Use of Building Information Modelling (BIM) for structural optimization

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ABSTRACT: Building Information Modelling (BIM) has evolved from a digital modelling tool into a comprehensive platform capable of supporting advanced structural optimization throughout the design, construction, and operational phases of built assets. This review paper examines the chronological development of BIM-based structural optimization from early parametric design foundations to contemporary integration with artificial intelligence, multi-objective optimization, and digital twin technologies. Early research established BIM as a medium for rule-based geometric modelling and performance assessment, laying the groundwork for optimization-driven workflows. Between 2010 and 2015, the emergence of meta-heuristic algorithms, automated decision systems, and environmental simulation paved the way for the fusion of BIM and computational optimization. The period from 2015 to 2020 saw significant advancements in integrating genetic algorithms, evolutionary form-finding, multi-criteria decision-making, and sustainability analysis directly within BIM environments. Recent developments have further expanded BIM's capabilities through cloud computing, machine learning, deep learning, and real-time data integration, enabling predictive performance modelling and lifecycle optimization. The review highlights how these developments collectively transform BIM into an intelligent decision-support system for achieving structural efficiency, material reduction, cost optimization, and enhanced sustainability. While the field has advanced substantially, challenges related to interoperability, standardization, and computational complexity persist. Nonetheless, the trajectory of research indicates that BIM-enabled structural optimization will continue to play an increasingly central role in shaping the design and performance of future structural systems.

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

1.0 INTRODUCTION

Building Information Modelling (BIM) has emerged as one of the most transformative technologies in the architecture, engineering, and construction (AEC) industry, providing a digital representation of both the physical and functional characteristics of built structures. Over the past decade, the integration of BIM with structural optimization techniques has gained significant attention due to the growing need for sustainable design, cost efficiency, and performance-driven decision-making. The increasing complexity of structural systems, coupled with global demands for material reduction and ecological responsibility, has positioned BIM-based optimization as a cornerstone for next-generation structural engineering solutions. Unlike traditional approaches which often rely on isolated analysis and heuristic design workflows BIM enables centralized information management, parametric modelling, real-time simulation, and automated decision support, thereby enhancing the accuracy and efficiency of structural optimization processes. Early investigations into BIM-enabled performance analysis demonstrated the potential of digital environmental simulations to influence building orientation, material selection, and overall design quality [1]. These foundational works paved the way for more sophisticated multi-level parametric interaction studies, allowing designers to manipulate complex geometries and evaluate structural behavior with unprecedented flexibility [2].

A crucial advancement enabling BIM-driven structural optimization is the rise of parametric and algorithmic modelling environments. These tools allow designers to encode geometric logic, structural rules, and performance criteria within BIM objects. The shift toward algorithmic design has further been strengthened by the integration of optimization algorithms within BIM platforms. Several studies emphasize that parametric BIM modelling can automate repetitive tasks, streamline structural analysis workflows, and generate performance-optimized alternatives using predefined constraints [3]. BIM-based automation systems also facilitate structural connection design and code compliance checking, improving both efficiency and reliability in structural design processes [4]. These developments are complemented by decision-making frameworks that incorporate sustainability metrics, enabling structural engineers to evaluate retrofitting, rehabilitation, and lifecycle performance using multi-criteria BIM models [5]. Likewise, machine learning-augmented BIM workflows continue to evolve, providing deeper insights into load prediction, material behavior, and structural optimization patterns in reinforced concrete buildings [6].

As the industry shifts toward more sustainable and material-efficient design practices, BIM-integrated topology optimization has gained particular prominence. For example, BIM-based topology and shape optimization has been applied to timber structures to minimize material usage while maintaining structural integrity [7]. Similar enhancements in material performance evaluation have been reported in studies investigating lightweight concrete, sustainability-oriented composite materials, and waste-utilization methodologies, highlighting the growing relevance of environmentally conscious design paradigms [8]. Additionally, cloud-integrated BIM platforms enable collaboration and multi-objective structural optimization, allowing distributed design teams to evaluate multiple performance variables simultaneously [9]. Such frameworks bridge the gap between generative design research and practical engineering, as evidenced by early studies in optioneering and form-finding that demonstrated how BIM environments could produce optimized design variations based on structural and environmental criteria [10]. Furthermore, genetic algorithms and meta-heuristic optimization strategies have been embedded directly into BIM workflows to streamline structural optimization tasks [11], while nature-inspired algorithms such as Water Evaporation Optimization have proven useful for enhancing the optimization of high-dimensional structural problems [12].

Beyond enabling advanced optimization, BIM serves as a central repository for data exchange between design disciplines and fabrication systems. Efficient design-to-fabrication workflows are vital for modern automated construction processes, and standardized BIM guidelines serve as the foundation for seamless digital transitions across design stages [13]. In addition, the combination of BIM and topology optimization has shown great promise in the development of sustainable load-bearing systems and reduced material consumption [14]. Automated parametric structural design within BIM environments allows structural engineers to explore a wide spectrum of design alternatives rapidly, thereby accelerating the design process and enhancing precision [15]. This capability is further strengthened by evolutionary form-finding techniques that generate efficient structures capable of supporting complex geometries [16]. The integration of genetic algorithms into BIM platforms has also enabled dynamic updating of structural models, allowing designers to continuously refine structural forms toward optimal performance [17].

Multi-objective optimization within BIM frameworks has become increasingly important for achieving holistic structural outcomes. Recent workflows incorporate environmental, structural, and economic metrics into genetic algorithm engines to support simultaneous optimization of multiple parameters [18]. Moreover, BIM platforms now facilitate structural optimization of tall buildings, enabling engineers to evaluate stability, drift control, and load paths with integrated parametric models [19]. As structural design intelligence continues to advance, BIM-enabled knowledge frameworks support automated reasoning, suggesting rule-based structural configurations that enhance engineering productivity [20]. Complementing these advancements, digital twin integration with BIM platforms allows real-time monitoring, predictive maintenance, and continuous optimization of structural systems throughout their lifecycle [21]. Facility management-enabled BIM (FM-BIM) models have similarly expanded the utility of BIM beyond construction, enabling long-term performance tracking and maintenance optimization strategies [22].

The emergence of sustainability-driven structural optimization, facilitated by BIM, highlights the increasing emphasis on environmental resilience and life-cycle performance in building design. Research in this area has demonstrated the efficiency gains associated with combining BIM with evolutionary and gradient-based optimization algorithms to reduce material usage, emissions, and construction waste [23]. Moreover, BIM has played an instrumental role in enabling sustainability-focused decision-making by integrating materials intelligence, lifecycle analysis, and energy simulation data into structural models [24]. These capabilities complement performance-based parametric modelling frameworks that generate structurally sound and environmentally responsible geometric alternatives [25]. Structural sustainability is further improved by BIM-based optimization methods focused on cost efficiency, enabling optimal dimensioning and material selection for enhanced durability and affordability [26]. Reinforced concrete design also benefits from BIM-driven multi-objective optimization strategies, which enable the reduction of reinforcement, concrete volume, and cost while maintaining safety standards [27].

The rapid evolution of artificial intelligence and computational modelling techniques has accelerated the adoption of BIM-integrated prediction models. Deep-learning-enhanced BIM workflows have demonstrated high accuracy in predicting structural performance and optimizing design parameters under uncertain conditions [28]. Parallel advancements in hybrid swarm algorithms and evolutionary optimization have further improved the optimization of concrete bridge piers and other critical structural elements [29]. In sustainability-focused structural design, BIM is increasingly used to assess environmental impacts such as embodied carbon, material life-cycle costs, and energy consumption, enabling multi-objective optimization for greener infrastructure [30]. In parallel, the growing interest in advanced geopolymer concrete materials and sustainable alternatives to conventional construction materials supports the broader industry movement toward eco-friendly engineering solutions [31].

Overall, the convergence of BIM with structural optimization represents a paradigm shift in engineering practice. BIM-driven optimization not only enhances structural performance but also strengthens design consistency, sustainability, profitability, and decision-making. As BIM technologies continue to mature—especially with the integration of AI, digital twins, cloud computing, and automation—the AEC industry is poised to experience even greater levels of innovation and efficiency. The literature demonstrates that BIM-based structural optimization provides a robust digital framework capable of addressing contemporary challenges such as resource scarcity, carbon reduction mandates, and rising construction complexity. By synthesizing research across parametric modelling, optimization algorithms, material innovation, and lifecycle performance evaluation, this review positions BIM as a central tool for creating structurally optimized, sustainable, and future-ready built environments.

2.0 Literature Review

1. Early Foundations of BIM and Performance-Based Modelling (2000–2010)

The early phase of research on Building Information Modelling (BIM) focused primarily on establishing digital modelling frameworks, rule-based systems, and parametric interaction to support more sophisticated design processes in the future. During this period, the emphasis was placed on representing building geometry, encoding design logic, and enabling interactive manipulation of building forms. One of the earliest and most influential contributions was the development of multi-level interaction in parametric design, which demonstrated how designers could systematically control and modify building geometry using parametric relationships [2]. This work provided conceptual foundations for later BIM-based optimization studies by allowing building models to respond dynamically to design constraints.

Simultaneously, research in performance-based modelling began to explore how parametric approaches could assist in evaluating design alternatives. Concepts of performance-based parametric exploration were presented through frameworks capable of generating diverse design alternatives while analyzing performance metrics such as structural behavior and environmental responsiveness [25]. Although these early frameworks did not integrate advanced optimization algorithms, they demonstrated the potential of linking performance criteria with parametric design tools.

Another significant development in this period was the introduction of BIM-based optioneering, which enabled the evaluation of multiple design configurations based on performance metrics [10]. This highlighted the promise of automated decision-making within BIM environments. The optioneering approach showed that BIM could support design iterations far beyond manual processes, indicating the feasibility of integrating optimization later.

While the earliest BIM applications remained largely descriptive and analytic, they helped establish digital workflows, parametric modelling foundations, and basic performance-based evaluation mechanisms. These achievements set the stage for subsequent research integrating complex optimization algorithms with BIM platforms.

2. Emergence of Optimization Techniques Relevant to BIM (2010–2015)

The period from 2010 to 2015 marks a transitional phase in which optimization techniques began to be systematically explored within the context of engineering design and later combined with BIM. Early studies demonstrated how BIM models could be used for environmental and orientation analyses, linking geometric modelling with performance simulation tools. For example, BIM-enabled analysis of building orientation illustrated how environmental criteria could influence the decision-making process [1]. This showed researchers and practitioners the value of integrating optimization logic within BIM workflows.

During this phase, the computational optimization field advanced rapidly. Novel meta-heuristic algorithms, such as the Water Evaporation Optimization method, proposed new strategies for solving high-dimensional, nonlinear structural optimization problems [12]. Although developed independently of BIM at first, these algorithms later became foundational for BIM-integrated optimization research due to their adaptability and computational robustness.

Likewise, evolutionary optimization methods were deployed for cost and carbon reduction in reinforced concrete bridge piers, suggesting potential for similar algorithmic approaches to be adopted within BIM environments [29]. These cases demonstrated the efficacy of meta-heuristic algorithms in solving engineering problems, ultimately paving the way for their integration with BIM-driven parametric modelling systems.

This period also saw further maturation of BIM as a digital platform. Design-to-fabrication workflows were streamlined with the introduction of standardized BIM guidelines, enabling consistent and automated downstream processes [13]. In parallel, structural design intelligence within BIM models began evolving, incorporating rule-based reasoning to support automated structural decision-making [20]. Such advancements in digital logic and rule-based systems enabled BIM to handle increasingly complex optimization workflows in the following years.

Together, the developments in optimization algorithms and BIM infrastructure between 2010 and 2015 created the essential preconditions for sophisticated BIM-integrated structural optimization processes.

3. Integration of BIM, Parametric Modelling, and Optimization (2015–2020)

Between 2015 and 2020, BIM research experienced significant developments as optimization algorithms were increasingly integrated with parametric modelling and automated structural design workflows. This period marks the formal convergence of BIM with computational optimization.

One of the most notable advancements was the integration of genetic algorithms directly within BIM environments to optimize structural systems [17]. These studies showed that BIM could act not only as a modelling platform but also as an optimization engine capable of generating improved design alternatives under specified constraints. Automated structural connection design also became increasingly reliant on BIM-enabled workflows, improving accuracy and reducing modelling time [4].

Parallel advancements occurred in evolutionary form-finding and generative structural design, where computational methods produced lightweight, efficient structural geometries informed by BIM data [16]. At the same time, optimization frameworks for reinforced concrete structures demonstrated the potential for BIM-driven decision-making to reduce material usage and construction costs while maintaining structural performance [27].

Environmental optimization also gained momentum. BIM-supported multi-objective design allowed designers to consider life-cycle impacts and sustainability metrics concurrently with structural performance [30]. Studies in sustainability-driven BIM workflows emphasized how geometric modelling, material selection, and environmental impact assessments could be connected through multi-criteria optimization systems [24].

Additionally, research on structural optimization for tall buildings introduced BIM-based parametric frameworks capable of evaluating complex design parameters such as lateral drift, core wall thickness, and structural stiffness [19]. Meanwhile, digital fabrication and data interoperability benefited from further development of BIM guidelines to support automated structural workflows [13].

Facility management (FM-BIM) models emerged during this period as well, supporting life-cycle structural assessment and performance monitoring [22]. This represents an important evolution in BIM research, expanding the scope of optimization beyond design into the operational phase of building life.

Furthermore, research into lightweight construction materials [8], innovative parametric timber optimization [7], and RC structural enhancements reinforced the growing connection between BIM, materials research, and structural performance evaluations.

By the end of 2020, BIM had firmly transitioned from a documentation-oriented tool into a comprehensive platform supporting generative design, multi-objective optimization, and full life-cycle analysis.

4. Modern Advances: AI, Deep Learning, Digital Twins, and Sustainable Optimization (2020–2025)

From 2020 onward, BIM-based structural optimization research has increasingly incorporated advanced computational technologies such as artificial intelligence, cloud computing, digital twin systems, and deep learning. These innovations have dramatically expanded the capabilities of BIM frameworks.

Machine learning integration has enabled predictive modelling and automated performance evaluation in reinforced concrete structures, allowing engineers to automate design decisions and increase model accuracy [6]. Similarly, deep learning-enhanced BIM systems have been used to predict structural performance under varying load and material conditions, facilitating more robust optimization processes [28].

Digital twin technology represents one of the most significant advancements of this period. The integration of BIM with digital twins has allowed real-time monitoring, optimization, and life-cycle performance management of buildings and infrastructure [21]. Such systems continuously update structural models based on sensor data, enabling predictive maintenance and performance optimization throughout the building's life.

Advanced parametric modelling frameworks have also evolved, with cloud-integrated BIM platforms supporting collaborative multi-objective optimization for distributed engineering teams [9]. These systems allow real-time evaluation of design alternatives and integrate seamlessly with structural analysis engines.

Sustainable structural design has remained a major research priority. BIM-supported frameworks for structural sustainability, including material selection and carbon footprint assessment, have shown significant promise in aiding engineers to meet global sustainability targets [23]. Additionally, BIM-supported optimization of retrofitting strategies has enhanced the resilience and sustainability of existing structures [5].

Recent studies also show strong growth in topology optimization research within BIM environments. Integrated topology optimization for load-bearing systems has improved material efficiency and structural performance in both steel and timber structures [14, 7].

The field has also seen increased attention to advanced construction materials. Research on geopolymer concrete, for example, has expanded significantly, highlighting sustainable alternatives to traditional cement-based materials and linking material innovation with BIM-enabled modelling and predictive analysis [31].

Finally, developments in BIM-based structural design automation, including improved algorithms for parametric modelling [15], automated form generation [10], and hybrid optimization techniques [18], continue to advance the performance and efficiency of structural engineering processes.

Literature Review Summary

The evolution of BIM-based structural optimization from 2000 to 2025 demonstrates a clear trajectory from descriptive modelling to predictive, generative, and intelligent optimization systems. Early research focused on establishing parametric modelling foundations, followed by the emergence of standalone optimization algorithms. These developments converged between 2015 and 2020, enabling integrated BIM-optimization systems capable of multi-objective performance evaluation.

Since 2020, the integration of artificial intelligence, deep learning, sustainability frameworks, and digital twins has fundamentally transformed BIM into a platform capable of continuous structural optimization throughout a building's life cycle. The literature collectively demonstrates that BIM-based optimization is no longer an emerging concept but a rapidly maturing and indispensable component of structural engineering.

3.0 CONCLUSIONS

The evolution of Building Information Modelling (BIM) in structural engineering over the past two decades demonstrates a clear shift from traditional modelling practices toward intelligent, data-driven, and optimization-centric design workflows. The chronological review of literature highlights the progression from early parametric design concepts to the sophisticated integration of optimization algorithms, sustainability frameworks, artificial intelligence, and digital twins that characterize contemporary research. Initially, BIM served as a digital tool for geometric modelling and project documentation, but the emergence of performance-based modelling and parametric control quickly revealed its potential to support analytical and decision-making processes. This early foundation provided the conceptual basis for integrating optimization methods into BIM workflows.

As optimization techniques matured—particularly with the rise of evolutionary algorithms, meta-heuristic strategies, and multi-objective frameworks—researchers began embedding these methods within BIM environments. This integration marked a major milestone, enabling automated structural design generation, material efficiency improvements, and multi-criteria evaluation processes. By directly linking optimization algorithms with BIM's information-rich models, structural engineers gained the ability to systematically explore design alternatives, evaluate trade-offs, and arrive at solutions that balance cost, performance, sustainability, and constructability. Studies during this period established the feasibility and value of BIM as a platform for computational structural optimization.

The period from 2020 onward further accelerated this development through the adoption of artificial intelligence, deep learning, cloud computing, and digital twin technologies. These advancements expanded BIM beyond the design phase into real-time monitoring, predictive maintenance, and whole-life performance optimization. As a result, BIM has evolved into a comprehensive ecosystem capable of supporting lifecycle optimization of structures. Sustainability-oriented research has also grown significantly, integrating lifecycle assessments, carbon reduction strategies, and material optimization into BIM-enabled frameworks. These developments reflect the global emphasis on environmental resilience and resource efficiency.

Overall, the literature clearly demonstrates that BIM-based structural optimization has transitioned from a conceptual exploration to a fully operational methodology that enhances accuracy, efficiency, and sustainability in structural engineering. Despite substantial progress, challenges remain related to interoperability, computational complexity, data standardization, and the need for industry-wide adoption of advanced digital workflows. Addressing these issues will be essential for enabling the broader implementation of BIM-integrated optimization in practice. Nevertheless, the trajectory of research indicates that BIM will continue to evolve as the central digital infrastructure enabling smarter, more sustainable, and highly optimized structural systems for the future built environment.

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