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Review

Efficient Truss Design: A Hybrid Geometric Mean Optimizer for Better Performance

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INTRODUCTION

Because of their efficacy in solving complicated optimization issues, metaheuristic approaches are finding more and more applications in engineering and research. When it comes to optimizing multimodal functions with actual values, Price [1] highlighted the effectiveness of diferential evolution (DE), an evolutionary technique that is both simple and powerful. Results from 11 out of 15 test functions demonstrate that DE achieves faster solutions than several modern optimization approaches. Holland also went above and beyond the limitations of traditional frameworks by developing a mathematical model that serves as a basis [2]. From economic theories to the creation of advanced technological gadgets, this paradigm has made it easier to apply genetic algorithms (GAs) to a wide range of complicated adaptive systems. In their study, Kennedy and Eberhart introduced a method called particle swarm optimization (PSO) for optimizing nonlinear functions. They covered the method's evolution, how it is implemented, potential uses in neural network training and non-linear optimization, and how it relates to artificial life and GA. Ant colony optimization (ACO) was the subject of the groundbreaking work of Dorigo et al. [4], who established the notion of swarm intelligence. Since its debut, this method—which draws inspiration from ant foraging behavior—has attracted a lot of attention from scholars and practitioners. Since its beginnings, ACO has spawned a growing body of theoretical insights and a plethora of successful implementations. Mechanical design optimization is a challenging task, but Rao et al. [5] introduced teaching-learning-based optimization (TLBO) as a viable solution. TLBO's efficacy was confirmed by extensive testing, where it underwent

2. evaluate it in relation to other population-based optimization methods using a range of benchmark functions and in real-world settings. Using ideas from heat transport and thermodynamics, Patel and Savsani [6] developed a new metaheuristic optimization technique. We used our approach to 24 restricted optimization problems from the CEC 2006 suite to show how effective it is. The algorithm's competitive performance was validated by rigorous statistical analysis when tested against existing algorithms.

A system modeled after the bubble-net hunting approach seen in humpback whales, the whale optimization algorithm (WOA) was developed by Mirjalili and Lewis [7]. It has been shown that this approach outperforms both traditional and current meta-heuristic techniques on mathematical optimization problems and structural design issues. Taking cues from the coordinated actions of dragonflies, Mirjalili [8] introduced the DA, a new approach to optimization. The effectiveness of DA in global optimization and the realization of Pareto optimum solutions has been shown by mathematical tests and a case study on submarine propeller design. It has also been expanded to multiobjective and binary forms. Also, a big improvement was when Mirjalili [9] introduced the ant lion optimizer (ALO), which is based on how antlions hunt. Mathematical functions and engineering optimization problems were used to test ALO's performance, which showed that it was good at exploring and avoiding local optima.

Optimization in engineering, project management in the construction industry, and logistics are just a few areas that have benefited greatly from metaheuristic algorithms' ability to tackle complicated optimization issues. To optimize resource consumption and efficiency, these algorithms are essential for finding the best solutions to design and operational problems in engineering [10–12]. Metaheuristics are very useful in the construction industry for managing the complex relationship between time and money [13–16]. They allow project managers to find the sweet spot where time and money are both considered. These algorithms are also crucial in logistics for solving vehicle routing issues [17, 18]. The goal is to optimize transportation schedules and routes to save costs and maximize service efficiency.

In the last few decades, metaheuristic algorithms have made tremendous strides in the structure optimization field. These algorithms have drastically cut down on project material needs without compromising safety or functionality by assessing different situations and comparing the effectiveness of different design solutions. Not only do these cuts help reduce costs and environmental effect, but they also contribute to global climate change mitigation efforts and the promotion of a sustainable future by cutting down on carbon emissions from material manufacturing and transportation. The construction industry is demonstrating its dedication to creating a sustainable future by significantly reducing material use and improving production processes. This has a positive impact on future generations by helping to preserve natural resources and ecosystems.

Mladenovic and Hansen [19] presented the variable neighborhood search (VNS), a local search method that improves upon the current approach by using three separate operators: insert, verse, and swap. To provide a nearby solution, these operators are used. Instead of focusing on a single neighborhood structure, VNS switches between them in order to explore the solution space more thoroughly and avoid local optima. This is what makes VNS unique. A wide variety of optimization problems have been successfully addressed using this approach. One approach to the profile reduction issue in undirected simple graphs was put out by Palubeckis [20], who combined VNS with multistart simulated annealing to create a hybrid technique. This method achieves better outcomes for 50 benchmark examples than current metaheuristic methods, as shown in computational trials. A VNS algorithm with a two-stage procedure for improving solution quality was developed by Xu and Cai [21] for the consistent vehicle routing problem (ConVRP). Innovative methods, such as a shaking method and a new way to calculate time difference excess, enhance this procedure. Its benefits over existing ConVRP technologies were brought to light in comparative testing.

The geometric mean optimizer (GMO) is an innovative optimization method that uses the geometric mean operator to evaluate the variety of solutions and performance metrics in optimization problems. Rezaei et al. [22] introduced the GMO. The principle of geometric mean of scaled objective values of agent opposites is used as weight in directing the search process, making GMO unique in its parameter-free design. This design enhances dependability and simplicity. An extensive battery of 52 typical benchmark problems, including classical, CEC-2017, and restricted engineering test functions, is used to assess the efficacy of GMO. When compared to more modern and well-established metaheuristic algorithms, GMO clearly comes out on top in many different scenarios, indicating that it might be a powerful optimization tool.

Among the many noteworthy ways this research advanced the state of the art in beam optimization are the following:

(i) The suggestion of hybrid GMO as a powerful optimization tool by combining GMO with VNS to enhance GMO's exploration capabilities

(ii) The model was tested on four truss design issues with discrete and continuous size factors to see how well it worked.

Following is the structure of the study. In Section 2, the difficulties of truss design are examined in detail. The hGMO's structure is dissected in Section 3. In Section 4, we will try to make clear the mathematical concepts that are the bedrock of the truss design issue. The results and validation of the hGMO are then presented in Section 5, with four distinct truss design situations serving as examples. To get a better understanding of the suggested framework's overall effectiveness, Section 6 gives a thorough analysis of its outcomes, potential, and limits. The article is wrapped up in Section 7, which summarizes the study results and their contributions in great detail.

Literature Review

The past few years have witnessed a significant rise in the development of metaheuristic techniques aimed at opti- mizing structural layouts. Tejani et al. [23] enhanced the TLBO with a multiple-teacher model, an adaptive teaching factor, and self-motivated, tutorial-driven learning. This led to the development of modified TLBO, exhibiting improved performance in truss optimization compared to existing algorithms. Kumar et al. [24] investigated the enhancement of discrete optimization techniques for truss design prob- lems. Their findings revealed that the integration of random mutation and simulated annealing-based selection into metaheuristic frameworks such as TLBO, WOA, DA, HTS, and ALO markedly enhances their ability to manage complex problems, such as concurrent topology and sizing optimization of trusses. Singh et al. [25] introduced an enhanced follow-the-leader algorithm, inspired by sheep flock behavior, which exhibited superior performance across various optimization challenges, including complex truss design problems, outshining several well-established algo- rithms in various benchmark tests.Tejani et al. [26] conducted a study on the grey wolfoptimizer (GWO), stochastic fractal search, and adaptive DE with optional external archive algorithms in the context of optimizing a planar steel frame design. The focus was on minimizing weight while complying with strength and displacement constraints as per AISC-LRFD standards. This study also involved a comparison of these metaheuristics with other advanced algorithms. Kumar et al. [27] tackled the size and topology optimization of planar and spatial trusses by applying advanced metaheuristics, which were enhanced by random-migration search and simulated annealing. Their efectiveness in complex design scenarios under various constraints was demonstrated. In another study, Tejani et al. [28] introduced an improved HTS al- gorithm. This enhancement of the basic HTS included the integration of simultaneous heat transfer modes and a population regeneration mechanism. Its efectiveness in optimization tasks was demonstrated through benchmark functions and truss design problems, showing competitive results when compared to existing optimization methods.

Kaveh et al. [29] introduced a chaotic variant of the water strider algorithm (WSA) for addressing frequency- constrained design challenges in large-scale structures. This variant incorporates a circle map to probabilistically alternate between explorative and exploitative states. The efectiveness of this approach was validated through the optimization of large dome trusses, demonstrating superior performance and convergence speed compared to the basic version of WSA and other established algorithms. Ghannadi et al. [30] tackled the challenge of defect detection in complex engineering structures. They used a semirigidly connected frame element for finite element model updating. The study compared the efectiveness of various optimiza- tion algorithms in aligning experimental and numerical data, focusing on enhancing safety and reliability. Kaveh and Rad [31] employed the algebraic force method (AFM) for the optimal design of truss layouts. The research findings underscored the efficiency of AFM in reducing CPU time, particularly in cases where the degree of statical in- determinacy is lower than the degree of kinematic in- determinacy. In addition, the improved vibrating particle system algorithm was utilized in the optimization process. Ghannadi et al. [32] conducted an in-depth analysis of the applications of the DE algorithm in structural damage detection over more than two decades. Their comprehensive review covered methodologies, objectives, and findings from approximately 50 publications between 2001 and 2022. This review also included statistical insights into the evolution of objectives, types of structures studied, annual publication trends, and the prevalence of single-step, two-step, and multiple-step approaches in this field. Bakhshpoori and Asadi Abadi [33] introduced the hybridization of orthogonal experimental design with various population-based meta- heuristics, aiming to enhance their efficiency in structural optimization. This enhancement focused on improving search information utilization, convergence speed, and ac- curacy, and the methods were validated against complex benchmark problems. Ghannadi and Kourehli [34] in- vestigated the efectiveness of the slime mold algorithm (SMA) and the marine predator algorithm (MPA) in structural damage detection. They compared these algo- rithms with established ones and evaluated various objective functions. Their research revealed that SMA, when com- bined with the modified total modal assurance criterion, was particularly accurate in damage identification.

Goodarzimehr et al. [35] introduced an enhanced var- iant of the MPA for the structure layout design with natural frequency constraints. This enhanced algorithm demon- strated its efectiveness in complex nonlinear structural optimization through the successful optimization of various truss designs. Ghannadi et al. [36] emphasized the critical role of structural health monitoring in engineering, with a focus on PSO for damage detection. They assessed over 50 studies to evaluate the efectiveness of the methodology, computational efficiency, and accuracy in structural safety assessments. Dogˇan and Saka [37] developed a particle swarm method-based optimization technique for designing unbraced steel frames. This algorithm ensures compliance with LRFD-AISC standards and lateral torsional buckling considerations. It efectively selects optimal W sections from a wide range to minimize frame weight while meeting design constraints.

Camp and Bichon [38] developed an ACO-based design procedure for space trusses, transforming their discrete optimization into a modified variant of the traveling salesman challenge. This approach aimed to minimize mass or cost and involved a comparison of its efectiveness with GA and classical optimization methods. Barbosa et al.[39] introduced a novel GA encoding that implements con- straints on the number of elements in structural design problems. This encoding technique facilitates selecting a specific group from available options and permits the automatic association of variables. Its efficiency was dem- onstrated through computational experiments involving both discrete and continuous variables. Sadollah et al. [40] introduced the mine blast algorithm (MBA), an optimiza- tion algorithm inspired by the explosion dynamics of mine bombs. The efficiency of MBA in truss design problems using discrete sizing variables was evaluated, showing faster convergence rates and superior optimal solutions in contrast to well-established methods.

Camp and Farshchin [41] introduced a customized version of the TLBO method for optimizing space trusses. This modified TLBO was demonstrated to be efective in handling both discrete and continuous variables, producing designs superior to traditional evolutionary optimization methods while enhancing computational efficiency. Kaveh and Talatahari [42] developed the discrete heuristic particle swarm ACO, a novel method that integrates elements of PSO, ACO, and harmony search (HS). Its efficiency in optimizing truss structures with discrete variables was proven through comparative analysis with the existing versions of PSO. Miguel and Miguel [43] investigated thepplied Computational Intelligence and Soft Computing 5

Inverse operator: As shown in Figure 3, this op- erator determines two positions, pi and pj, at random within a selected solution and reverses the sequence of values from pi and pj, efectively inverting the order of a section of the solution.

Insert operator: As demonstrated in Figure 4, this operator picks two positions, pi and pj, in the se- lected solution. It then moves the values between

Truss Design Problem

Optimization of the mass of truss structures is identified as a crucial component of sustainable construction practices. The design and construction of buildings are required to be con- ducted in a way that not only meets usability and safety re- quirements but also minimizes the quantity of materials utilized for the structure. Such a strategy is instrumental in reducing the demand on natural resources and contributes to the diminution of CO2 emissions associated with the pro- duction and transportation of construction materials. The objective function for the problem of optimizing the mass of the truss is illustrated in the formula provided below:

Case Study 1: 10-Bar Truss. The geometric layout of the 10-bar truss problem is depicted in Figure 7, while Table 1 outlines the specific design parameters of this problem. This example encompasses 10 sizing variables that have a sub- stantial impact on the overall design configuration. Fur- thermore, Table 2 displays the optimal design results obtained through the application of diferent techniques for case study 1, highlighting the relative efficacy of these ap- proaches in realizing an efficient design solution.

From Table 2, it becomes evident that hGMO achieves a solution with a weight of 5060.915 lb and a standard de-information regarding the specific design parameters associ- ated with this problem is systematically presented in Table 3. In this context, 12 sizing variables are pivotal in shaping the final design solution, as outlined in Table 4. Notably, nodes 17, 18, 19, and 20 were subjected to vertical and horizontal forces, Py 200 kN and Py 100 kN, respectively. Table 5 outlines the available profiles for sizing, ofering a range of options for the optimization process. Furthermore, Table 6 discloses the op- timal design outcomes obtained by applying various meth- odologies to the 52-bar truss design task.

The data presented in Table 6 indicate that the hGMO identified a solution with a total weight of 1902.605 kg and a SD value of 2.813, achieved within 1950 analyses, outperforming the original GMO. This performance surpasses those of DHPSACO [42] and PSOPC [56]. While other methodologies such as MBA [40], WCA [57], aeDE [58], WOA [59], and MCOA [60] also reached the same design weight of 1902.605 kg, they required a significantly higher number of analyses, specifically 5450, 7100, 3720, 15000, and 5390, re- spectively. Although CET-DE [61] can find a better solution with a weight of 1899.654 kg, it requires 3404 analyses. By integrating VNS into GMO, the new model can handle the design problem using discrete variables. VNS facilitates the exploration of new solutions, helping hGMO avoid local op- tima. These findings highlight the efficiency of hGMO in addressing the truss design problem with discrete sizing var- iables, demonstrating its ability to find optimal solutions with reduced computational efort.

5.2. Case Study 3: 72-Bar Truss. Figure 9 presents the geometric layout of case study 3, providing a visual depiction of the structure targeted for optimization. Table 7 ofers a comprehensive overview of specific design parameters relevant to this challenge, facilitating a deep understanding of the problem scope. Two distinct loading conditions are applied to the structure, as outlined in Table 8. Table 9 organizes element groups for case study 3, and Table 5 introduces profiles available for cross-sectional areas. This optimization problem, characterized by 16 sizing variables, highlights the significant impact each variable has on the final design outcome, emphasizing the task complexity and depth. Furthermore, Table 10 discloses optimal design outcomes achieved through the application of various methodologies to the 72-bar truss design task.

Table 10 elucidates that the hGMO successfully identified a solution with a total weight of 389.334 lb and a SD value of 0.267, achieved within 3950 analyses, outperforming the original GMO. This result demonstrates the efectiveness of VNS in solving truss design problems using discrete variables. This achievement outperforms the results obtained by DHPSACO [42], MBA [40], and CBO [62]. Furthermore, while

IMBA [57], aeDE [58], MOCA [60], and MGA [63] matched the optimal design weight of 389.334 lb, the number of analyses they required was significantly higher than that of hGMO, which necessitated only 3950 structural analyses. In contrast, these methodologies demanded 6250, 4160, 5750, and 20000 analyses, respectively. In this case study, CETDE [61] is the best model, achieving the optimal solution with a weight of 389.070 lb within 2750 analyses. These findings indicate that CETDE [61] and hGMO are valuable tools in addressing truss design problems characterized by discrete sizing variables.

The load conditions used in this problem are presented in Table 12. The problem includes 29 sizing variables that significantly influenced the overall design configu- ration, as elaborated in Table 13. In addition, the optimal design results obtained using various techniques are presented in Table 14, demonstrating the comparative efectiveness of these methods in achieving an efficient design solution.

The results detailed in Table 14 indicate that the enhanced hGMO identified a solution weighing 25453.62 lb with a standard deviation (SD) of 87.51, achieved within 20000 analyses, surpassing the perfor- mance of the original GMO. This performance exceeds that of other techniques such as SAHS [52], WEO [64], IGWO [65], PO [53], MFO [66], MPSO [67], and

Discussion

The hGMO showed robust performance across all four case studies, efectively optimizing truss structures with varying complexity and constraints. Specifically, the following:

(i) 10-bar truss: achieved an optimal weight of 5060.915 lb with a standard deviation (SD) of 0.127, illustrating the algorithm's ability to consistently produce lighter designs with fewer analyses

(ii) 52-bar truss: recorded an optimal weight of 1902.605 kg with an SD of 2.813, outperforming other established methods in both weight and computational efficiency

(iii) 72-bar truss: reached an optimal weight of 389.334 lb with an SD of 0.267, matching the bestsolutions of other advanced algorithms but with fewer analyses, indicating superior efficiency

(iv) 200-bar truss: obtained an optimal weight of 25453.62 lb with an SD of 87.51, surpassing other state-of-the-art methods and highlighting hGMO's capability in handling large-scale optimization problems

Combining GMO and VNS enhances both exploration and exploitation in the optimization process. The addition of VNS introduces randomness to neighborhood structures, aiding in escaping local optima and thoroughly exploring the solution space. This hybrid approach prevents the optimizer from becoming trapped in suboptimal solutions and ac- celerates convergence to the global optimum. The versatility and robustness of the hGMO framework across diferent truss design problems render it suitable for a wide range of engineering optimization challenges, efectively handling both continuous and discrete variables.

Despite its promising performance, the hGMO frame- work has certain limitations. The integration of VNS into GMO introduces additional complexity to the imple- mentation of the framework. Users must have a thorough understanding of both methods to efectively utilize hGMO. Although hGMO is designed to be parameter-free, the ef- ficiency of VNS can be sensitive to the choice of neigh- borhood structures and randomization parameters, which might require fine-tuning for specific problems.

Conclusion

This research presents a novel method for optimizing truss structures called the hybrid geometric mean optimizer (hGMO), which combines the best features of both the geometric mean optimizer (GMO) and variable neighborhood search (VNS). The exploitation capabilities of the hGMO are greatly improved by adding VNS, which allows it to make abrupt changes in solution locations during optimization. Because of this property, the hGMO is effective for problems with both continuous and discrete truss designs, since it is able to avoid local optima. Benchmark issues including 10, 52, 72, and 200-bar truss constructions were used to assess the efficiency and robustness of the hGMO model. It was shown that the model could provide better results than other optimization methods when it came to finding optimum solutions. This study's results show that hGMOs may be useful tools for researchers and engineers because of their versatility and capacity to solve difficult optimization challenges. The hGMO's shown promise in truss design issues implies that its usefulness might be expanded to other fields. In keeping with the goals of sustainable development, this expansion would promote creative ideas and enhance engineering in all its forms.

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Data Availability

The corresponding author is available to provide the data, model, or code underlying the findings of this study upon request, in accordance with reasonable conditions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

All authors, including V.H.S.P., N.T.N.D., and V.N.N., jointly contributed to the writing of the main manuscript, preparation of all figures and tables, and reviewed and approved the final version prior to submission.

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