Metaheuristic Optimization Review

♦ **ISSN:** 2692-4048 **Vol:** 07, No. 01, 2026 ♦ PP. 08–17

Article DOI: https://doi.org/10.54216/MOR.070102

REVIEW ARTICLE

Metaheuristic Optimization for Complex Engineering Design: A Comprehensive Review of Structural and Mechanical Challenges

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Received: February 05, 2026 Revised: April 02, 2026 Accepted: June 04, 2026 ⋆ Corresponding author

ABSTRACT

Metaheuristic Optimization in Engineering has gained much attention recently because of its application in solving challenging problems and nonlinear and constrained design often encountered in structural and mechanical design. These optimization techniques are derived from natural phenomena, including Bio-evolution, Animal instincts and the physical world, necessitating efficient and inexpensive design for engineers. In conventional design processes, the design process may be tiresome and often unable to cope with large and complex engineering endeavors; however, metaheuristic algorithms exhibit high effectiveness and functionality in optimizing designs in various sectors about reinforced concrete structures and steel reinforced frames, mechanical parts, among others. This literature review explains the current metaheuristic algorithms and their applicability to solving engineering problems, particularly regarding computational time, quality and physical solution constraints. Difficulties regarding mechanical properties, structural, and dynamic performances can effectively be resolved by utilizing metaheuristic algorithms such as harmony search, teaching-learning-based optimization and other useful hybrid strategies to elevate the engineering optimization field to another level. It also emphasizes CI application in improving the design processes and offers clues on the future application of both the hybrid and the multi-objective optimization strategies in engineering.

Keywords: Metaheuristic Optimization ▪ Engineering Design ▪ Computational Efficiency ▪ Hybrid Algorithms ▪ Structural Optimization

1. INTRODUCTION

Metaheuristic optimization has started to receive much attention in the recent past as an ideal technique for solving complex, real-world engineering problems. Many classical methods, such as linear programming or gradient-based approaches, do not scale well due to their assumptions of convexity and smoothness of the objective and constraints, and they can get trapped in local optima. On the other hand, metaheuristic optimization algorithms can provide a more flexible and more robust approach to the large and multi-dimensional search space. They can reach near optimality solutions even in the presence of highly nonlinear, noisy, or constrained environments. This makes metaheuristics very suitable in a wide range of fields, such as static, structural, and mechanical engineering, since the problems encountered are difficult to handle optimally using conventional optimization techniques [1].

There has been much focus in the area of applying metaheuristic optimization in prediction models. For example, Long Short-Term Memory (LSTM) networks, which are widely used for time-series forecasting, have been enhanced using metaheuristic optimization techniques. Such approaches assist in tuning the parameters of LSTM networks and, as such, can offer high forecasting accuracy in intricate scenarios, including disease-related prediction tasks such as monkeypox classification. This not only proves that the metaheuristic approach is capable of dealing with dynamic and uncontrolled environments but also illustrates that it can be applied widely in many fields, such as healthcare and system improvement.

In the context of cybersecurity, metaheuristic optimization has been used to enhance smartphone user authentication. Integrating keystroke dynamics with metaheuristic optimization algorithms has greatly enhanced user authentication security and accuracy by reducing fraud and unauthorized access. These studies underscore a trend whereby optimization assumes a critical role in improving both the effectiveness and the security of modern technological solutions.

Subsequently, metaheuristic optimization has not only been used in technological systems but has also been developed through nature-inspired algorithms. The Greylag Goose Optimization (GGO) algorithm, a recent development in the field of nature-inspired metaheuristics, is based on the natural behavior of geese during migration. This algorithm has exhibited potential for solving real-life engineering problems by emulating geese behavior, such as coordinated movement, to identify the best solutions within large solution domains.

The last of the fields discussed here is one of the most interesting applications of metaheuristics, namely autonomous driving technology. Self-driving cars are a recent technological phenomenon, and the current systems that support them require high-level algorithms for road classification and decision-making. The Dipper Throated Optimization (DTO) algorithm, combined with transfer learning, has been successfully applied to classify potholes and plain roads, improving the safety and performance of autonomous driving systems. This advancement is important because metaheuristic algorithms have been shown to be capable of being tailored according to the requirements of real-time decision-making in volatile and unpredictable environments.

Metaheuristic optimization has also found a place in renewable energy systems. For instance, photovoltaic (PV) systems are highly sensitive to environmental factors, and their energy extraction efficiency can be significantly affected by these variables. In order to improve the energy generation of PV systems, metaheuristic optimization has been used to fine-tune real-time system performance for optimum energy yield under different conditions. This application further shows how optimization is critical to the progress of renewable power solutions and the wider sustainability agenda.

Using metaheuristics in feature selection tasks has proven very effective in the medical field. For instance, the Dipper Throated Algorithm (DTO) has been applied in the classification of electrocardiogram (ECG) signals, assisting in selecting the most relevant features for diagnosis. This leads to enhanced classification outcomes, which in turn contributes to faster diagnosis, an essential requirement for clinical management. Likewise, metaheuristic optimization has been applied in climatological areas, including forecasting sunshine duration. By applying ensemble learning methods that enhance accuracy in production planning, researchers have incorporated metaheuristic techniques, producing significant impacts on energy production and agriculture.

This scalability and efficiency of metaheuristics are further revealed in big data mining frameworks that have used metaheuristic algorithms to enhance the performance of mining processes despite imbalanced datasets. Hamiltonian optimization offers a useful solution to the problem of dealing with large, unconstrained, and unbalanced datasets, whereas metaheuristics generally assure efficiency and effectiveness in data optimization despite the large amount of data involved.

An important area of application of metaheuristics has been cancer diagnosis, more specifically feature selection and classification in breast cancer diagnosis. Previous methods have provided significant approaches for choosing the right features from extensive data and enhancing diagnostic models used in cancer detection. In communication technology, metaheuristic optimization has been central in formulating optimized antenna configurations. For instance, optimization algorithms have been applied to enhance artificial intelligence techniques used in the design of double T-shaped monopole antennas, which are crucial in boosting wireless communication systems. This is yet another testament to how metaheuristics can contribute to solving design-parameter problems across highly technical and specialized engineering disciplines.

In addition, metaheuristics have demonstrated their potential in predicting metamaterial antenna bandwidth, where they have been employed for modifying and enhancing models for better accuracy and performance. Most metaheuristic optimizations can be applied broadly in engineering optimization with little modification, and this adaptability is one of the strong points of this approach.

Metaheuristic optimization in supply chain management has equally enhanced risk identification in Industry 4.0. With dynamic voting classifiers fine-tuned using metaheuristics, organizations are capable of identifying potential risks and avoiding them, making business supply chains more efficient and resilient. This is especially important in the current world of rapid industrial change and significant disruption potential.

Precision farming has also benefited from metaheuristic applications, especially in agriculture, by providing proper and faster solutions. For instance, in wheat farming, metaheuristic optimization has been applied in the identification of weeds in drone-acquired imagery. This technology increases productivity in farming systems and decreases the amount of manual work required. Likewise, metaheuristic optimization has found its way into other renewable energy projects, including solar energy in hyper-arid regions, where accurate forecast models for direct normal irradiation are pivotal for energy planning.

Metaheuristics have also been used to solve unconstrained function optimization problems. For example, Chaotic Harris Hawks Optimization is a strong method for analyzing numerous engineering problems and offering stable solutions in challenging optimization search spaces. Newer forms of algorithms, such as the Waterwheel Plant Algorithm, are progressively being invented, expanding the pool of metaheuristic methods available to engineers and researchers aiming to address more complicated issues.

The latest addition to the metaheuristic approach is known as the Al-Biruni Earth Radius (BER) optimization algorithm. This algorithm has been widely applied to solve real-world optimization problems, from engineering applications to environmental areas, through the integration of mechanisms such as a new search technique that has improved this algorithm. Researchers have also applied the BER algorithm in deep learning and proposed its use in monkeypox disease classification, among other applications.

Metaheuristic algorithms are commonly applied to various environmental issues, and their significance grows due to climate change. For instance, metaheuristics have been applied to enhance the performance of daily reference evapotranspiration calculations in semi-arid environments for irrigation and crop-calendar planning. In communication systems, extreme ensemble techniques have been used to estimate significant quantities in metamaterial antenna configurations, again indicating the versatility of metaheuristic optimization.

In wireless sensor networks, metaheuristic techniques such as Stochastic Fractal Search (SFS) and Particle Swarm Optimization (PSO) have been integrated to extend conventional techniques, including k-nearest neighbors. This has led to substantial enhancement of network functionality and robustness. Metaheuristic algorithms have, therefore, been shown to enhance the functionality of existing technologies. Likewise, Waterwheel Plant Algorithm hyperparameters have been used to predict energy efficiency in buildings in order to support energy sustainability.

Metaheuristics have also contributed to the optimization of wireless sensor networks by applying the Al-Biruni Earth Radius Optimization technique. Network performance has increased, energy consumption has decreased, and wireless sensor networks have become more efficient and sustainable with more durable operation. Metaheuristic algorithms such as Greylag Goose Optimization (GGO) have also been adopted in educational applications to supplement student-performance prediction models and provide information for improving individualized learning programs.

Comparative machine learning analysis has been carried out more recently to build additional layers of the general framework of predictive modeling in educational settings, relying on metaheuristic optimization or further refinement of models with the aim of improving prediction accuracy [25]. The role of metaheuristics in satellite images for environmental monitoring is increasing and remains a work in progress, particularly in tasks such as oil detection, where it provides superior and faster classification ability in comparison with other techniques. Finally, in road maintenance, metaheuristic optimization has been used to enhance the identification of potholes on asphalted roads so that safer and more efficient road networks may be established.

Finally, it can be concluded that metaheuristic optimization methods are increasingly becoming key instruments for handling various engineering difficulties. These algorithms tackle tasks ranging from fixing structural and mechanical issues to streamlining complex tasks in technology, healthcare, and environmental management, where such tasks cannot otherwise be addressed optimally. Metaheuristic optimization will remain a dynamic subfield that will find broader implementation in the formation of essential solutions to modern engineering problems.

Figure 1 illustrates the general concept of metaheuristic optimization and its broad applicability across several real-world domains. The figure emphasizes that metaheuristic algorithms are inspired by natural behaviors and biological processes, such as bird migration, penguin behavior, flower pollination, and swarm movement. These natural mechanisms are transformed into computational search strategies capable of exploring complex solution spaces and identifying near-optimal solutions. The central part of the figure presents the main optimization cycle, beginning with the definition of the problem domain, followed by search and optimization procedures, and ending with the identification of optimal solutions for engineering applications.

The figure also highlights the practical importance of metaheuristic optimization in diverse fields, including structural design, mechanical design, antenna design, autonomous driving, supply chain management, data mining, cybersecurity, healthcare, precision agriculture, and renewable energy systems. These applications demonstrate the flexibility of metaheuristic algorithms in handling nonlinear, multidimensional, and constrained problems. In particular, the figure shows that these methods can improve structural safety, enhance mechanical and industrial design, support disease prediction, strengthen authentication systems, optimize renewable energy performance, and assist smart farming technologies. Therefore, the visual representation confirms that metaheuristic optimization provides a powerful computational framework for solving complex engineering and technological problems where traditional optimization methods may be insufficient.

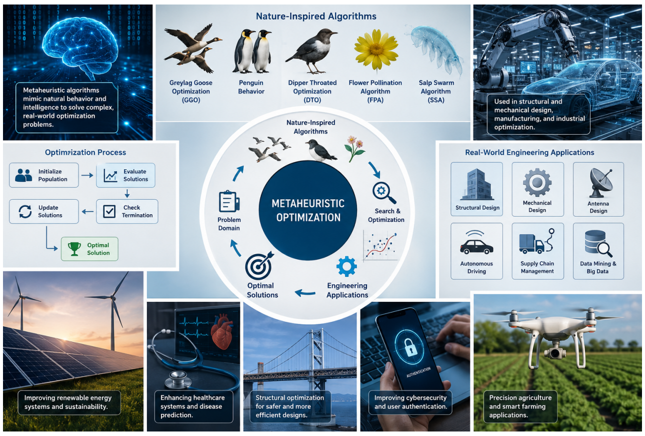

Figure 1. Overview of metaheuristic optimization concepts, nature-inspired algorithms, optimization process, and real-world engineering applications.

Figure 2 presents a comprehensive overview of metaheuristic optimization, showing both its application areas and its general computational workflow. The upper-left part of the figure summarizes the major domains in which metaheuristic algorithms can be applied, including structural engineering, mechanical design, healthcare, cybersecurity, renewable energy, autonomous driving, and data mining. This illustrates the interdisciplinary nature of metaheuristic optimization and its ability to address complex problems that involve nonlinear behavior, multiple design variables, uncertain environments, and difficult search spaces. The upper-right part of the figure explains the main objective of metaheuristic optimization, which is to find the best or near-best solution within a complex search space. The search process begins with a set of initial candidate solutions and then moves through exploration and exploitation phases until an optimal or near-optimal design is obtained. This process is particularly important in engineering design because it can reduce cost and time, improve performance, support sustainable solutions, and produce reliable designs. The illustrated examples, such as bridge structures and optimized building models, indicate how metaheuristic algorithms can contribute to safer and more efficient structural systems. The lower part of the figure describes the basic steps of the metaheuristic optimization process. First, the problem is defined by identifying the objective function, design variables, and constraints. Then, an initial population of random solutions is generated and evaluated using a fitness function. After that, the algorithm searches and updates the candidate solutions by balancing exploration, which investigates new regions of the search space, and exploitation, which refines promising solutions locally. Better solutions are then selected until the optimal solution is achieved. The figure also highlights several nature-inspired sources of metaheuristic algorithms, such as bird flocking, animal behavior, swarm intelligence, water flow, plant growth, and physical phenomena. These inspirations demonstrate how natural processes can be translated into computational mechanisms for solving engineering problems.

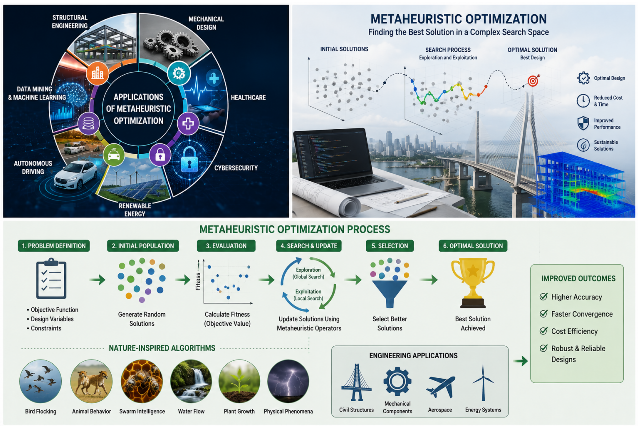

Figure 2. Metaheuristic optimization applications, search mechanism, nature-inspired sources, and general optimization process.

Figure 3 illustrates the general workflow of metaheuristic optimization and its relationship with real-world engineering applications. The figure presents the optimization procedure as an iterative sequence that begins with problem definition, where the objective function, design variables, and constraints are identified. After that, an initial population of candidate solutions is generated and evaluated using a fitness function. The algorithm then performs global exploration to search different regions of the solution space and local exploitation to refine promising solutions. This balance between exploration and exploitation is essential because it allows the algorithm to avoid premature convergence while still improving solution quality during successive iterations. The figure further shows that the optimization process continues through population updating and stopping-criteria checking until an optimal or near-optimal solution is obtained. If the stopping criterion is not satisfied, the algorithm repeats the search cycle and updates the population again. This iterative mechanism reflects the adaptive nature of metaheuristic algorithms, which makes them suitable for complex, nonlinear, and constrained optimization problems. The figure also connects this workflow to several practical applications, including bridge and steel-structure optimization, reinforced concrete footing design, mechanical spring and gear design, photovoltaic energy systems, healthcare ECG analysis, and self-driving car technologies. These examples demonstrate that metaheuristic optimization is not limited to one engineering field but can be applied across structural, mechanical, energy, biomedical, and intelligent transportation systems.

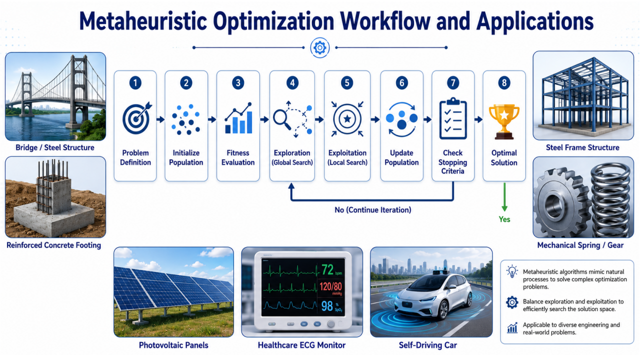

Figure 3. Workflow of metaheuristic optimization and its applications in structural, mechanical, renewable-energy, healthcare, and autonomous-driving systems.

Figure 4 provides a summarized representation of metaheuristic optimization in structural and mechanical engineering. The figure shows that many engineering design problems are characterized by large search spaces, nonlinear behavior, multiple constraints, and expensive function evaluations. These characteristics make traditional optimization approaches less effective, especially when the problem involves complex structural responses, discrete design variables, or highly constrained mechanical components. Metaheuristic optimization addresses these difficulties by using guided search mechanisms that balance exploration, which searches globally across the design space, and exploitation, which improves promising solutions locally until a near-optimal or optimal design is obtained. The figure also presents several nature-inspired algorithms commonly used in engineering optimization, including Greylag Goose Optimization (GGO), Dipper Throated Optimization (DTO), Cuckoo Search (CS), Particle Swarm Optimization (PSO), Water Cycle Algorithm (WCA), and Al-Biruni Earth Radius Optimization (BER). These algorithms imitate natural behaviors such as migration, swarm movement, nesting strategy, water flow, and mathematical-geographical search mechanisms. Their main purpose is to generate candidate solutions, evaluate their quality using a fitness function, update the solutions through iterative search operators, and finally return the best solution. In this context, the optimization process is shown as a sequence beginning with population initialization, followed by fitness evaluation, exploration and exploitation, solution updating, and final selection of the best design. Furthermore, the figure highlights the main engineering applications and benefits of metaheuristic optimization. These applications include reinforced concrete footing design, steel structure optimization, mechanical gear design, autonomous driving systems, renewable energy systems, and feature selection. The benefits shown in the figure include robustness, flexibility, cost reduction, fast convergence, and the ability to handle nonlinear constraints. Overall, the figure demonstrates that metaheuristic optimization acts as a bridge between nature-inspired intelligence and engineering design, offering efficient, sustainable, and adaptable solutions for complex structural and mechanical engineering challenges.

Figure 4. Metaheuristic optimization in structural and mechanical engineering, including nature-inspired algorithms, optimization process, engineering applications, and major benefits.

2. RELATED WORK

This literature review focuses on the developments made in metaheuristic optimization techniques with specific reference to structural and mechanical engineering design issues. These methods, derived from nature, processes, and phenomena, are effective instruments for solving complicated nonlinear and constrained optimization problems. The review also emphasizes the need to increase the role of computational intelligence techniques in realizing inexpensive and optimized designs for structures such as reinforced concrete structures, steel frame structures, and mechanical parts. Recent techniques such as hybrid algorithms exhibit high effectiveness in solving real-life engineering problems by improving computational solutions and the quality of solutions obtained. This section presents information on how new optimization algorithms are transforming engineering processes through improvements that address the problems posed by previous methods.

The goal of an engineer, in this case, is to use the least amount of money to realize any design; thus, costs must be minimized, and this can only be achieved through many trial-and-error attempts. In research by Lee et al. [2], among the considered methodologies, a more robust methodology emphasizing high computational speed is suggested for achieving optimal design in engineering applications. Specifically, the optimal design of Reinforced Concrete (RC) structural members represents a particularly complex challenge due to the distinct characteristics and cost variations of the materials involved, especially considering that these materials exhibit drastically different tensile behaviors. In addition, geotechnical limit states must also be met in RC footing, contrary to superstructure components, which makes the design more complicated. The study introduces metaheuristic algorithms for cost optimization of RC footing using several classical and recent algorithms for optimizing nonlinear cost functions. This methodology considers not only the optimum dimensions of the footing but also the possible orientation of supported columns and the reinforcement design to be used. The innovative metaheuristic algorithms employed, such as Harmony Search (HS), Teaching-Learning Optimization (TLBO), and the Flower Pollination Algorithm (FPA), have shown considerable promise in achieving optimal designs for RC footings, underscoring the potential of computational intelligence in enhancing engineering practices.

The main challenge facing the development of metaheuristic algorithms for optimizing structural systems is the time-consuming structural analysis needed to discern feasible solutions. In the analysis conducted in [3], a novel Upper Bound Strategy (UBS) is introduced to mitigate the overall number of structural analyses necessary in the metaheuristic-driven design optimization of steel frame structures. This strategy uses the Big Bang–Big Crunch algorithm and its two developed forms to analyze the impact of UBS on the speed of these optimization approaches. The numerical results presented show that the UBS is effective in decreasing the total computational costs of metaheuristic optimization processes for steel frames. In addition to reducing the amount of analysis required, UBS also optimizes the metaheuristic optimization process, thereby improving the practical usefulness of this technique in solving structural engineering problems.

The Chimp Optimization Algorithm (ChoA) represents a novel metaheuristic approach inspired by the individual intelligence and sexual motivation of chimpanzees, aimed at improving the identification of local optima while addressing slow convergence speeds. As detailed in [4], a hybrid algorithm that combines sine–cosine functions with the attacking strategy of the Spotted Hyena Optimizer (SHO) has been developed, termed the Sine–Cosine and Spotted Hyena-based Chimp Optimization Algorithm (SSC). For challenging real-world issues, this novel form of the SSC algorithm incorporates both sine–cosine strategies and SHO hunter exploration tactics. These mechanisms strengthen the approaches required for algorithmic control of the solution process and compensate for the shortcomings of ChoA, including slow convergence and entrapment in local optima. As shown in experiments using CEC'17 benchmarks and engineering design problems such as welded beam design, tension/compression spring design, pressure vessel design, multiple disk clutch brake design, gear train design, and car side crashworthiness, the proposed algorithm yields faster and better convergence than other existing techniques. This validation highlights the power of the SSC algorithm in finding maxima and minima and supports its use in engineering optimization.

Although the mode shape is probably the most important parameter of structural systems in the dynamic regime, vibration frequencies are also essential and easily measurable characteristics. Using the approach described in [5], it is shown that fixing parameters characterizing the natural frequencies of a structure can be useful for several reasons. For example, limiting these frequencies is critically important to avoid resonance with external stimuli, since failure and structural damage are otherwise likely. Further, in the case of space structures used in microgravity, suppression of natural frequencies is crucial in the vibration response to orbital orientation corrections. The problem of approximating the maximum or minimum of a weight- or cost-related function subject to lower and/or upper bound constraints on vibration frequencies is a classical problem of structural optimization with frequency constraints. The paper also presents a categorization of different metaheuristic optimization methods employed to solve this problem in several examples. Through evaluation of these approaches, the study contributes significantly to advancing metaheuristic algorithms in solving frequency-constrained structural optimization problems.

This paper proposes an efficient Artificial Neural Network (ANN) that integrates the global search capabilities of Evolutionary Algorithms (EAs) for identifying damage in laminated composite structures. Despite remarkable advancements in ANN, it often struggles with local minima due to its reliance on Gradient Descent (GD) techniques, which can hinder its effectiveness and accuracy, as noted in [6]. To this end, the proposed improvement uses both GD's faster convergence rates and EAs' global search potential during ANN training to guide the search toward the global minimum more effectively while avoiding entrapment in local minima. Additionally, a hybrid metaheuristic optimization algorithm (HGACS) is proposed, merging the strengths of Genetic Algorithm (GA) and Cuckoo Search (CS) to enhance global search efficiency. GA creates the first generation with good genes from crossover and mutation, while CS searches for the best solutions. Thus, the training process is accelerated, and because the objective function contains many variables, a vectorization technique is applied to the data. The findings illustrate that the proposed method provides higher accuracy and lower computational cost than standard ANN models, other combined ANN techniques, and HGACS, indicating that the method can serve as a framework for enhanced damage identification in laminated composite structures.

Research into metaheuristic optimization algorithms has been performed in order to find the best solutions for the active control of structures. Traditional methods, such as the Linear Quadratic Regulator (LQR), have limitations, as they often neglect external excitations when solving the Riccati equation, resulting in insufficient optimality. In order to improve the performance of LQR and overcome this non-optimality, as reported in [7], six optimization techniques—bat, bee, differential evolution, firefly, harmony search, and imperialist competitive algorithm—are incorporated into the wavelet-based LQR formulation to obtain optimal feedback gains. This development helps eliminate the conventional solution of the Riccati equation, offering an opportunity to introduce excitation effects in the control process. By applying each of these six algorithms to three-story and eight-story structures subjected to various earthquake scenarios, the study seeks to identify the best solution, convergence rates, and computational efforts associated with all methods. The findings underscore the superiority of the Imperialist Competitive Algorithm (ICA) in deriving optimal responses for the active control problem. Computational studies have shown that the adopted controller reduces structural responses and requires less control energy than LQR methods, with practical gains for structural engineering applications.

Metaheuristic algorithms have become invaluable for engineering designers because they identify the best solution to numerous optimization problems arising in practical engineering design. These algorithms are usually stochastic in nature and are often named based on naturally occurring phenomena or processes that provide paradigms for the algorithm's working mechanism. As stated in [8], due to the satisfactory results achieved by metaheuristic approaches in solving a wide range of engineering design problems, new algorithms with diverse metaphors are being proposed in the current literature. Although these avenues have been corroborated in many fields, some skepticism remains regarding their credibility because of the absence of a measured theoretical framework and the shallow use of metaphors. However, the major issue for practitioners is whether these methods produce efficient and stable numerical solutions for structural engineering applications. Therefore, what is important about the use of metaphors in algorithms is not the metaphors themselves, but the practical effectiveness of the algorithms. The paper presents the historical background of structural optimization and discusses criticisms concerning the novelty of metaheuristics, with the aim of correcting misconceptions since metaheuristics have demonstrated remarkable efficiency in engineering applications.

This paper introduces a novel optimization technique known as the Water Cycle Algorithm (WCA), designed to address a variety of constrained optimization and engineering design problems. As described in [9], WCA is based on principles from nature, particularly the flow of water from higher to lower ground, similar to rivers and streams flowing into the ocean. The optimization process itself is informed by this natural metaphor. Further, a comparative analysis is conducted to compare WCA with other established optimization techniques. The results indicate that WCA consumes fewer function evaluations and yields better function values than these methods. From this study, WCA is shown to be a promising tool for providing optimal solutions to complex engineering design optimization problems.

The Emperor Penguin and Salp Swarm Algorithm (ESA) is a hybrid bio-inspired metaheuristic optimization approach that combines the huddling behavior of emperor penguins with the swarming dynamics of salps. The performance of ESA was tested in [10], and different techniques such as scalability analysis, convergence analysis, sensitivity analysis, and ANOVA tests were employed. These tests were conducted on 53 test functions consisting of linear, continuous, and nonlinear classical optimization problems, as well as several IEEE CEC-2017 functions. A number of classical and well-known metaheuristics were employed to compare the performance of ESA, especially regarding the quality of the solutions provided. Furthermore, the performance of the proposed method was tested on six constrained engineering problems and one unconstrained engineering problem to check its sensitivity. The results supported the idea that ESA delivers better optimal solutions than other algorithms, proving the efficiency of the system in tackling optimization issues. Every day, immature sunflowers exhibit heliotropic movements driven by two growth mechanisms: phototropism, which is realized by the growth hormone auxin, and night orientation, which is regulated by the biological clock. Based on these natural mechanisms, a new nature-inspired optimization algorithm called the Smart Flower Optimization Algorithm (SFOA) is introduced in [11]. SFOA works under two scenarios: sunny conditions and dark or rainy weather conditions. The algorithm is analyzed through three benchmarking stages. Initially, statistical measurements and Wilcoxon's test are employed using a set of 15 benchmark functions from CEC 2015. Second, SFOA is applied to design an adaptive Infinite Impulse Response (IIR) system to model unknown systems. Finally, the algorithm is employed to solve four engineering design problems: the three-bar truss, tension/compression spring, speed reducer, and welded beam. Benchmarking results show that SFOA has a strong capability for finding optimal solutions. Furthermore, its use in IIR system identification and engineering design problems demonstrates its capability to solve real-world problems with unknown search spaces.

In this study, a novel metaheuristic optimization algorithm known as Cuckoo Search (CS) is introduced to tackle structural optimization problems. As explained in [12], the CS algorithm, incorporating Lévy flights, is initially tested in a benchmark nonlinear constrained optimization problem. Subsequently, the algorithm is tested on 13 design problems often encountered in structural engineering literature for further examination. The results demonstrate that CS performs better than other dominant state-of-the-art computational methods in effective optimization. More often than not, solutions identified by computational studies are more effective compared to other approaches. The work also examines features of CS in detail, such as its specific search strategies based on Lévy flights, and considers possible future developments in optimization methods. This shows that the algorithm is particularly strong in structural applications and promising for future use.

Indeed, metaheuristic optimization algorithms are only mildly sensitive to computational costs, and their success results from finding the right exploration–exploitation trade-off. In the research presented in [13], an important challenge in metaheuristic optimization is highlighted: there is no guarantee that current new trial designs will always be better than the current best solution. Thus, no single metaheuristic algorithm is dominant over all others for every problem. This study compares three advanced formulations of state-of-the-art metaheuristic optimization algorithms—Simulated Annealing (SA), Harmony Search (HS), and Big Bang–Big Crunch (BBBC)—which incorporate enhanced approximate line-search techniques and computationally efficient gradient-evaluation strategies. These new formulations produce high-quality trial designs by selecting descent directions during the optimization process. The study also combines HS, BBBC, and SA with gradient information along with an improved one-dimensional probabilistic search inherited from SA, which makes the search converge faster toward the global optimum in the design space. The algorithms are applied to four weight-reduction issues for skeletal structures and three mechanical/civil engineering design issues, involving up to 204 continuous/discrete variables and 20,070 nonlinear constraints. Since these problems have multiple local optima, the presented optimization procedure reduces function evaluations and structural analyses considerably compared to methods reported in the literature. Furthermore, the improvements increase the reliability of metaheuristic search engines, resulting in better optimization outcomes.

In civil and industrial engineering applications, design optimization problems often have many objectives within a single system, such as investment cost and risk. As stated in [14], this creates not a single optimal solution for all objectives at the same time, but a set of solutions representing trade-offs among multiple objectives. The paper provides an update on new developments in multi-objective metaheuristics, especially regarding topology, shape, and size optimization of civil engineering structures. It discusses both solvers and algorithms, including important aspects of key solvers and the challenges presented by design optimization problems. Several points for further research are identified at the end of the review, especially in improving algorithms for multi-objective optimization.

Finding the best solutions for practical mechanical design problems is difficult when using newly established swarm intelligence algorithms. As pointed out in [15], several difficulties must be considered: the presence of mixed decision variables, a variety of constraints, inherent errors, conflicting objectives, and many locally optimal solutions. This study analyzes the performance of nine metaheuristic algorithms: Salp Swarm Algorithm (SSA), Multi-Verse Optimizer (MVO), Moth-Flame Optimizer (MFO), Atom Search Optimization (ASO), Ecogeography-Based Optimization (EBO), Queuing Search Algorithm (QSA), Equilibrium Optimizer (EO), Evolutionary Strategy (ES), and Hybrid Self-Adaptive Orthogonal Genetic Algorithm (HSOGA). These algorithms are evaluated using eight mechanical design problems related to solution quality and convergence performance. Overall, the results show that these algorithms are useful in solving versatile real-world design problems and help develop highly efficient mechanical design solutions.

This paper introduces an Improved Accelerated Particle Swarm Optimization algorithm (IAPSO) designed to address constrained nonlinear optimization problems with various design variables. In the research described in [16], several crucial enhancements of conventional Particle Swarm Optimization are mentioned: storing and contributing individual particles' memories to increase swarm variability and introducing two specific functions that regulate the exploration–exploitation ratio during the search. These modifications are used to revise particle positions in the swarm, improving search effectiveness. The capability of IAPSO in solving mechanical engineering design optimization problems is illustrated using six reference mechanical design problems. Compared with other recent metaheuristic algorithms, IAPSO is identified as having a high degree of accuracy and relatively faster convergence rates, confirming its efficiency in solving hard optimization problems.

In mechanical engineering, in order to optimize a product, mechanical engineers must revise designs several times with manufacturing engineers and other domain specialists to avoid last-stage modifications. Knowledge-Based Engineering (KBE), derived from the work in [17], describes methods to capture and integrate engineering design knowledge into generic product models or decision-support systems. One important strategy aimed at cooperation and integration of concurrent design processes and multi-criteria decision-making is the use of multi-agent systems. These systems include self-contained modules that possess features of intelligent agents in relation to their environments and are able to communicate and collaborate. The paper discusses the integration of such a multi-agent system into Computer-Aided Design (CAD) software, where agents act as domain experts, such as manufacturing technologists, providing suggestions for optimizing mechanical engineering designs. One area of concern is the collaboration mechanism between agents for information and knowledge sharing, and an action-item list is suggested as the main tool for such sharing. This approach improves communication and coordination in the optimization process, increasing effectiveness and efficiency.

The Moth-Flame Optimization (MFO) algorithm, inspired by the transverse orientation behavior of moths toward light, is a widely used method for solving global optimization problems. However, as described in [18], the MFO algorithm suffers from several problems, including convergence issues, low population variety, trapping in local optima, and conflict between exploration and exploitation. To address these issues, an improved version of the algorithm, known as I-MFO, is proposed. In I-MFO, a memory system is defined for each moth to identify when it is stuck at a local optimum. To assist trapped moths in escaping local minima, the Adapted Wandering Around Search (AWAS) strategy is applied. The performance of I-MFO is analyzed using CEC 2018 benchmark functions and contrasted with other metaheuristic algorithms. The experimental results are subjected to statistical analysis using the Friedman test for dimensions of 30, 50, and 100. Furthermore, three problems from the latest CEC 2020 test suite are used to compare I-MFO in terms of its applicability for finding the best solutions to mechanical engineering problems. These experimental and statistical results show that I-MFO greatly surpasses its competitors and improves the drawbacks of MFO methods.

This work mainly offers a detailed review of deep learning and machine learning techniques in the context of the design and optimization of machine parts and nodes. More detailed guidance on how these methods can be used effectively in mechanical design is provided in [19], and the potential benefits to society and progress in contemporary mechanical engineering are shown. The review starts by describing artificial intelligence, followed by an analysis of machine learning, the definition of deep learning, and the classification and comparison of these methods. It also defines the most used programming languages, frameworks, and software in mechanical engineering and discusses input data formats and suitable datasets for performing machine learning in this branch. The second portion of the review is devoted to existing practical applications of machine learning in mechanical design and optimization, demonstrating numerous examples explored by researchers worldwide. The last section provides a brief discussion of how advances in fields such as machine learning and neural networks can be explored for future development to redesign and optimize mechanical structures.

Computational and non-differentiable optimization issues tend to perplex ordinary optimizers since they may not reliably arrive at the most optimal solution in a complicated search space. According to the literature reported in [20], integrated methods are highly useful when solving these challenges in practical engineering design applications. This paper introduces FVIMDE, a novel hybrid optimization algorithm that combines the Four Vector Intelligent Metaheuristic (FVIM) with Differential Evolution (DE). FVIMDE is rigorously tested on two widely recognized benchmark suites, CEC2017 and CEC2022, along with an additional set of 50 challenging benchmark functions. The proposed algorithm is compared with three other methods, and statistical tests such as the mean, standard deviation, and Wilcoxon rank-sum test are used to assess its efficacy. The evaluation of FVIMDE shows its versatility and stability in numerical performance compared with several other optimizers in the literature. In addition, the algorithm is applied to five problems in the structural engineering field, where it outperforms current methods. These results support the claim that FVIMDE can serve as a powerful means of addressing a broad range of difficult optimization problems in various fields and industries.

A novel metaheuristic optimization algorithm inspired by the Enterprise Development (ED) process was developed to address complex optimization challenges. ED provides a detailed description of tasks and structures, as well as technology and human activities, into process models and employs a switching-activity mechanism that successively optimizes solutions. As detailed in [21], the ED optimizer was evaluated using 50 mathematical functions and 54 benchmark functions from the IEEE Congress on Evolutionary Computation (CEC), comparing its performance against six cutting-edge algorithms, three CEC 2020 winners, and ten widely recognized methods. The evaluation showed that the ED optimizer is more effective at solving mathematical tests. Moreover, finite element simulations were used, where the optimal design of steel structural elements was performed with limited weight and frequency characteristics. The performance of the algorithm was evaluated on several engineering design problems, such as a 37-bar planar truss, a 52-bar dome, a 72-bar space truss, a 600-bar dome, and a 1410-bar dome, for which the algorithm produced superior solutions with far fewer function evaluations than those reported in the literature. These findings validate that the presented ED optimizer is an efficient and effective method for solving complex structural design problems.

Altogether, the developments of metaheuristic optimization algorithms are revolutionizing the frontiers of engineering design optimization. This paper reveals how the development of these algorithms yields enhanced computational performance and higher convergence rates for the formulation of efficient and inexpensive approximations to sophisticated engineering challenges. Examples include algorithms for analyzing reinforced concrete footings and frequency-constrained steel structure solutions, indicating the usefulness of these algorithms in improving structural and mechanical design requirements. Thus, the future appears to lie in improving and strengthening these methods; the use of hybrid and multi-objective engineering optimization is expected to continue. Hence, the inclusion of these advanced algorithms is expected to greatly boost the development of engineering.

3. CONCLUSION

This review has emphasized new trends in metaheuristic optimization algorithms and their use in structural-mechanical engineering design. These algorithms, known as metaheuristics and drawn from natural processes, are useful solutions for nonlinear and constrained optimization issues. In areas such as reinforced concrete structures and mechanical components, reliable techniques such as Harmony Search, Cuckoo Search, and the Sine–Cosine and Spotted Hyena-based Chimp Optimization Algorithm have yielded higher precision, convergence rates, and effectiveness. Moreover, the integration of hybrid and multi-objective optimization strategies has been discussed in relation to enhancing solution quality, improving computational costs, and addressing the drawbacks of traditional methods. Although some researchers question the theoretical foundation of these algorithms, their practical application in engineering problems remains difficult to challenge. Future work is expected to bring more refined solutions and novel techniques derived from hybrid forms of the methods presented in this study, advancing both theoretical knowledge and engineering design methodology. Unquestionably, numerous opportunities exist for these tools to produce substantial changes in engineering optimization in the future.

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