Metaheuristic Optimization Review

♦ ISSN: 2692-4048 Vol: 03, No. 02, 2024 ♦ PP. 06–10

Article DOI: https://doi.org/10.54216/MOR.030202



REVIEW ARTICLE

Metaheuristic Algorithms in Optimizing Structural Design of Bridges: A Review

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Received: October 17, 2024 Revised: December 08, 2024 Accepted: January 07, 2025 ⋆ Corresponding author

ABSTRACT

Metaheuristic optimization algorithms become essential to solving structural design problems because they can handle nonlinear, multiple-mode, large-scale, and other difficulties. This review focuses on how MOAs have been developed and utilized and how they have compared efficiency in structural engineering design optimization. It describes some of the main milestones, such as hybrid and ensemble algorithms, as well as quantum annealing and finite elements, to improve the accuracy of the results. The study organizes and assesses modern approaches scientifically and accentuates their benefits and pitfalls in practical applications. Hypotheses derived from benchmarking and statistical exercises show that enhanced MOAs are reliable and fast in yielding almost ideal structures within a manageable computational frontier. Finally, the review outlines the limitations of the current research and suggests research foci for the future advancement of metaheuristic methods and their use in structural engineering optimization.

Keywords: Metaheuristic algorithms ▪ structural optimization ▪ quantum annealing ▪ hybrid methods ▪ engineering design ▪ computational efficiency

1. INTRODUCTION

Optimization is an important application in analyzing design problems for optimal solutions in civil engineering, focusing on the least cost of implementation and the highest performance and structural integrity. Standard optimization methods, including gradient-based procedures, cannot solve nonlinear, multimodal, and large-scale problems; hence, possibilities must be sought. Metaheuristic optimization algorithms (MOAs) are practical solutions adopting stochastic and nature-inspired strategies to overcome MOA challenges. The following review focuses on the MOAs employed in structural engineering design, their evolution and their effectiveness in solving practical problems [1].

Swarm intelligence, genetics, laws of physics, and combined algorithms are widely used metaheuristics in solving precarious real-life multi-objective and constraint engineering issues. Among these algorithms, Particle Swarm Optimization (PSO), Genetic Algorithms (GA), and Grey Wolf Optimization (GWO) are some of the algorithms that have been implemented in the field of structural design optimization because of the flexibility of use and short-time of the search. Heuristic methods, in particular, are applied in these algorithms to search and optimize the solution space by solving problems more efficiently than traditional methodologies under adverse conditions [2].

An important benefit of MOAs is the capability to deal with the enormous complexity of real-life structural design applications. Implementation difficulties in problems with coordinate variables, nonlinearity, and strict constraints, which may exist in bridge, truss, or beam problems, have also been addressed by MOAs. Progress in solving these algorithms has been made possible by increased computation that makes their solutions effective in handling significant problems with

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practical solutions [3].

The advancements have led to the introduction of hybrid and ensemble algorithms, which integrate other metaheuristics to form enhanced algorithms. For instance, LX-BBSCA and Refinement Firefly Algorithm show improvements in convergence and solution quality, effectively avoiding local optima traps. Moreover, synthesizing MOAs with quantum annealing and finite elements offers new directions in approaching and solving structural optimization in more precise and creative solutions for single and complex structures [4].

Comparative evaluation and benchmark assessment have been used to compare and assess the various MOAs used in structural design optimization. The research results indicate that advanced and hybrid MOAs are faster, more accurate, and more robust compared to traditional and basic models. Such evaluation helps determine the effectiveness and the limitations of different algorithms and the right one to be adopted, given a particular engineering application [5].

In this review, only up-to-date metaheuristic optimization practices in structural design are presented systematically. Based on a review of existing literature, the value and developability of MOAs from an engineering perspective are stressed. Moreover, it outlines research limitations and directions for future research on metaheuristics development and its application in more detailed structural optimization problems [6].

2. LITERATURE REVIEW

Metaheuristic optimization algorithms are powerful tools for solving complex optimization problems in various fields of engineering. Their effectiveness in dealing with complex, nonlinear, and large-scale problems has placed them among the favored methodologies in current structural design optimization. This literature review discusses the different fields of using MOAs and the evolution of opportunities for handling actual structural issues. It also demonstrates basic and new approaches, algorithmic expressions, and comparisons to measure the performance of these approaches. The results presented in this research highlight the increasing importance of MOAs in providing optimal solutions for cost, reliability, and computational time in structural engineering applications.

As detailed in [7], optimization challenges closely mirror complex real-world problems, often requiring robust solutions. These challenges are addressed using approximate and exact methods, with metaheuristic algorithms playing a prominent role within the approximate category. These algorithms effectively navigate local optima and provide efficient solutions by leveraging systematic principles. This study focuses on a comparative analysis of 11 metaheuristic algorithms, including atomic orbital search, chaos game optimization, energy valley optimizer, firefly algorithm, genetic algorithm, gray wolf optimization, harmony search, material generation algorithm, particle swarm optimization, social network search, and whale optimization algorithm, applied to structural optimization problems such as trusses, beams, and columns. Performance metrics include computational efficiency, accuracy, and statistical outcomes over 50 iterations, highlighting particle swarm optimization and social network search as particularly effective across various scenarios.

The research presented in [8] addresses real-world engineering design problems characterized by complex objective functions and constraints through comparative analysis of seventeen metaheuristic algorithms applied to twelve engineering design tasks. The study emphasizes the lack of comparative analyses of recent methods under real-world conditions and provides a valuable guideline for engineering and artificial intelligence researchers. This work is a foundation for future studies aiming to benchmark emerging optimization techniques in engineering contexts.

As outlined in [9], optimal designs for reinforced concrete slab bridges can be developed using metaheuristic algorithms modified with the Fitness Distance Balance (FDB) selection method. The study compares the performance of eleven metaheuristic algorithms and highlights the FDB-enhanced AGDE algorithm as the most stable and efficient alternative for bridge superstructure optimization.

The review in [10] focuses on the use of nature-inspired algorithms in civil infrastructure optimization models. It highlights the practical application of stochastic algorithms in solving civil engineering design challenges, showing that metaheuristics can provide feasible and cost-effective solutions for complicated infrastructure systems.

Dillen et al. [11] study the influence of algorithmic control parameters through Monte Carlo-based performance assessment of metaheuristic algorithms. Their findings identify critical parameters that influence algorithm performance and show the need for careful calibration to obtain reliable structural optimization results.

Genetic algorithms have also been assessed for structural optimization performance [11]. Novel assessment methods improve the interpretation of results for benchmark structural problems and clarify how robustness and convergence behavior should be compared.

Cable-stayed bridges are addressed in [12], where CMA-ES and genetic algorithms are used to reduce construction cost while maintaining structural safety. The findings show that CMA-ES can achieve cost-effective and structurally safe bridge designs.

The Refinement Firefly Algorithm introduced in [13] improves the standard Firefly Algorithm for structural design. Its optimized designs are validated through finite element analysis and remain within acceptable engineering limits. Although it improves the original Firefly method, the reported comparisons show that GWO and PSO may still be more effective in selected cases.

Comprehensive reviews of structural optimization algorithms [3, 2] outline state-of-the-art developments in population-based, swarm-based, physics-based, evolutionary, and human-based metaheuristics. These reviews demonstrate the continuing importance of algorithmic innovation for addressing increasingly complicated structural design problems.

Quantum annealing has recently become an emerging research direction. Structural design optimization problems have been formulated for quantum annealing in [14, 15, 16], demonstrating feasibility for small-scale structural design problems. Sukulthanasorn et al. [17] further introduce an iterative optimization framework using quantum annealing and a multiplicative design update, achieving results comparable to

classical optimality criteria methods.

Abualigah et al. [18] present a broad review of metaheuristic algorithms for engineering design problems. The review emphasizes the lack of prior surveys or comparative analyses on this topic and identifies optimization methods that outperform others in addressing engineering challenges. It also offers future research directions and serves as a valuable resource for exploring metaheuristic techniques in engineering and artificial intelligence domains.

As discussed in [19], the LX-BBSCA ensemble metaheuristic algorithm combines Laplacian Biogeography-Based Optimization with the Sine Cosine Algorithm to address structural engineering design optimization challenges. The algorithm is designed to reduce the likelihood of local minima and enhance convergence speed. Its performance is evaluated using 23 benchmark functions and five real-world structural design problems. Comparative analysis highlights its superiority over basic BBO, SCA, LX-BBO, and other state-of-the-art metaheuristics in terms of objective function values and convergence. Rigorous statistical tests, including the t-test and Wilcoxon rank test, validate the robustness and effectiveness of the LX-BBSCA algorithm.

The analysis conducted in [2] examines MOAs for their capability to address multimodal nonlinear structural optimization problems. The study highlights the role of computational advancements in enabling the application of MOAs to real-world structural design optimization within practical timeframes. A state-of-the-art review of past and current developments is presented alongside an evaluation of 24 population-based MOAs, classified into swarm-based, physics-based, evolutionary-based, and human-based methods. These algorithms are tested on 11 single-objective benchmark problems of varying complexity, involving 3 to 328 unknowns and 2 to 264 constraint functions. The findings underscore the effectiveness of MOAs in optimizing structural performance concerning deformation and stress limits.

The details of the various metaheuristic optimization algorithms that have been considered in the existing literature and their application in structural design are presented in Table 1. Different areas of focus discussed in the studies are learned from comparative study of mathematical techniques and evolving new heuristic techniques suitable for engineering problems. The present study identifies productivity, reliability, efficiency, and robustness as key areas of improvement exemplified through advanced and hybrid methods, namely the LX-BBSCA and the Refinement Firefly Algorithm, surpassing traditional approaches. Also worth noting is the marriage of quantum annealing and finite element methods to provide unique structural optimization solutions.

3. DISCUSSION

The reviewed studies underscore the importance of metaheuristic optimization algorithms in tackling structurally demanding design problems. These algorithms have been demonstrated to work well in nonlinear, multimodal, and large-scale optimization cases, which are generally challenging to tackle in standard approaches. They also introduce new algorithms and combine the existing ones, broaden the range of their applications, and improve their efficiency within various engineering fields [15].

Comparative studies reveal that sophisticated and blended methods, for instance, LX-BBSCA and Refinement Firefly Algorithm, are more effective than fundamental metaheuristics, including GA and PSO. These improvements result from faster convergence, lower tendencies to converge to local optimum, and the capability to solve high-dimensional and constrained problems. QA integration is also a significant improvement; it provides accurate results for minor-scale problems and prepares the foundation for the next scalable step [16].

Benchmarking and statistical validation methods, like t-tests or Wilcoxon rank tests, are used in this framework. These methods give consistency in comparing the algorithms and thereby increase the applicability of results in actual scenarios. Nevertheless, the scalability of metaheuristic approaches to extra-large and dynamically changing problems has not been investigated sufficiently, especially regarding industry relevance [2].

In any case, MOAs encounter difficulties in achieving a balance between algorithmic computational runtime and solution quality in objectives that have conflicting features, such as the cost and strength of structures to be constructed. Although integrating hybrid techniques and ensemble methods highlights some of the mentioned limitations, further investigations are needed to develop them for practical use [17].

Further research efforts should be directed towards combining machine learning and various forms of data with metaheuristic-based techniques in order to improve decision-making capability. Moreover, enriching the metaheuristic concepts with new features, including dynamic, multi-objective problems with real-time constraints, could add a new era to metaheuristic research. From this discussion, MOAs offer significant growth potential for structural engineering design optimization while pointing in several directions where developments are still required to manage and optimize the methodology's potential.

4. CONCLUSION

Considering the continuously increasing complexity of structural engineering design problems, metaheuristic optimization algorithms have become a key instrument. That is why they are preferred over more traditional gradient-based methods, especially for nonlinear, multimodal, and large-scale optimization problems. The complexity of various real-life structures discussed in the review reaffirms the appropriateness and efficiency of MOAs for a broad range of applications, from simple trusses to complex actual-world structures. The growth of computational possibilities and new ideals for algorithmic formulations has stimulated their use in engineering optimization.

The result of the review, which deserves to be emphasized, is that most of the proposed hybrid and ensemble approaches, like LX-BBSCA and Refinement Firefly Algorithm, outperform others due to the utilization of several techniques to improve convergence performance and solution quality. Furthermore, the combination of QA with MOAs is still on the research frontier of optimization. However, it shows robust and promising performance for small-scale problems and

Table 1. Summary of Literature Review

Study Reference	Focus Area	Key Findings
[7]	Comparative analysis of 11 metaheuristic algorithms for structural optimization	Particle Swarm Optimization and Social Network Search performed best
[8]	Comparative analysis of 17 metaheuristic algorithms for real-world engineering tasks	Identified lack of comparative studies and emphasized benchmarking emerging methods
[9]	Optimization of reinforced concrete slab bridges using 11 metaheuristic algorithms	FDB-enhanced AGDE algorithm emerged as the most stable and efficient
[10]	Application of nature-inspired algorithms in civil engineering design optimization	Highlighted practical application of stochastic algorithms in addressing design challenges
[11]	Monte Carlo-based performance evaluation of metaheuristic algorithms	Identified critical control parameters impacting algorithm performance
[11]	Performance assessment of genetic algorithms for structural optimization	Improved performance for two benchmark problems using novel assessment methods
[12]	Optimization of cable-stayed bridges using CMA-ES and Genetic Algorithm	CMA-ES demonstrated cost-effective and structurally safe solutions
[13]	Introduction of Refinement Firefly Algorithm for Structural Design	Improved performance over standard Firefly but less effective than GWO and PSO
[13]	Efficiency of Refinement Firefly Algorithm in Structural Optimization	Validated optimized designs through finite element analysis with acceptable limits
[3]	Comprehensive review of various metaheuristic algorithms for structural optimization	Outlined state-of-the-art advancements in structural optimization algorithms
[14]	Formulation of structural design optimization problems for quantum annealing	Demonstrated feasibility of QA for small-scale structural design problems
[17]	Iterative optimization framework using quantum annealing for structural design	Achieved results comparable to classical optimality criteria methods
[18]	Review of metaheuristic algorithms for engineering design problems	Highlighted superior performance of advanced metaheuristic algorithms
[19]	Ensemble LX-BBSCA algorithm for structural optimization	Improved convergence speed and avoided local minima
[2]	Evaluation of 24 population-based MOAs on structural benchmarks	Demonstrated effectiveness for nonlinear and constrained structural optimization

suggests ways to extend the application in the future. Such advancements help broaden the application of MOAs to address structural design issues more effectively and within the shortest time.

However, there are still many difficulties. The feasibility of extending MOAs to solve ultra-large problems and their reactivity to changing real-world engineering environments are two important issues that deserve more research attention. Further, the problem of a trade-off between time and space complexity and solution quality remains an essential concern, especially in problems with multiple objectives like cost function minimization and safety function maximization. To overcome these limitations, sustained research and algorithm design and validation developments are necessary, always keeping benchmarking standards in mind.

As for future work, the present study shows that combining machine learning and data-driven techniques with MOAs could offer tremendous contributions to advancing structural optimization. It is possible to improve decision-making approaches and use them to offer applicable solutions to continually changing engineering issues. The complexity of structural systems in today's architectural designs requires powerful, generalized, and optimal algorithms. With knowledge and development that extends from those highlighted in this review, researchers and practitioners can establish newer directions in algorithm design in pursuit of dilation of the field of structural design optimization.

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