Integrating BIM for Structural, Cost, and Schedule Optimization: Evidence from a Comparative Construction Study

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ABSTRACT: Building Information Modelling (BIM) has emerged as a transformative approach in the architecture, engineering, and construction (AEC) industry, enabling enhanced visualization, coordination, and data-driven decision-making. Despite its increasing adoption, quantitative evidence demonstrating BIM's effectiveness in structural and schedule optimization compared to traditional practices remains limited. This study investigates the application of BIM for structural optimization and construction scheduling, with a particular focus on cost efficiency and performance improvement. The results demonstrate that the BIM-assisted approach achieved an overall cost reduction of approximately **4.33%** compared to traditional estimation methods, with notable savings observed in structural framing and fenestration components. BIM-based modelling also improved accuracy in quantity estimation, enhanced coordination among disciplines, and supported informed decision-making during early design stages. The findings confirm that BIM offers measurable benefits in structural optimization and construction efficiency, highlighting its potential as a reliable decision-support tool for modern construction projects.A BIM-based workflow was developed using Autodesk Revit to create a detailed three-dimensional structural model incorporating geometric, material, and design parameters. The proposed approach was evaluated through a comparative analysis between conventional manual estimation and BIM-assisted methods. Key structural components—including columns, framing, slabs, walls, and openings were analyzed in terms of quantity take-off, cost estimation, and structural response parameters. Additionally, BIM-enabled coordination and clash detection were examined for their influence on construction efficiency and schedule reliability.

Keywords:BIM; structural optimization; parametric modelling; evolutionary algorithms; multi-objective optimization; digital twin; artificial intelligence; sustainability; performance-based design; lifecycle optimization

1.0 INTRODUCTION

The architecture, engineering, and construction (AEC) industry is experiencing rapid digital transformation driven by increasing project complexity, cost overruns, sustainability requirements, and the demand for higher productivity. Structural design and construction planning decisions made during the early stages of a project significantly influence material consumption, construction duration, cost efficiency, and long-term performance. However, conventional structural design and estimation practices largely dependent on two-dimensional drawings and manual calculationsoften suffer from limited visualization, coordination conflicts, estimation inaccuracies, and inefficiencies in responding to design changes.

Building Information Modelling (BIM) has emerged as a comprehensive digital platform capable of integrating geometric, material, and performance-related information within a unified parametric environment. Early studies established BIM as a tool for design pioneering and generative exploration, enabling the systematic evaluation of multiple design alternatives based on performance criteria rather than static representations [1,2]. The incorporation of parametric modelling principles further enhanced BIM's capacity to support interactive and multi-level design manipulation, allowing engineers to efficiently explore structural variations and design constraints [3].

As BIM technologies matured, research shifted toward embedding intelligence and analytical feedback within BIM environments. Structural design intelligence frameworks demonstrated how BIM could integrate engineering analysis directly into design workflows, improving coordination between modelling and structural evaluation [4]. BIM has also been applied to environmental and sustainability-driven design assessments, enabling the evaluation of building orientation, energy performance, and environmental impact within the same digital environment [5]. These capabilities laid the foundation for performance-based and optimization-oriented design processes.

The integration of optimization algorithms with BIM has been widely explored to enhance structural efficiency and material utilization. Genetic algorithms, meta-heuristic approaches, and evolutionary optimization techniques have been successfully coupled with BIM platforms to optimize structural configurations, cost, and environmental performance [6–8]. BIM guidelines for optimized design-to-fabrication workflows further demonstrated how digital models could bridge the gap between design intent and constructability [9]. Several studies confirmed that BIM-based optimization supports sustainable building design by enabling trade-offs between cost, material efficiency, and structural performance [10–12].

Parametric BIM-driven optimization frameworks have been developed for reinforced concrete structures and complex building systems, enabling automated generation, evaluation, and comparison of multiple design alternatives [13–15,32]. These approaches significantly reduce manual effort while improving design consistency and optimization accuracy. In parallel, BIM-based optimization has been applied to sustainable structural systems, highlighting its potential to reduce environmental impacts and improve lifecycle performance [17,29].

Recent advancements have expanded BIM-based optimization toward automation, intelligent systems, and emerging digital technologies. Automated BIM workflows for structural connection design and topology optimization have demonstrated improved material efficiency and constructability, particularly for complex structural systems and timber structures [18,19]. The integration of BIM with digital twin concepts has further enabled lifecycle-based structural optimization by linking design models with operational data and performance monitoring [20]. Parametric BIM frameworks have also been extended to tall buildings and load-bearing systems, supporting optimization under complex structural and geometric constraints [21,22].

Cloud-based BIM platforms and fully automated parametric BIM models have been proposed to enhance scalability, collaboration, and computational efficiency in multi-objective structural optimization [24,25]. More recently, BIM-based decision-support frameworks have incorporated multi-criteria decision-making techniques to support structural retrofitting and sustainability-oriented design [26]. The convergence of BIM with machine learning and deep learning techniques has further strengthened its predictive and optimization capabilities, enabling accurate performance prediction and intelligent structural optimization in reinforced concrete buildings and complex structural systems [27,30].

Beyond structural optimization, BIM-based research has demonstrated its relevance in advancing sustainable construction materials and systems. Studies on innovative construction materials, such as lightweight aggregates, floating concrete systems, geopolymer concrete, and artificial intelligence–assisted material optimization, highlight the expanding role of BIM-supported workflows in sustainable construction research and practice [16,23,28]. Additionally, BIM-enabled facility management models have reinforced the importance of information-rich digital models for long-term asset performance and decision-making [31].

Despite the extensive body of literature demonstrating BIM's potential, a critical gap persists in the **quantitative comparison between BIM-assisted structural optimization and conventional manual approaches**. Many studies emphasize algorithm development, simulation-based optimization, or conceptual frameworks, while limited research provides empirical evidence of cost savings, estimation accuracy, and efficiency improvements achievable through BIM in practical construction workflows. Moreover, the integration of BIM-based structural optimization with conventional estimation practices remains underexplored in real project contexts.

Accordingly, this study aims to address this gap by developing a BIM-based structural modelling and estimation workflow and performing a **comparative analysis with traditional manual methods**. By evaluating cost estimation accuracy, material optimization, and structural performance indicators, the study provides quantitative evidence of BIM's effectiveness as a practical decision-support tool for structural optimization. The findings contribute to existing BIM research by bridging the gap between theoretical optimization frameworks and real-world construction applications, thereby supporting informed BIM adoption in the AEC industry.

2.0 METHODOLOGY

2.1 Research Framework

This study adopts a **comparative, model-driven research framework** to evaluate the effectiveness of Building Information Modelling (BIM) for structural optimization relative to conventional manual methods. The methodology is designed to quantify differences in cost estimation accuracy, material utilization, and structural performance by applying both approaches to the same building configuration under identical design assumptions. The overall workflow integrates BIM-based parametric modelling, automated quantity extraction, and structural performance evaluation, followed by a systematic comparison with traditional estimation procedures.

The methodological framework is structured into four main stages:

(i) development of a BIM-based structural model,

(ii) implementation of traditional manual estimation and design procedures,

(iii) extraction and evaluation of cost and structural performance metrics, and

(iv) comparative analysis of outcomes.

2.2 BIM-Based Structural Modelling Workflow

A detailed three-dimensional structural model was developed using a BIM platform (Autodesk Revit) to represent the geometry, material properties, and structural components of the building. The BIM environment enables parametric modelling, where changes in dimensions, materials, or configurations are automatically propagated across the model and associated documentation. This parametric capability supports efficient exploration of design alternatives and ensures consistency between drawings, schedules, and quantity take-offs, as established in prior BIM-based generative and parametric design studies [1–3].

Structural components—including columns, beams, slabs, walls, stairs, doors, and windows—were modelled as intelligent objects containing embedded information related to dimensions, materials, and quantities. The BIM model facilitated multidisciplinary coordination and minimized modelling inconsistencies, aligning with BIM-enabled structural intelligence and coordination frameworks reported in earlier studies [4,9].

2.3 Structural Optimization Approach within BIM

Structural optimization was conducted within the BIM environment by refining element dimensions and configurations while maintaining compliance with structural design requirements. The optimization process focused on improving material efficiency and reducing unnecessary overdesign without compromising safety or serviceability. This approach is consistent with BIM-integrated optimization strategies reported in the literature, where parametric modelling enables rapid iteration and evaluation of alternative structural configurations [6,10–15].

Although advanced optimization algorithms such as genetic algorithms and meta-heuristic techniques have been widely applied in BIM-based optimization research [6–8,14,15], the present study emphasizes **practical structural optimization** achievable through BIM-supported parametric control and coordinated modelling. This approach reflects real-world industry adoption scenarios, where fully automated optimization algorithms may not always be implemented due to project constraints.

2.4 Traditional Manual Estimation Method

For comparison purposes, the same building was analyzed using a **conventional manual estimation approach** based on two-dimensional drawings and the centre-line method. Quantities were calculated manually by measuring lengths, widths, and heights of structural elements, followed by deduction of overlaps and openings. Cost estimation was then performed using standard unit rates applied to the calculated quantities.

This traditional approach represents commonly used practices in construction projects and serves as a benchmark for evaluating the benefits of BIM-assisted estimation. However, manual estimation is inherently susceptible to human error, time inefficiency, and inconsistencies arising from design modifications, as widely reported in construction management literature.

2.5 Automated Quantity Take-Off and Cost Estimation Using BIM

In the BIM-based approach, quantities were automatically generated using the scheduling and quantity take-off functionalities of the BIM platform. The software extracted quantities directly from the 3D model, ensuring high accuracy and eliminating the need for repetitive manual calculations. Any design modification in the BIM model was instantaneously reflected in the quantity schedules, significantly improving efficiency and reliability.

Cost estimation was carried out by linking extracted quantities with predefined unit rates for each structural component. This automated process aligns with BIM-supported cost optimization and sustainability-driven estimation approaches reported in previous studies [10–13,17]. The BIM-based estimation workflow also supports transparency and traceability, as each quantity can be visually verified within the 3D model.

2.6 Structural Performance Evaluation

In addition to cost estimation, key structural performance parameters—such as axial forces, bending moments, shear forces, and displacements—were evaluated for critical structural elements. The BIM model served as a central data repository, facilitating coordination between structural modelling and analysis outputs. This integration reflects BIM-driven performance evaluation approaches reported in earlier research [4,18,20].

The structural performance results were used to verify that optimized BIM-based designs met acceptable performance criteria and did not compromise structural integrity. This step ensured that cost and material reductions achieved through BIM optimization were technically justified.

2.7 Comparative Analysis Metrics

The comparison between the traditional and BIM-based approaches was conducted using the following metrics:

- **Cost difference (%)** between manual and BIM-based estimates
- **Element-wise quantity variation** for major structural components
- **Overall material efficiency improvement**
- **Consistency and update efficiency** under design modifications
- **Structural performance compliance** based on key response parameters

These metrics have been widely adopted in BIM-based optimization and sustainability studies to evaluate practical benefits and decision-making efficiency [12,17,21,24–27].

3.0 Results and Discussion

3.1 Impact of BIM Integration on Project Efficiency and Schedule Performance

The results indicate that BIM can be effectively integrated into construction project workflows to enhance efficiency and reduce schedule-related risks. As summarized in **Table 1**, different BIM integration approaches demonstrate varying levels of impact on efficiency improvement and delay reduction. The adoption of **4D BIM scheduling** shows a significant improvement in project efficiency, primarily due to enhanced visualization of construction sequences and early identification of scheduling conflicts. This finding is consistent with previous studies that emphasize the role of BIM-based visualization and time integration in improving construction planning accuracy [1,2].

Collaborative BIM approaches exhibit a significant impact on reducing delays, highlighting BIM's ability to improve coordination and information exchange among stakeholders. Improved collaboration reduces communication gaps and rework, which are common causes of schedule overruns in traditional construction practices [4,9]. Furthermore, BIM-based clash detection demonstrates moderate improvements in both efficiency and delay reduction, confirming that early identification and resolution of design conflicts can prevent costly on-site modifications, as reported in earlier BIM coordination studies [18,31].

The results further show that **BIM integrated with lean principles and IoT technologies** delivers the most significant combined impact on efficiency enhancement and delay reduction. This supports recent research emphasizing the convergence of BIM with advanced digital technologies to enable real-time monitoring, improved workflow synchronization, and proactive decision-making [20,24,25].

3.2 Challenges and Mitigation Strategies for BIM-Based Scheduling Adoption

Table 2 presents the key challenges associated with BIM-based scheduling adoption along with potential mitigation strategies. A major challenge identified is the **lack of BIM expertise among project stakeholders**, which can hinder effective implementation and reduce the expected benefits. This aligns with previous findings that emphasize the importance of training, organizational readiness, and skill development for successful BIM adoption [26,31].

Integration challenges with existing project management systems and data quality issues are also identified as critical barriers. Interoperability limitations between software platforms and inconsistent data standards can compromise BIM's effectiveness in schedule optimization. These findings are consistent with earlier studies highlighting the need for standardized data exchange protocols and robust information management strategies [9,24]. Resistance to change and high initial investment costs further underline the necessity of structured change management frameworks and cost–benefit justification to support BIM adoption at an organizational level [17,26].

3.3 Comparative Cost Analysis: Traditional vs. BIM-Based Estimation

The comparative cost analysis presented in **Table 3** demonstrates clear quantitative differences between traditional manual estimation methods and BIM-based estimation. The BIM-assisted approach resulted in an overall **cost reduction of approximately 4.33%** compared to the traditional method. This reduction is primarily attributed to improved accuracy in quantity take-off, elimination of manual calculation errors, and enhanced coordination among structural elements.

Element-wise analysis reveals that **structural framing and window components** exhibit the highest percentage reductions (7.58% and 8.03%, respectively), indicating that BIM is particularly effective in optimizing repetitive and dimension-sensitive elements. These results are in agreement with previous BIM-based cost optimization studies, which report that automated quantity extraction significantly reduces overestimation and material wastage [10–13].

Components such as furniture show no cost difference, highlighting that BIM's optimization benefits are most pronounced in structurally intensive elements rather than standardized or fixed-cost items.

The findings reinforce that BIM-based estimation not only improves cost accuracy but also enhances transparency and traceability, as quantities are directly linked to the 3D model. This capability supports informed decision-making and rapid design iteration, as emphasized in BIM-driven parametric optimization research [14,15,32].

3.4 Structural Performance Evaluation

The structural performance results summarized in **Table 4** indicate that the BIM-optimized structural configuration satisfies acceptable performance criteria. Maximum axial force, bending moment, shear force, and displacement values remain within permissible limits, confirming that cost and material reductions achieved through BIM-based optimization do not compromise structural safety or serviceability.

These results demonstrate that BIM-supported structural optimization can effectively balance material efficiency and performance compliance. This observation is consistent with previous studies integrating BIM with structural analysis and optimization techniques, which emphasize that performance-driven design can be achieved without sacrificing safety margins [4,6,21]. The ability to validate structural performance alongside cost estimation further strengthens BIM's role as an integrated decision-support platform rather than a standalone modelling tool.

4.0 CONCLUSION

This study investigated the application of Building Information Modelling (BIM) for structural and construction optimization through a comparative assessment with conventional manual estimation and design practices. By integrating parametric BIM modelling, automated quantity take-off, and structural performance evaluation within a unified workflow, the research provides quantitative evidence of BIM's effectiveness as a practical decision-support tool in building projects.

The results demonstrate that BIM-assisted estimation and optimization lead to measurable improvements in cost efficiency and coordination. An overall cost reduction of approximately **4.33%** was achieved when compared with traditional manual estimation methods, with notable savings observed in structurally intensive components such as framing and fenestration. These reductions are primarily attributed to improved quantity accuracy, elimination of manual calculation errors, and enhanced consistency between design and estimation outputs. Importantly, structural performance checks confirmed that the optimized BIM-based configuration satisfied acceptable limits for axial forces, bending moments, shear forces, and displacements, indicating that cost and material savings were achieved without compromising structural safety or serviceability.

Beyond cost benefits, the study highlights BIM's capability to improve construction efficiency and schedule reliability through enhanced visualization, clash detection, and interdisciplinary coordination. The findings confirm that even without the implementation of advanced optimization algorithms or artificial intelligence, industry-standard BIM tools can deliver tangible improvements when applied systematically within real construction workflows. This reinforces BIM's relevance not only as a modelling or visualization platform but also as an integrated framework for performance-driven decision-making.

From a practical perspective, the proposed BIM-based workflow offers a replicable approach for engineers and project managers seeking to improve estimation accuracy, optimize material usage, and enhance coordination in building projects. The outcomes support wider BIM adoption by demonstrating clear economic and operational benefits that can justify initial implementation costs.

Nevertheless, the study is limited to a single building case and does not incorporate real-time construction data or fully automated optimization algorithms. Future research should extend the proposed framework by integrating advanced optimization techniques, machine learning, and digital twin technologies to support dynamic, real-time structural and schedule optimization across diverse project types. Such advancements would further strengthen BIM's role in achieving sustainable, efficient, and resilient construction practices.

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