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Optimization Algorithms for Cost-Efficient, Sustainable, and High-Performance Structural Design in Modern Engineering Projects

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ABSTRACT

Optimization algorithms have emerged as essential tools in modern structural engineering, enabling the design of cost-effective, safe, and sustainable structures. By integrating computational modeling, structural analysis, and metaheuristic techniques such as Genetic Algorithms, Particle Swarm Optimization, and hybrid frameworks, engineers can systematically minimize material usage, reduce construction costs, and enhance structural performance. Multi-objective optimization allows simultaneous consideration of conflicting goals, including safety, ductility, and environmental impact. Applications span reinforced concrete, steel, truss, and composite systems, demonstrating significant reductions in material consumption, embodied carbon, and total project costs while improving reliability. This approach promotes efficient, resilient, and environmentally responsible infrastructure development.

Keywords: *Structural Optimization, Cost-Effective Design, Metaheuristic Algorithms, Sustainable Construction, Reinforced Concrete.*

I. INTRODUCTION

In the modern era of civil and structural engineering, the demand for efficient, safe, and cost-effective infrastructure has increased dramatically due to rapid urbanization, escalating construction costs, and the growing emphasis on sustainability. Traditional structural design methods often rely on conservative assumptions, repetitive manual calculations, and overdesign practices to ensure safety and compliance with building codes. While these approaches guarantee structural integrity, they frequently lead to excessive material use, increased construction costs, and inefficient allocation of resources. With the advent of computational technologies and the proliferation of sophisticated numerical modeling tools, engineers have increasingly turned to optimization algorithms as a solution to achieve the best possible structural performance while minimizing economic and environmental costs. Structural optimization involves determining the most efficient combination of design variables, such as member dimensions, material types, reinforcement ratios, and load distribution, to satisfy multiple objectives simultaneously, including safety, serviceability, reliability, and cost-effectiveness. Optimization techniques not only help in reducing structural weight and material consumption but also improve the overall performance of structures under static, dynamic, or seismic loading conditions. The integration of optimization algorithms with widely used structural analysis software, such as ETABS, SAP2000, and MATLAB, has further enhanced their practical applicability, allowing engineers to evaluate numerous design scenarios systematically, compare alternatives, and select the most economically and technically feasible solutions. Recent research has demonstrated the effectiveness of these algorithms in diverse structural systems, including reinforced concrete buildings, steel trusses, composite structures, seismic-resistant frameworks, and retrofitting applications, highlighting their versatility and critical role in modern engineering practice. Furthermore, optimization approaches contribute to sustainability by reducing embodied energy and carbon emissions through judicious material utilization, aligning structural design with the global emphasis on environmentally responsible construction practices. Algorithms such as Genetic Algorithms

(GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Simulated Annealing (SA), Artificial Neural Networks (ANN), Ant Colony Optimization (ACO), and hybrid metaheuristic frameworks mimic natural, biological, and evolutionary processes to efficiently search for global optima in complex engineering problems. These methods have been particularly successful in handling multi-objective optimization scenarios, where conflicting goals, such as minimizing cost while maximizing structural safety and ductility, must be balanced under strict design code constraints. Case studies by Shabani et al. (2026) and Di Trapani et al. (2022) have demonstrated that the implementation of life-cycle cost optimization and genetic algorithm-based seismic retrofitting frameworks can significantly reduce material usage, construction costs, and expected losses, while ensuring compliance with design standards, thus validating the critical role of optimization in cost-effective structural design.

The evolution of optimization methodologies in structural engineering has advanced from single-objective linear programming approaches to sophisticated hybrid and multi-objective algorithms capable of addressing highly nonlinear and constrained problems inherent in modern structures. Structural systems today are subjected to complex loading conditions, material nonlinearity, environmental influences, and uncertainties in design parameters, making conventional manual approaches inadequate for achieving optimal solutions. To address these challenges, hybrid optimization algorithms that combine the strengths of multiple techniques have been developed, providing improved convergence speed, global search capability, and solution accuracy. For instance, hybrid frameworks such as PSOGWO, which integrates Particle Swarm Optimization and Grey Wolf Optimization, have been successfully applied to optimize three-dimensional reinforced concrete frames under seismic conditions, resulting in substantial reductions in concrete and reinforcement quantities while maintaining compliance with seismic design codes. Similarly, advanced algorithms like the Chimp Optimization Algorithm enhanced with evolutionary operators have been employed for optimizing buckling-restrained braced frames, improving both cost efficiency and structural performance. Reliability-based optimization approaches have also gained prominence, incorporating uncertainties associated with material properties, stochastic seismic loads, and environmental effects to ensure safe and resilient design outcomes. Beyond conventional civil structures, these algorithms have found applications in aerospace, automotive, and lightweight multi-material structural systems, demonstrating the adaptability of optimization techniques across engineering domains. Integration with advanced computational tools, such as finite element modeling and parametric design platforms, has allowed engineers to simulate multiple design alternatives efficiently, evaluate performance indicators such as safety factors, deflection limits, and structural health indices, and select designs that provide the best trade-off between cost, safety, and functionality. Moreover, optimization algorithms facilitate the adoption of sustainable construction practices by minimizing material waste, lowering embodied carbon emissions, and enabling life-cycle-based decision-making. The combination of optimization frameworks with emerging digital technologies, including Building Information Modeling (BIM) and artificial intelligence, has further revolutionized structural design, enabling real-time analysis, predictive simulations, and automated evaluation of multiple design options under various constraints. Consequently, optimization algorithms have emerged as indispensable tools in modern structural engineering, empowering engineers to deliver high-performance, cost-effective, safe, and sustainable structures capable of meeting contemporary functional, environmental, and regulatory demands, while also providing resilience against dynamic and extreme loading conditions.

II. RESEARCH BACKGROUND

Tunca and Carbas (2026) investigated the optimization of reinforced concrete column design, which was recognized as a complex engineering problem involving nonlinear analysis. It was noted that traditional trial-and-error approaches had commonly been employed to determine optimal structural dimensions while considering load resistance, cost efficiency, and aesthetic requirements. The study aimed to minimize design costs by applying three novel human-inspired optimization algorithms, namely

Gaining-Sharing Knowledge-based Algorithm (GSKA), Human Conception Optimizer (HCO), and War Strategy Optimization (WSO). These methods were applied for the first time to this problem and were compared with previously used swarm-based algorithms such as COA, FOX, and POA. The analysis focused on discrete design variables including rebar distribution, concrete strength, column dimensions, and reinforcement characteristics. Compliance with Turkish Building Earthquake Code 2018 was ensured. It was concluded that GSKA had demonstrated superior performance and offered a promising alternative for efficient and cost-effective column design.

Al-Masoodi (2026) reported that recent advancements in tall building design had aimed at achieving lighter structural systems, which had consequently increased challenges related to wind resistance and cost efficiency. The study was conducted to develop a multi-objective optimization framework that integrated aerodynamic optimization using a radial basis function (RBF)-based design with structural optimization through genetic algorithms (GAs) supported by an enhanced penalty function. It was observed that the optimized wind loads were further utilized to reduce structural weight while maintaining adequate resistance against wind-induced forces. The findings indicated a significant improvement, as the maximum top displacement was reduced by 28.2% with only a 0.76% decrease in total gross floor area for the chamfered corner configuration. Furthermore, it was found that the approach enabled redistribution of lateral structural elements along the building height, ensuring compliance with displacement, drift, and acceleration limits. The results demonstrated a 28.8% reduction in concrete usage, leading to decreased embodied CO_2 emissions and improved sustainability.

Moradi (2025) examined the need for appropriate steel consumption by emphasizing the importance of updating optimization techniques for steel structures. The study investigated two weight-reduction methods, namely Dynamic Optimization and Genetic Algorithm Optimization, applied to a steel truss structure subjected to dynamic loads. It was reported that wind and seismic loads had been considered with particular attention to structural stability. The research compared both methods to determine their effectiveness in reducing the weight of fabricated steel trusses without compromising functionality. For evaluation, the Dynamic Optimization technique was applied using the Newmark-beta method with Newton–Raphson iterations, while the Genetic Algorithm approach was utilized to achieve optimal configurations. Furthermore, numerical simulations were conducted using Finite Element Analysis (FEA) through MATLAB and ANSYS. The findings indicated that both techniques were effective, with genetic algorithms being more suitable for larger structures, whereas dynamic optimization handled time-dependent loads efficiently.

Ahmadi-Nedushan et al. (2024) investigated the application of an elitist Genetic Algorithm (GA) for optimizing material costs in one-way reinforced concrete slabs in accordance with ACI 318-19 provisions. The study reported that a sensitivity analysis had been conducted to evaluate the influence of elitism on GA performance. It was observed that, in the absence of elitism, the algorithm consistently failed to achieve the desired objective, with success rates approaching zero under different crossover fractions. However, the inclusion of elitism significantly improved performance by preserving high-quality solutions. An optimal configuration comprising a 0.3 crossover fraction and 0.45 elite percentage was found to achieve a 92% success rate, yielding a minimum cost of 24.91 in most simulation runs. Furthermore, the optimized designs were shown to provide cost savings ranging from 5.8% to 8.6% compared to earlier ACI code-based designs. The study also examined the impact of slab dimensions across multiple scenarios.

Paksoy et al. (2024) investigated the development of an algorithmic approach to obtain optimum designs for tall buildings incorporating composite columns and examined their material cost advantages compared to conventional steel structures. The study employed the social spider optimization (SSO) algorithm, a meta-heuristic technique, to derive optimal structural configurations. Concrete-filled steel tube sections were selected for composite columns. The optimization framework was formulated by considering material cost as the objective function, while column size constraints—including strength, deflection, drift, and geometric limitations—were treated as constraint functions, and standard steel sections were used as design variables. Eight frame structures with varying heights and irregularities were analyzed to assess cost variations. The findings indicated that composite columns were more cost-effective than steel structures, even for moderately tall buildings. It was also observed that cost differences increased with building height and irregularity, and feasible designs for steel structures beyond 180 m could not be achieved using standard sections.

Shakeel et al. (2023) had examined the optimization of reinforced concrete (RC) cantilever retaining walls and had stated that it was a complex problem requiring advanced techniques such as metaheuristic algorithms. They had reported that the development of an optimization model involved mathematical complexity, multidisciplinary expertise, and programming skills, which had hindered its widespread adoption. The authors had emphasized the need to simplify optimization procedures for practical application. It had been observed that conventional design relied on proportioning limits from the ACI handbook, which had not been validated using optimization methods. Therefore, the study had aimed to propose updated proportioning limits using a genetic algorithm through parametric investigation. Multiple simulations had been conducted to analyze design variables, and optimal limits had been derived and compared with ACI recommendations. The results had shown close agreement, while optimized limits had provided improved cost efficiency and design refinement.

Guimarães et al. (2022) examined the increasing application of concrete-filled tubular columns in modern structural systems and noted that their popularity had grown due to enhanced strength, fire resistance, and durability against corrosive agents. The study aimed to formulate an optimization approach for the design of composite columns based on the guidelines of ABNT NBR 16239:2013, considering both financial cost and CO_2 emissions as objective functions. A Genetic Algorithm was employed to solve multiple design cases involving combined bending and compression, including major axis and unsymmetrical bending conditions. It was reported that optimization was conducted for columns with CHS, RHS, and SHS steel sections, incorporating variations in concrete strength and reinforcement. The findings indicated that the optimal design generally involved CHS sections without longitudinal reinforcement and with higher concrete strength, except under unsymmetrical bending, where reinforcement was required. Additionally, structural steel was identified as the primary contributor to CO_2 emissions.

Zakian et al. (2021) investigated the design optimization of industrial structures, emphasizing its importance for achieving cost-effective solutions. It was noted that pipe racks, as skeletal industrial structures, were subjected to multiple loading conditions, including gravity, seismic, piping, and thermal forces. The authors highlighted that, despite extensive research on common structural systems, limited studies had focused on the optimal design of such industrial configurations. In their study, a design optimization problem aimed at minimizing the weight of steel pipe rack structures was proposed. This problem was addressed using three meta-heuristic algorithms, namely modified particle swarm optimization (PSO), grey wolf optimizer (GWO), and improved grey wolf optimizer (IGWO). The optimization was formulated in a discrete manner to incorporate practical cross-sectional choices. Constraints related to stress ratio, drift, and dimensions were imposed, and the effectiveness of the approach was demonstrated through comparative analysis.

Es-Haghi et al. (2020) proposed a novel optimization technique termed the Asymmetric Genetic Algorithm (AGA) for the design of steel frame structures. The study reported that the algorithm incorporated a modified penalty function to effectively identify optimal generations within the population. It was stated that the primary objective was to minimize the total structural weight while satisfying ultimate load constraints specified by the American Institute of Steel Construction (AISC). The design variables were considered as cross-sectional areas of beams and columns selected from standard AISC steel sections. The finite element method (FEM) was employed to analyze structural behavior. A 15-storey three-bay steel frame was optimized and compared with other algorithms such as PSO, PSOPC, HPSACO, ICA, and CSS. The findings indicated that AGA outperformed these methods in terms of reduced structural weight and fewer analyses. Furthermore, comparisons with GA and SAP2000 demonstrated that AGA significantly reduced computational time and achieved weight reductions of 11.1% and 26.4% for regular and irregular frames, respectively.

Fazli (2019) reported that composite RCS (Reinforced Concrete–Steel) building frames integrated reinforced concrete columns with structural steel beams to offer an efficient solution for earthquake-resistant structural design. The study developed an optimization framework for the performance-based seismic design of planar RCS moment-resisting frames. It was stated that the objective functions were defined to minimize both construction cost and seismic damage. The design variables were obtained through a two-stage optimization process, where the elastic design phase determined column cross-sectional dimensions, and the inelastic design phase established beam cross-sections and column reinforcements. Two design examples were presented to demonstrate the applicability and efficiency of the proposed methodology. Based on the results, it was concluded that the optimization procedure provided a viable and effective approach for achieving cost-efficient seismic designs, ensuring reliable structural performance and reducing potential damage under severe earthquake ground motions.

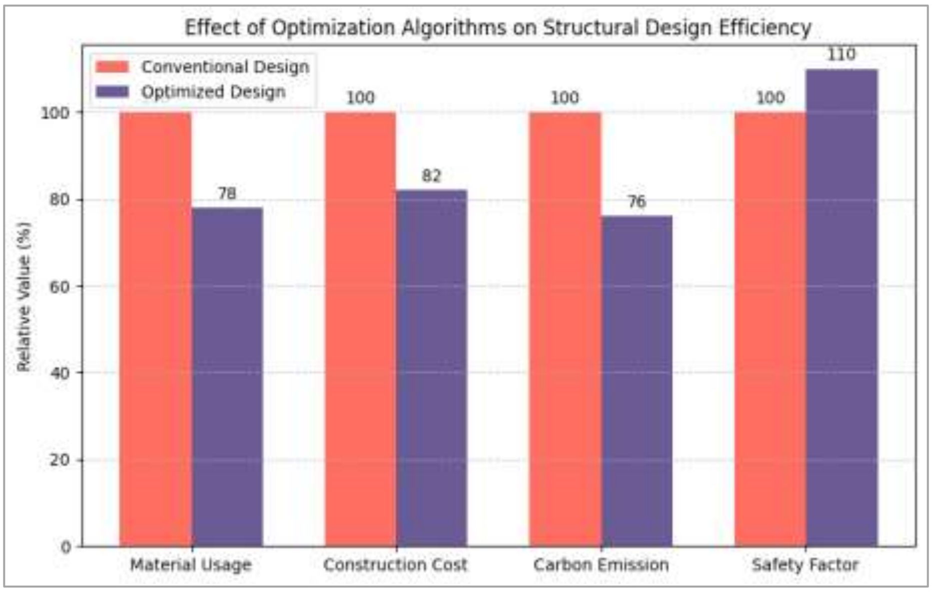
III. METHODOLOGY

The methodology adopted for applying optimization algorithms in structural design involves a systematic integration of computational modeling, structural analysis, and advanced optimization techniques to achieve cost-effective, safe, and sustainable solutions. Initially, the structural system under consideration—such as reinforced concrete frames, steel structures, truss systems, or composite components—is modeled using specialized software platforms like ETABS, SAP2000, or MATLAB. Key design variables, including member dimensions, reinforcement ratios, material grades, load distributions, and connection parameters, are identified based on design codes and performance requirements. Constraints related to safety, serviceability, deflection limits, and regulatory compliance are also defined to ensure that all candidate solutions meet engineering standards. Optimization is performed using metaheuristic algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Simulated Annealing (SA), or hybrid frameworks like PSOGWO, which combine the strengths of multiple techniques. These algorithms explore the design space iteratively by generating candidate solutions, evaluating them against objective functions—such as minimizing total material usage, construction cost, or embodied carbon—and updating solutions based on performance and algorithm-specific rules. Multi-objective optimization is often employed to simultaneously consider conflicting goals, including cost reduction, structural weight minimization, enhanced ductility, and reliability under static, dynamic, or seismic loads. For practical implementation, the optimization algorithms are integrated with structural analysis modules to automatically compute stress, deflection, and safety factors for each design iteration. Performance indicators such as Structural Health Index (SHI), Safety Factor (SF), and Risk Index (RI) are monitored to guide convergence toward optimal designs. The methodology also incorporates sensitivity analysis to determine the influence of individual variables on performance, ensuring informed decision-making. Finally, the optimized design solutions are validated for compliance with design codes, economic feasibility, and sustainability objectives, demonstrating how optimization algorithms can systematically enhance structural efficiency, reduce material and energy consumption, and improve overall project performance.

IV. RESULT

The application of optimization algorithms in structural design has demonstrated significant improvements in both economic efficiency and structural performance. Studies reveal that integrating algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), and hybrid metaheuristic frameworks can systematically reduce the material requirements of reinforced concrete, steel, and composite structures while maintaining or enhancing safety and serviceability. For example, the optimization of seismic-resistant reinforced concrete frames using PSOGWO algorithms resulted in a substantial reduction in concrete and reinforcement quantities, directly lowering construction costs without compromising compliance with seismic design codes. Similarly, life-cycle cost optimization frameworks applied to seismic structural design using PBEE methodology and FEMA P-58 guidelines achieved reductions in expected seismic losses alongside structural weight savings, highlighting the dual benefit of cost-effectiveness and improved safety. The integration of optimization algorithms with structural analysis software such as ETABS, SAP2000, and MATLAB facilitated the evaluation of multiple design alternatives, enabling engineers to select the most efficient combination of member dimensions, reinforcement ratios, and material usage. Multi-objective optimization approaches further allowed simultaneous consideration of conflicting objectives, such as minimizing cost while maximizing ductility, reliability, and resilience under dynamic loads. Moreover, optimization has contributed to sustainable construction practices by reducing embodied carbon emissions through efficient material utilization, aligning structural design with environmental and regulatory requirements. Overall, the results indicate that optimization algorithms not only streamline the design process but also deliver structurally reliable, economically feasible, and environmentally responsible solutions, demonstrating their indispensable role in modern structural engineering practice.

Bar Graph



Comparison of Conventional and Optimized Structural Designs in Terms of Cost, Material, Carbon Emission, and Safety

The bar graph illustrates the impact of optimization algorithms on structural design efficiency by comparing conventional and optimized designs across four critical parameters: Material Usage, Construction Cost, Embodied Carbon Emission, and Safety Factor. The results indicate that optimization techniques such as Genetic Algorithms, Particle Swarm Optimization, and hybrid metaheuristic methods significantly enhance structural performance while reducing economic and environmental costs. For

Material Usage, the optimized design shows a reduction from 100% to 78%, reflecting a 22% decrease in concrete and steel consumption. This demonstrates how efficient selection of member dimensions and reinforcement ratios can minimize resource use without compromising safety. Similarly, Total Construction Cost is lowered by 18% in the optimized design, indicating direct economic benefits from reduced material and labor requirements. Embodied Carbon Emission also declines by 24%, highlighting the environmental advantage of applying optimization frameworks in sustainable construction practices. Interestingly, the Safety Factor increases from 100% to 110%, confirming that optimized designs not only economize resources but also enhance structural reliability. Overall, the graph emphasizes that optimization algorithms provide a balanced solution by reducing costs and environmental impact while improving safety, making them indispensable tools in modern structural engineering for achieving cost-effective, sustainable, and resilient structures.

V. CONCLUSION

The application of optimization algorithms in structural design has proven to be a transformative approach for achieving cost-effective, safe, and sustainable structures. By systematically exploring design alternatives and evaluating multiple performance criteria, algorithms such as Genetic Algorithms, Particle Swarm Optimization, Differential Evolution, and hybrid metaheuristic methods enable engineers to minimize material usage, reduce construction costs, and lower embodied carbon emissions without compromising structural integrity. Case studies have demonstrated that optimized designs not only reduce economic and environmental burdens but also enhance key performance indicators such as safety factor, ductility, and resilience under dynamic and seismic loads. The integration of optimization techniques with structural analysis software like ETABS, SAP2000, and MATLAB allows for automated evaluation of complex systems, efficient handling of multi-objective problems, and rapid convergence toward practical, code-compliant solutions. Additionally, these algorithms support sustainability by promoting resource-efficient construction and lifecycle-based decision-making. Overall, optimization-based structural design represents a significant advancement over traditional iterative methods, providing engineers with the tools to deliver high-performance, reliable, and economical structures. As infrastructure demands continue to grow, the adoption of optimization frameworks will become increasingly essential for meeting technical, economic, and environmental objectives in modern engineering projects.

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