Space trusses optimization using metaheuristic methods: a review

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Abstract. Space trusses are one of the most widely studied elements in structural optimization. Many metaheuristics were used for this purpose over the years, ranging from established methods such as Genetic Algorithms (GA) and Simulated Annealing (SA), through widespread population methods like Ant Colony Optimization (ACO) and Particle Swarm Optimization (PSO) reaching the new generation of heuristic search algorithms (Mine Blast Optimization (MBO), Bat-Inspired Algorithm (BA) and the Charged System Algorithm (CSA), for example). In recent years, in addition to the appearance of numerous brand new search methodologies, it has become extremely common the use of hybrid search methods - mixing two or more algorithms - for the optimization of space trusses. With focus on the exponential increase in publications on the subject, the present work reviews studies about the optimization of space trusses using heuristic methods, searching studies available in scientific journals and classifying them using an own methodology. At the end of the article, an overview of the topic is reported.

Keywords: Space Trusses; Optimization; Metaheuristics.

1 Introduction

Structural optimization is one of the most important branches of engineering. Building using the least possible material consumption is the main objective in any project. Steel trusses provide ample spaces without intermediate supports, a demand that is increasingly common in current works. With this premise, ways are sought to reduce the weight of structures without losing their performance, safety and manufacturing efficiency, making this a common challenge in the structural analysis process. Obtaining the optimal global weight of an element is a difficult task because it is a problem of combinatorial nature, often with discrete variables, not allowing it to be solved in an acceptable time by mathematical methods. Therefore, to obtain this optimality, approximate methods called metaheuristics are used to optimize structures in various aspects, with the objective, for example, of designing them with the smallest possible steel section or the lowest manufacturing cost.

Metaheuristics are computational algorithms commonly used to solve optimization problems. Basically they are divided into two categories, being them, population or neighborhood movement. These algorithms have a good performance to find optimal or close to optimal solutions for combinatorial problems. To maximize their efficiency, their original codes are improved. Several methodologies are used, such as hybridization of two methodologies.

For the present study, a search with the key term is proposed. Results are filtered based on qualitative criteria (impact factor, number of citations and year of publication). Potential methodologies for optimizing space trusses are described and relevant papers developed from them are exposed. In the last chapter, pertinent conclusions are presented.

2 Bibliometric analysis

In order to obtain scientific studies for the present work, the computational tool *Publish or Perish* was used. This software allows searching for keywords in several databases of large online repositories. The databases consulted were: *Google Scholar*, *Scopus* and *Web of Science*, with the search term "*Space Trusses Optimization*", returning 965 results. Fig. 1 shows the temporal distribution of the theme, with the first publication dated 1968 and the most recent in 2021.

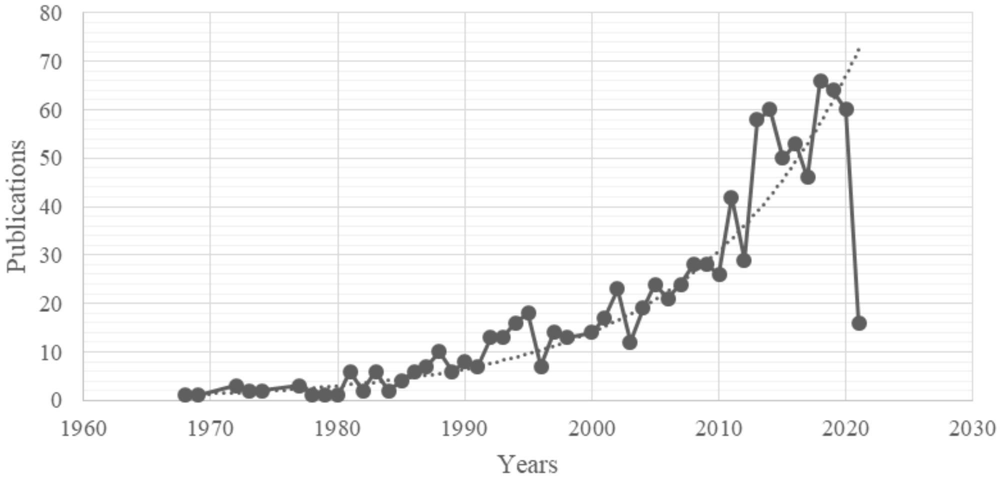

Figure 1. Temporal distribution of works.

From these publications, the periodicals that published on the subject were analyzed. The journals *Structural and Multidisciplinary Optimization* and *Computers & Structures* were the most relevant, with 104 and 92 publications, respectively.

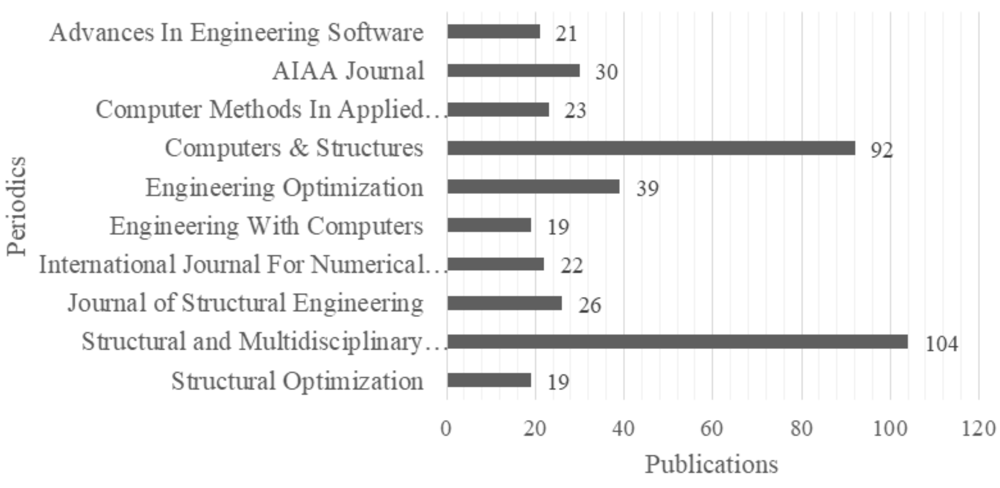

Figure 2. Number of publications in scientific journals.

Based on the data presented in Fig. 2, it was possible to verify the impact factor of each journal. It is observed that the journals with the highest volume of publications - *Structural and Multidisciplinary Optimization* and *Computers & Structures* - occupy an intermediate classification, scoring 3.925 and 3.664. The best impact factor scientific journals were *Computer Methods in Applied Mechanics and Engineering* (5.763) and *Engineering With*

Computers (5.03).

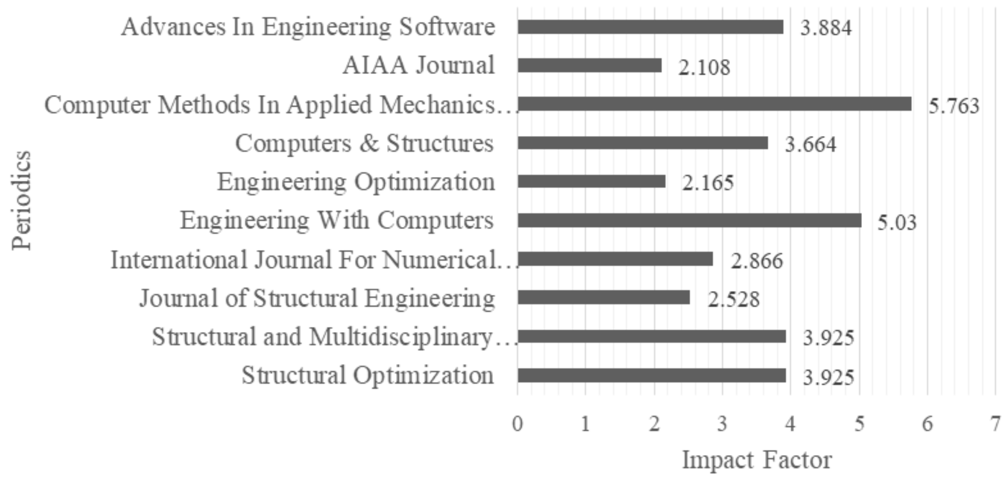

Figure 3. Impact factor of scientific journals.

Over the years, several authors have gained notoriety with publications on the proposed theme. As Fig. 4 shows, Ali Kaveh is the one with the most number of studies, contributing with several works and methods in the academic world. However, it is noteworthy that he has published in journals with very low impact factor.

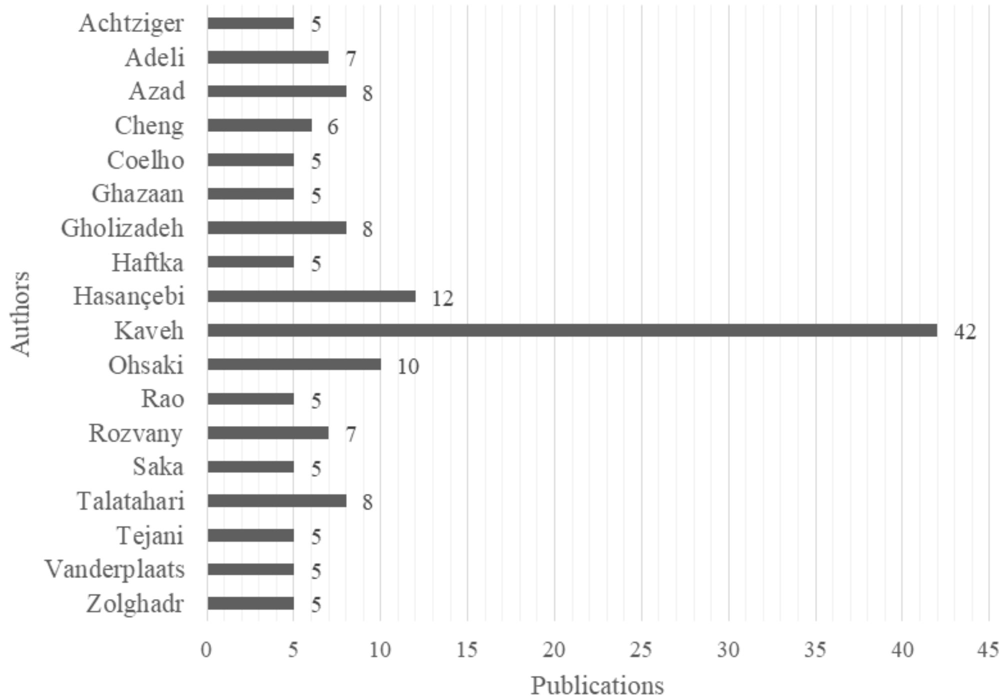

Figure 4. Renowned authors.

Through a word cloud analysis presented in Fig. 5, it is verified that the most recurring word is optimization (861x, 11%), followed by truss (369x, 5%), structures (279x, 4%), algorithm (278, 4%) and design (274, 4%). Then, some trends can be noted: in addition to the most cited words, one can notice terms that are parts of heuristic names (swarm, genetic, evolution and colony), type of analysis (nonlinear and multi-objective) and also the term hybrid, which refers to the mixture of two methods for creating a new one.

Figure 5. Word cloud.

At the end of this analysis, a huge database with articles related to the topic was obtained, most of which were of low relevance. Due to this volume of papers, the present study used a filtering method, classifying the heuristic algorithms and examples of work developed using these methods, taking into account the Impact Factor of the journal in which the study was published, number of citations of the article and year of publication. This allowed both new relevant studies and classic works on space trusses optimization to be used in this study and mainly, this filtering allowed that studies of low relevance to be discarded. Throughout this work, heuristic optimization methods and studies that received the highest score according to the criterion exemplified above will be discussed.

3 Space trusses optimization

Goldberg [1] published his most relevant work, entitled *Genetic Algorithms in Search,* where a heuristic search method based on evolutionary processes - such as natural selection, heredity and mutation - was presented. This algorithm, over the years, has served as basis for important works on the optimization of space trusses, and is even, one of the most recurrently used.

Despite being widely used, consolidating itself as one of the most efficient optimization algorithms for structural disciplines, there was a clear disadvantage of GA in relation to other heuristic method: the computational slowness [2]. Although robust, the method was slow to create generations of individuals. A work of great relevance was developed by Yeh [2] in order to minimize the recurrent drop in performance. For this, the author proposed a hybrid GA algorithm combining concepts of survival of the fittest using the *Fully Stressed Design* (FSD) [3], a very simple and efficient truss optimization technique. Basically, the method considers the dimensioning of the elements after each stress analysis, making the ratio between the acting stress and the limit stress approaching the unit. If the bar or element is under tension, only the tension check is performed. If it is compressed, failure checks by compression and buckling are necessary. It is still possible to establish a limit to the maximum possible cross-section area that a given element can have. FSD allows a considerable improvement in the generation of individuals, converging with greater speed for optimal results. The author observed an improvement in both the average and minimum weights obtained by the hybrid algorithm when compared to the original algorithm.

Particle Swarm Optimization (PSO) is a heuristic method that simulates cooperative behavior between individuals. It is possible to observe similarities with various elements of nature, such as flocks of birds, where the individuals of the flock are guided by exchanging information about a certain common objective, converging towards it. Over time, PSO has become one of the most successful heuristic search methods, with several important works being published.

Dome-shaped truss structures were optimized by Gomes [5] using the PSO with frequency constraints, that is, with the algorithm seeking the lowest weight for the structure in question, respecting the minimum value for its natural frequency. This characteristic is decisive in the application of certain components, once the excitation frequency can be responsible for the occurrence of resonant vibrations, compromising the structure.

Teaching–learning-based optimization (TLBO) is a fresh new heuristic method with great applicability in Space Trusses Structures. Proposed by Rao, Savsan and Vakharia [6], the method simulates the influence of a teacher's interacting with his/her students, which is, the method is based on a population of individuals. Basically, it can be divided into two phases, respectively, Teacher Phase and Learner Phase. The first simulates learning through the teacher's teaching, while the second, through student interaction.

Recently, some outstanding works can be mentioned, such as the one by Dede and Ayvaz [7], where an algorithm was developed using the TLBO for dimensional and shape optimization of plane and space trusses. Another interesting study using TLBO was developed by Camp and Farshchin [8]. In it, the authors, using continuous and discrete variables, proposed a comparative study between TLBO and other search algorithms. Advantages of this algorithm are clearly evidenced, such as simplicity and little need for initial parameters to obtain good results. Improvements were evidenced both in the performance of the algorithm and in the results of mass reduction of the truss elements when using discrete variables. The use of weighted average for decision making contributed to a better convergence to the global optimum.

Storn and Price [9] developed a heuristic method called *Differential Evolution* (DE). The process is very similar to GA, even with some operators, a characteristic that is somewhat common in methods that use populations for optimization. A specific work deserves to be mentioned for using this method in a hybrid way, enhancing its convergence and performance capacity.

Jia et al. [10] proposed a new approach for the DE algorithm, which combines constraints on the optimization algorithm with an adaptive compensation model based on archiving. This model employs several mutation and crossover strategies to generate new populations, increasing performance in the search area. Considering that the method uses continuous variables in the optimization, Ho-Huu et al. [11] applies it to layout optimization of space trusses by changing variables to discrete. The performance of the algorithm, according to the authors, shows that it has an excellent ability to deal with problems of this nature, converging very quickly to the global optimum.

Certainly, one of the most consolidated, efficient and simple to implement search methods, *Simulated Annealing* (SA) was proposed by Kirkpatrick [12] and makes an analogy to the annealing of metals. The method - unlike most seen until now - does not work with populations. The original algorithm works through simple parameters, namely, an initial temperature, a temperature decrease factor, and the number of iterations that will happen with each decrease. The algorithm's search sensitivity is through the tempering of the metal, once, if it is cooled very quickly, the steel becomes brittle, as opposed to a slower cooling, where the arrangement of atoms is more orderly, providing greater strength. The algorithm then tests several hypotheses, accepting better solutions and penalizing worse solutions. Still, solutions with a slight worsening at high temperatures (begin of the optimization process) are accepted, based on the *Metropolis Criterion*. This criterion, also known as the *Metropolis-Hastings Algorithm*, was developed by Metropolis et al. [13] and establishes that the solution will be accepted if a random number generated between 0 and 1 is less than P (ΔE). This makes the algorithm capable of escaping from optimal locations, providing an enormous capacity for solving combinatorial and nonlinear problems.

Kripka [14] used the SA algorithm to optimize plane and space trusses. The author emphasizes in his work that most optimization problems are not aimed at real structural problems. Based on this premise, the study enables feasible solutions in their design and execution.

Based on Coulomb's Law and Newtonian Mechanics, Kaveh and Talatahari [15] proposed a new heuristic search method called *Charged System Search* (CSS). Coulomb's Law, formulated by the French physicist Charles Augustin de Coulomb (1736-1806) describes the interactions between electrically charged particles, while Newtonian Mechanics or Classical Mechanics, developed by Sir Isaac Newton (1643-1727), analyzes motion through space, energy variations and acting forces. CSS uses charged particles that interact through differences in each other's magnetic field, moving through the search space. The most relevant works developed using CSS to optimize lattice structures were, for the most part, developed by at least one of the creators of the method.

Kaveh and Zolghadr [16] investigate the topological optimization of plane and space trusses subject to displacement, strenght and frequency constraints. Due to the amount and sensitivity of constraints, the search space in this type of optimization problem is huge, testing the CSS algorithm's capability. CSS, according to authors, provides a good balance between local and global search capabilities, being able to distinguish these two phases clearly. This feature is very important in problems with several local optimums, just like the ones presented in the article. The algorithm presented a good performance when compared to the PSO, obtaining lighter structures.

Developed by Geem, Kim and Loganathan [17], *Harmony Search Optimization* (HSO) is a heuristic search method inspired by the improvisation process of musical ensembles. Solutions are represented by harmony vectors, and their variables are copied from a set of best solutions (As optimization takes place, the best solutions are stored in a harmonies memory, later used to create new solutions), previous solutions or solutions randomly defined, simulating the process of improvisation.

The practice of merging two methods, creating a hybrid algorithm, is quite common, as seen in the works discussed above. The increase in search capability, convergence and performance is very clear through the mix of two or more methods. Thus, Kaveh, Mirzaei and Jafarvand [18] proposed the improved magnetic charged system search method, applying it to solve optimization problems of truss structures, working with discrete and continuous variables. This variant joined the already hybrid *Magnetic Charged System Search* [19] with the *Improved Harmony Search Algorithm* [20].

The *Magnetic Charged System Search* considers, in addition to electrical forces, magnetic forces, based on the Biot-Savart law. This law presents an equation that provides the magnetic field generated by a certain electrical current. The *Improved Harmony Search Algorithm* introduces a new harmony vector, generated from three rules: memory consideration, pitch adjustment, and random selection.

Back to the work of Kaveh, Mirzaei and Jafarvand [18], it was possible to notice a quick convergence towards the optimal weight of structures. This convergence is better when compared to algorithms like the original PSO, GA and HS.

Recently, Cheng et al. [21] produced a study in which they present a hybrid algorithm variant of the HSO. It works by keeping most of the functions of the original HSO, mixing only the randomization part, applying the PSO for better local and global search, aiming to balance the algorithm's search capacity. In general, the algorithm obtained better results when compared to other search methods, such as the original HSO itself.

Proposed by Karaboga and Basturk [22], the *Artificial Bee Colony* (ABC) method is a swarm-type algorithm that is analogous to a bee hive. It works through the classification of bees into groups, which are employees, spectators or explorers, each with its respective function. Employees are sent to search for food, while explorers search for new sources in the search space close to employees and then, through positive or negative feedback, explorers are sent to perform global searches at random. In this way, we can associate the objective function as a source of food, in this case, nectar.

Sonmez [23] proposes an optimization of space truss structures using ABC with an adaptive approach to the penalty function. According to the study, when comparing the method with others in the literature, that it presents results as good or even superior to those analyzed. The difference between minimum and maximum results is less than 1%. As a burden, the proposal for the penalty function did not help to increase the speed of convergence to the global optimum.

4 Conclusions

The work developed showed very specific characteristics about the modeling and performance of optimization algorithms. Methods that work with individuals, known as populations, represent the largest portion of the researched studies, being them evolutionary or movement in the search space. Several published methods were not considered for the theoretical framework because of low relevance after the screening was performed. Sometimes, it was noted the lack of data to corroborate with common phrases such as "*the current method performed better than method x*" in the studies.

The performance of the algorithm must be measured by obtaining the optimality, but works that take into account a reliability analysis, weighing costs, ease of production and weight of the structure are less common. Note also the excellent performance of hybrid methods. As such, algorithms that work with topological, geometric and dimensional optimizations are the ones that have a better evaluation by the developed method, and are close to the design process performed by a structural engineer. It is also possible to add that mathematical methods such as *Fuzzy Logic*, *Graph Theory*, *Pareto's Principle* and the *Simplex Method*, when working together with the optimization algorithms, increase the search capacity, performance and speed of convergence for optimality.

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