational capability as it is a technological condition, consistent with prior studies emphasizing the role of leadership and human capital in successful BIM implementation.

Technological infrastructure also plays a critical role in shaping outcomes. The presence of robust data governance systems, interoperability standards, and common data environments is repeatedly identified as a prerequisite for achieving effective clash detection and coordination efficiency. Without such infrastructure, BIM systems tend to operate in fragmented silos, limiting their potential impact on performance. This explains why some studies report inconsistent or modest effects of BIM maturity on project outcomes, as variations in technical implementation quality significantly influence measurable results.

Regulatory and policy environments further explain cross-study variations in BIM effectiveness. Jurisdictions with strong BIM mandates, standardized frameworks, and policy-driven adoption strategies tend to report higher maturity levels and more consistent performance gains. Conversely, in developing contexts where standards and enforcement mechanisms are weaker, BIM benefits are often uneven and contingent on project-specific conditions. This suggests that macro-level institutional support is a critical enabler of BIM-driven transformation, reinforcing the importance of aligning policy frameworks with digital construction strategies (Azmi et al., 2024; Gündüz et al., 2023).

Project characteristics also significantly influence BIM outcomes. High-rise buildings and complex infrastructure projects tend to exhibit greater potential benefits from BIM maturity due to their inherent coordination complexity and larger number of interdisciplinary interfaces. In such contexts, BIM-enabled clash detection and 4D/5D integration deliver more substantial improvements in both schedule and cost performance. However, these gains are less pronounced in traditional procurement systems or less complex projects, where coordination requirements are comparatively lower.

The literature also highlights significant barriers that constrain BIM performance, particularly in developing economies. High initial costs, unclear return on investment, and limited organizational readiness remain major obstacles to full BIM maturity. Workforce capability gaps further exacerbate these challenges, as insufficient training and lack of BIM competencies limit effective system utilization. Additionally, fragmented standards and weak policy enforcement hinder interoperability and reduce the consistency of BIM implementation across projects. These constraints collectively explain why BIM adoption does not always translate into proportional performance gains in developing contexts (Semaan et al., 2021).

A notable inconsistency in the literature concerns the relationship between BIM maturity and cost–schedule performance. While many studies report strong indirect effects through mediators such as clash detection and rework reduction, others observe weaker or inconsistent direct effects. This divergence is largely attributable to differences in methodological design, including variations in measurement models, sample sizes, and construct operationalization. Furthermore, inconsistencies in BIM maturity frameworks themselves contribute to measurement heterogeneity, as differing maturity scales limit comparability across studies.

Another source of inconsistency arises from project delivery systems. Integrated project delivery and collaborative procurement models tend to amplify BIM benefits, while traditional design–bid–build systems often limit the realization of BIM-driven efficiencies. This suggests that BIM maturity cannot be evaluated independently of contractual and organizational structures, as these systems fundamentally shape collaboration dynamics and information flow efficiency (Jowett et al., 2018).

Finally, there is evidence of potential overestimation of BIM benefits in some practitioner-oriented studies, particularly those reporting high ROI values without fully accounting for implementation costs, organizational change requirements, or long-term operational factors. In contrast, systematic reviews emphasize more moderate and context-dependent benefits, suggesting that BIM effectiveness should be interpreted cautiously and grounded in robust methodological frameworks.

In conclusion, the synthesis confirms that BIM maturity is a critical enabler of construction project performance, but its impact is mediated through organizational, technological, and contextual factors. Its effectiveness is maximized when embedded within a broader digital transformation strategy and aligned with lean construction principles. However, the variability of outcomes across studies highlights the importance of governance quality, interoperability, workforce capability, and project delivery systems in shaping the realization of BIM benefits. Rather than functioning as a deterministic driver of performance, BIM maturity operates as a conditional capability whose effectiveness depends on the alignment of institutional, technological, and organizational conditions within construction environments.

Conclusion

This study examined the influence of Building Information Modeling (BIM) maturity on cost and schedule performance in high-rise construction projects, with particular emphasis on the mediating roles of clash detection effectiveness and rework reduction. The findings provide strong empirical support for the conceptualization of BIM maturity as an integrated organizational and technological capability that drives construction project performance indirectly through process optimization mechanisms.

The results demonstrate that BIM maturity has a significant positive effect on coordination effectiveness and clash detection performance. However, its impact on cost and schedule outcomes is predominantly indirect rather than direct. BIM maturity enhances coordination structures, information exchange systems, and interoperability, which in turn improve clash detection accuracy. Improved clash detection subsequently reduces rework, which emerges as a critical determinant of both cost efficiency and schedule performance.

The mediation analysis confirms that rework reduction plays a central role in translating BIM capabilities into measurable project outcomes. Projects with higher BIM maturity levels demonstrate fewer design inconsistencies, reduced change orders, and improved workflow efficiency. These improvements collectively contribute to lower cost overruns and reduced schedule delays.

From a theoretical perspective, the study reinforces the positioning of BIM within digital transformation theory as a socio-technical system rather than a standalone technological tool. BIM maturity reflects not only technical sophistication but also organizational readiness, governance quality, and process integration capability. The findings support the view that digital transformation outcomes in construction are achieved through the alignment of technology, people, and processes rather than technology adoption alone.

Furthermore, the results are consistent with lean construction principles, which emphasize waste reduction, workflow reliability, and continuous improvement. BIM maturity strengthens lean outcomes by enabling early identification of design conflicts and minimizing non-value-adding activities such as rework and redesign. The integration of BIM and lean construction principles is therefore reinforced as a synergistic approach to improving project performance.

For industry practitioners, the findings highlight that investment in BIM technology alone is insufficient to achieve significant performance improvements. Organizations must also develop BIM maturity through structured governance frameworks, workforce training, and standardized information management processes. The effectiveness of BIM is highly dependent on the quality of implementation, particularly in terms of interoperability, common data environment usage, and coordination protocols.

Project managers and stakeholders should prioritize early-stage coordination and clash detection processes, as these have been identified as primary mechanisms driving cost and schedule improvements. Additionally, construction organizations in developing contexts should focus on strengthening organizational readiness and aligning BIM implementation with broader project delivery strategies such as integrated project delivery or collaborative contracting models.

Research Contribution

This study contributes to the existing body of knowledge by empirically validating the indirect pathways through which BIM maturity influences project performance. Unlike studies that focus solely on direct relationships, this research demonstrates that BIM benefits are primarily realized through mediating mechanisms, particularly clash detection and rework reduction. It also integrates digital transformation and lean construction theories to provide a more comprehensive understanding of BIM's role in construction performance improvement.

Limitations and Future Research

Despite its contributions, this study has several limitations. First, the generalizability of findings may be constrained by contextual factors such as project type, regional BIM adoption levels, and data availability. Second, the reliance on structured indicators for BIM maturity and performance may not fully capture qualitative aspects of organizational behavior and project dynamics.

Future research is recommended to expand dataset diversity across different countries and project types, particularly in emerging economies where BIM maturity levels vary significantly. Longitudinal studies are also encouraged to examine how BIM maturity evolves over time and how its impact on performance changes across project lifecycle stages. Additionally, future studies may integrate sustainability and lifecycle performance indicators to extend the analysis beyond cost and schedule outcomes.

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