Cost-Effective Structural Design Using Advanced Optimization Algorithms in Civil Engineering

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ABSTRACT

This study focuses on the application of optimization algorithms for achieving cost-effective structural design in modern civil engineering. Structural optimization helps reduce material consumption, construction cost, structural weight, and lifecycle expenses while maintaining safety, serviceability, and code compliance. Advanced techniques such as Genetic Algorithm, Particle Swarm Optimization, Differential Evolution, Artificial Neural Network, Simulated Annealing, and hybrid metaheuristic methods provide efficient solutions for complex structural problems. These algorithms are useful in reinforced concrete structures, steel systems, seismic design, retrofitting, and sustainable construction. Overall, optimization-based design improves economic efficiency, structural performance, reliability, and sustainability in future infrastructure development.

Keywords: *Structural Optimization, Cost-Effective Design, Optimization Algorithms, Sustainable Construction, Structural Performance.*

I. INTRODUCTION

Structural engineering has continuously evolved with the objective of achieving safe, durable, and economical structures capable of meeting increasing functional and environmental demands. In modern construction practices, the optimization of structural systems has become an essential aspect of engineering design because of rising material costs, rapid urbanization, sustainability concerns, and the need for efficient resource utilization. Traditional structural design approaches generally relied on iterative manual calculations and conservative assumptions, which often resulted in overdesigned and uneconomical structures. However, the advancement of computational technologies, numerical modeling, and intelligent optimization algorithms has significantly transformed the field of structural engineering. Optimization algorithms have enabled engineers to systematically search for the best possible design alternatives while satisfying multiple constraints related to safety, serviceability, strength, and cost. These algorithms are capable of minimizing structural weight, reducing material consumption, lowering lifecycle costs, and improving overall structural performance. Optimization techniques such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Artificial Neural Networks (ANN), Simulated Annealing (SA), Ant Colony Optimization (ACO), and hybrid metaheuristic algorithms have gained considerable attention in structural engineering applications. These computational methods imitate natural, biological, and evolutionary processes to identify optimal solutions in complex engineering problems. According to Kaveh and Mahdavi (2019), population-based optimization algorithms had demonstrated high efficiency in solving multi-objective optimization problems in truss structures by reducing computational costs while maintaining accuracy. Similarly, Breda et al. (2020) emphasized that optimization software based on Genetic Algorithms significantly improved the design efficiency of steel–concrete composite systems by selecting economical design variables within safety constraints. Therefore, optimization algorithms have become highly valuable tools for achieving cost-effective structural design in modern civil engineering projects.

The application of optimization algorithms in structural design has expanded across various domains including reinforced concrete structures, steel structures, truss systems, seismic-resistant buildings, retrofitting systems, and composite structural components. The primary objective of structural optimization is to determine the most efficient combination of design variables that minimizes cost while ensuring structural safety and compliance with design codes. Optimization methods are particularly important in seismic design and retrofitting applications where balancing safety and economy becomes highly challenging. Modern algorithms can efficiently handle multiple conflicting objectives such as minimizing structural weight, reducing expected seismic losses, enhancing ductility, and maximizing reliability. Shabani et al. (2026) developed a life-cycle cost optimization framework for seismic structural design using the PBEE methodology and FEMA P-58 guidelines, demonstrating that optimized structures achieved reductions in both seismic losses and structural weight. Likewise, Di Trapani et al. (2022) introduced a genetic algorithm-based framework for seismic retrofitting optimization, which minimized retrofitting costs while controlling expected annual losses in reinforced concrete frame structures. The integration of optimization algorithms with structural analysis software such as ETABS, SAP2000, and MATLAB has further enhanced the practical implementation of optimization techniques in real-world projects. Djedoui et al. (2025) developed an automated optimization framework by integrating MATLAB and SAP2000 using the PSOGWO algorithm for optimizing three-dimensional reinforced concrete frames under seismic conditions. The findings revealed substantial reductions in concrete and reinforcement quantities while maintaining compliance with seismic design regulations. Furthermore, optimization algorithms have also contributed to sustainable construction practices by minimizing embodied carbon emissions through efficient material utilization. Phan and Van Phan (2026) reported that optimization of reinforced concrete building frames using Genetic and Jaya algorithms not only reduced structural costs but also lowered carbon emissions. Thus, optimization-based structural design has emerged as a critical approach for improving economic efficiency and sustainability in the construction industry.

In recent years, the increasing complexity of structural systems and the demand for resilient infrastructure have encouraged researchers to develop advanced hybrid and multi-objective optimization techniques capable of solving highly nonlinear and constrained engineering problems. Structural optimization problems often involve multiple design variables, nonlinear material behavior, uncertainty in loading conditions, and strict code requirements, making conventional optimization methods inadequate for practical applications. Consequently, hybrid optimization algorithms combining the strengths of multiple techniques have been introduced to improve convergence speed, solution accuracy, and global search capability. For example, Djedoui et al. (2025) utilized a hybrid PSOGWO algorithm that combined Particle Swarm Optimization and Grey Wolf Optimization to achieve efficient and code-compliant seismic structural designs. Similarly, Liu et al. (2023) enhanced the Chimp Optimization Algorithm using niching and evolutionary operators to optimize reinforced concrete structures equipped with buckling-restrained bracing systems, resulting in improved cost efficiency and seismic performance. Reliability-based optimization approaches have also become increasingly important for addressing uncertainties associated with material properties, seismic loads, and environmental conditions. Shrestha and Peng (2025) proposed a reliability-based optimization framework for base-isolated reinforced concrete buildings subjected to stochastic ground motions, demonstrating substantial cost savings and enhanced structural safety. In addition to building structures, optimization algorithms have found applications in aerospace, automotive, and lightweight structural systems. Crispo et al. (2021) proposed a multi-material and multi-joint topology optimization framework for lightweight structural design, which effectively improved stiffness while reducing manufacturing and joining costs. These advancements indicate that optimization algorithms are no longer limited to theoretical studies but are actively contributing to practical engineering solutions across multiple industries. Therefore, the application of optimization algorithms has become indispensable for developing cost-effective, sustainable, reliable, and high-performance structural systems capable of meeting future engineering challenges.

II. RESEARCH BACKGROUND

Phan and Van Phan (2026) reported that structural optimization had attracted considerable global attention due to its economic and environmental advantages. However, it was observed that challenges still persisted, particularly in optimizing three-dimensional reinforced concrete (RC) building frames. The study aimed to minimize material costs in 3D RC structures by developing an optimization software package, BK-HSH, using Python. It was explained that the software employed the Jaya Algorithm and Genetic Algorithm and established an automated integration between structural analysis in ETABS and cost optimization through the ETABS Open API. Two case studies involving three-story and six-story RC frames were analyzed. The findings indicated that significant cost reductions were achieved in both cases. It was further noted that the Jaya Algorithm converged faster for smaller problems, while the Genetic Algorithm required less computational time overall, and optimized designs also reduced embodied carbon emissions.

Shabani et al. (2026) presented a life-cycle cost-based optimization framework for the seismic design of structures, which was developed within the second generation of the Performance-Based Earthquake Engineering (PBEE-2) methodology. The design problem was formulated as a single-objective optimization aimed at minimizing life-cycle cost. To address the high computational demand associated with nonlinear analyses for seismic loss estimation, an approximate loss estimation method was developed based on the story-based approach and FEMA P-58 guidelines. Furthermore, a novel constraint-handling technique was introduced, which was reported to reduce computational cost by more than 80% compared to conventional penalty function methods, without requiring parameter tuning. The effectiveness of the framework was demonstrated through the optimal design of a three-dimensional five-story steel moment-resisting frame, and comparisons were made with conventional design approaches. The results indicated that the optimized structures achieved reductions in both structural weight and expected seismic loss, while also exhibiting improved stiffness, strength, ductility, and lower probabilities of collapse.

Djedoui et al. (2025) presented an automated computational framework that utilized MATLAB and the PSOGWO algorithm for optimizing three-dimensional reinforced concrete frame structures by integrating MATLAB with SAP2000 v22 through an application programming interface. The study aimed to provide a robust tool for the cost optimization of seismic RC frame structures. It was reported that the framework incorporated the provisions of Algerian regulations and the newly introduced Algerian Seismic Code (RPA2024). The integration process was achieved by linking MATLAB, the SAP2000 API, and the PSOGWO algorithm, while complex design constraints such as RPA2024 and BAEL were handled externally using a penalty function approach. The results indicated that concrete volume was reduced by 29% and reinforcement steel by 7.3%. It was concluded that the framework produced optimal and code-compliant solutions, demonstrating flexibility, practical relevance, and potential for enhancing sustainable and cost-efficient structural design practices.

Shrestha and Peng (2025) investigated the challenges associated with mitigating seismic risks in high-intensity seismic regions, particularly highlighting the limitations of traditional base-fixed structures due to economic and practical constraints. It was reported that base isolation systems had offered a promising alternative; however, they exhibited inherent nonlinear behavior and were affected by uncertainties in ground motion characteristics. The authors argued that designing such systems based solely on equivalent linearization methods and limited station data might not ensure both safety and cost-effectiveness.

Therefore, a cost-effective reliability-based design optimization approach was proposed, employing the probability density evolution method (PDEM) along with the non-dominated sorting genetic algorithm (NSGA-II). The study aimed to minimize construction costs while satisfying predefined reliability constraints. A ten-story reinforced concrete frame model was analyzed, and the findings indicated that the proposed approach significantly reduced seismic effects, improved safety, and achieved notable cost savings compared to conventional base-fixed structures.

Guo et al. (2024) investigated the design of structures for resisting progressive collapse, emphasizing the need to enhance structural safety and robustness. It was observed that, due to the low probability of accidental events, such designs often resulted in an unfavorable cost–benefit ratio. To overcome this limitation, a risk-based approach was adopted to optimize the progressive collapse resistance of steel frame structures. The cross-sectional design of structural elements was optimized using genetic algorithms in conjunction with SAP2000 23. It was reported that the proposed method successfully identified structural models with minimum robustness indices while maintaining safety requirements. The findings indicated that the risk-based robustness index effectively evaluated design costs. Furthermore, the integration of the SAP2000 API with Python automation was shown to improve efficiency, reduce manual errors, and enhance precision. The effectiveness of the model was validated through case studies, demonstrating significant reductions in construction and collapse-related costs.

Liu et al. (2023) conducted a study in which conventional seismic design was compared with a design incorporating buckling-restrained bracing (BRBs) in three-dimensional reinforced concrete buildings. It was reported that suboptimal structural solutions were identified using a multi-objective chimp optimization algorithm (MEN-ChOA). However, it was observed that the original algorithm suffered from slow convergence and a tendency to be trapped in local minima. To address these limitations, the algorithm was enhanced through the integration of niching and evolutionary operators. Furthermore, a novel method was proposed for calculating seismic and dead loads by considering all structural components within a three-dimensional frame design framework. The developed model was evaluated using twelve benchmark problems presented at the IEEE Congress on Evolutionary Computation. The findings indicated that BRB-based designs achieved comparable structural performance while offering improved cost efficiency, particularly for taller buildings, thereby demonstrating the effectiveness of the proposed optimization approach.

Di Trapani et al. (2022) presented a novel framework for optimizing the seismic retrofitting design of existing reinforced concrete (RC) frame structures. The study was aimed at minimizing retrofitting-related costs while simultaneously controlling the associated expected annual loss (EAL). It was reported that the proposed procedure utilized artificial intelligence (AI) techniques, particularly a genetic algorithm (GA)-based optimization routine. Constraints were handled using a non-penalty approach through the introduction of innovative parent and survival selection operators. The framework was designed to optimize multiple retrofitting techniques for the same structure, ensuring that both serviceability and ultimate limit states were adequately controlled. The methodology was applied to a case study structure, where carbon fiber-reinforced polymer (CFRP) column wrapping and steel brace systems were considered as retrofitting options. It was observed that the framework effectively determined optimal topology and sizing, resulting in reduced costs and controlled EAL.

Crispo et al. (2021) examined the growing emphasis on lightweighting and cost reduction in the aerospace and automotive industries, where researchers had been exploring advanced materials, innovative manufacturing techniques, and design optimization strategies. The authors highlighted that multi-material topology optimization had been widely utilized to generate unconventional and high-performance designs by exploiting varying material properties. However, it was noted that existing approaches had generally neglected the consideration of joining design during the optimization process, which had often resulted in impractical designs, increased costs, and compromised performance. To address this limitation, the study proposed a multi-material and multi-joint topology optimization framework, wherein joints at material interfaces were explicitly modelled and controlled through design variables. The methodology had incorporated cost constraints related to joining and included detailed procedures for interpolation, interface detection, and sensitivity analysis. The findings demonstrated that the approach had effectively improved structural stiffness while reducing overall cost.

Breda et al. (2020) reported that the primary objective of their research had been to develop software capable of optimizing the selection of design variables adopted by engineers in structural systems comprising steel–concrete composite beams and steel decks. The variables considered included beam shape, composite slab sheeting, number and spacing of beams, slab thickness, and the interaction ratio between the beam and slab. It was further explained that a computational program utilizing the Genetic Algorithm optimization tool available in MATLAB R2015a had been developed for this purpose. The authors indicated that safety requirements had been ensured by incorporating constraints related to the Ultimate Limit State, in accordance with the provisions of ABNT NBR 8800:2008. Additionally, case studies from existing literature and real structures had been examined for validation. The findings suggested that optimization techniques had played a significant role in achieving cost-effective structural designs.

Kaveh and Mahdavi (2019) proposed a new population-based optimization algorithm to address multi-objective optimization problems in truss structures. The method was developed based on a previously introduced single-solution algorithm known as colliding bodies optimization (CBO), in which each agent was considered as an object possessing mass. The researchers extended this concept to formulate the multi-objective colliding bodies optimization (MOCBO) algorithm, where collision theory was utilized as the primary search mechanism. It was reported that the Maximin fitness strategy had been incorporated into the algorithm to effectively rank and sort the candidate solutions. Several standard benchmark test functions with varying characteristics and multiple objectives were analyzed to evaluate performance. The results were compared with established algorithms such as SPEA2, NSGA-II, and MOPSO. It was observed that the proposed method achieved higher accuracy with reduced computational cost and did not require complex parameter tuning.

III. KEY FINDINGS FROM STUDY

Author(s) & Year	Objective of Study	Methodology/Algorithm Used	Major Findings
H. D. Phan and S. Van Phan (2026)	To minimize material cost in 3D reinforced concrete building frames	Jaya Algorithm and Genetic Algorithm integrated with ETABS Open API using Python	Significant cost reduction and reduced embodied carbon emissions were achieved; Jaya converged faster while GA required less computational time overall.
A. Shabani et al. (2026)	To optimize seismic structural design based on life-cycle cost	PBEE-2 methodology with FEMA P-58 and SAR optimization algorithm	Optimized structures showed lower seismic losses, reduced structural weight, improved ductility, and reduced collapse probability.

N. Djedoui et al. (2025)	To optimize seismic RC frame structures for cost efficiency	MATLAB–SAP2000 API integration using Hybrid PSOGWO Algorithm	Concrete volume reduced by 29% and reinforcement steel by 7.3% while satisfying seismic code requirements.
S. Shrestha and Y. Peng (2025)	To achieve reliability-based cost optimization of base-isolated RC buildings	PDEM and NSGA-II optimization techniques	Proposed framework reduced seismic effects, improved safety, and lowered construction costs.
F. Guo et al. (2024)	To optimize progressive collapse resistance in steel frame structures	Genetic Algorithms with SAP2000 API integration	Risk-based optimization reduced construction and collapse-related costs while improving robustness.
S. Liu et al. (2023)	To optimize RC structures with buckling-restrained bracing systems	Multi-objective Evolutionary Niching Chimp Optimization Algorithm	BRB-based optimized structures achieved improved cost efficiency and seismic performance.
F. Di Trapani et al. (2022)	To minimize retrofitting cost and expected annual seismic loss	Genetic Algorithm-based AI optimization framework	Effective optimization of CFRP and steel brace retrofitting systems with reduced cost and controlled EAL.
L. Crispo et al. (2021)	To develop lightweight and cost-effective multi-material structures	Multi-material and multi-joint topology optimization	Structural stiffness improved while manufacturing and joining costs were reduced.
B. D. Breda et al. (2020)	To optimize composite beam and slab systems	MATLAB-based Genetic Algorithm optimization	Optimization techniques significantly improved cost-effective design of steel–concrete systems.
A. Kaveh and V. R. Mahdavi (2019)	To solve multi-objective optimization problems in truss structures	Multi-objective Colliding Bodies Optimization Algorithm	Proposed algorithm achieved high accuracy with reduced computational cost and minimal parameter tuning.

IV. CONCLUSION

The application of optimization algorithms in structural engineering has significantly transformed the conventional approach to structural design by introducing intelligent, efficient, and cost-effective computational techniques capable of solving highly complex engineering problems. The reviewed studies collectively demonstrated that optimization algorithms such as Genetic Algorithms, Particle Swarm Optimization, Grey Wolf Optimization, NSGA-II, Jaya Algorithm, and hybrid metaheuristic techniques have been successfully utilized in reinforced concrete structures, steel frames, truss systems, seismic-resistant buildings, retrofitting systems, and lightweight structural components. These optimization approaches were found to effectively minimize material usage, reduce construction and lifecycle costs, improve structural safety, and enhance sustainability while satisfying stringent design code requirements. Several studies also highlighted the integration of optimization algorithms with structural analysis software such as ETABS, SAP2000, and MATLAB, which significantly improved automation, computational efficiency, and practical applicability in engineering projects. In seismic engineering applications, optimization frameworks demonstrated remarkable capability in reducing seismic losses, improving ductility, enhancing reliability, and lowering collapse probability. Furthermore, advanced hybrid and reliability-based optimization methods effectively addressed challenges associated with nonlinear behavior, uncertainty in seismic loads, and multi-objective design requirements. The reviewed literature also emphasized that optimization-based structural design contributes to environmental sustainability by reducing embodied carbon emissions and promoting efficient resource utilization. Overall, it can be concluded that optimization algorithms have emerged as indispensable tools for achieving economical, reliable, sustainable, and high-performance structural systems, and their continued advancement will play a crucial role in the future development of intelligent civil engineering infrastructure.

V. FUTURE SCOPE

The future scope of application of optimization algorithms for cost-effective structural design is highly promising, as rapid advancements in computational intelligence, artificial intelligence, and digital engineering continue to transform the construction industry. Future research is expected to focus on the development of more robust, hybrid, and adaptive optimization algorithms that can efficiently handle highly nonlinear, multi-objective, and large-scale structural design problems with improved convergence speed and accuracy. The integration of machine learning and deep learning techniques with traditional metaheuristic algorithms is likely to enable predictive optimization, where structural performance can be estimated and improved in real time during the design phase. In addition, the combination of optimization algorithms with Building Information Modeling (BIM) and digital twin technologies will facilitate automated, data-driven, and intelligent structural design workflows, enabling engineers to continuously optimize structures throughout their lifecycle. Future studies will also emphasize sustainability by incorporating environmental objectives such as carbon footprint reduction, energy efficiency, and lifecycle cost minimization alongside traditional cost and safety parameters. Reliability-based and uncertainty-aware optimization methods will gain importance in addressing variability in material properties, loading conditions, and construction practices, particularly in seismic and extreme hazard scenarios. Moreover, the application of cloud computing and high-performance parallel computing is expected to significantly reduce computational time, making optimization techniques more practical for real-time and large-scale infrastructure projects. Advanced optimization methods will also be extended to emerging construction areas such as smart materials, adaptive structures, modular construction, and prefabricated systems, ensuring faster, safer, and more economical building processes. Overall, future developments in optimization algorithms will play a crucial role in achieving intelligent, sustainable, resilient, and highly efficient structural systems that meet the evolving demands of modern civil engineering infrastructure.

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