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Metaheuristics in structural optimization and discussions on harmony search algorithm

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ABSTRACT

Metaheuristic algorithms have provided efficient tools to engineering designers by which it became possible to determine the optimum solutions of engineering design optimization problems encountered in every day practice. Generally metaheuristics are based on metaphors that are taken from nature or some other processes. Because of their success of providing solutions to complex engineering design optimization problems the recent literature has flourished with a large number of new metaheuristics based on a variety of metaphors. Despite the fact that most of these techniques have numerically proven themselves as reliable and strong tools for solutions of design optimization problems in many different disciplines, some argue against these methods on account of not having mathematical background and making use of irrelevant and odd metaphors. However, so long as these efforts bring about computationally efficient and robust optimum structural tools for designers what type of metaphors they are based on becomes insignificant. After a brief historical review of structural optimization this article opens this issue up for discussion of the readers and attempts to answer some of the criticisms asserted in some recent publications related with the novelty of metaheuristics.

1. Introduction

Structural optimization came to life with the first publication of Schmit [48]. This new branch of structural engineering formulates the structural design problem as a decision making problem. Decision making is a cognitive process where one tries to select the best of action among several alternatives. Operations research is a post-second world-war discipline which makes use of mathematical modeling, simulation, statistical analysis and mathematical optimization to determine the solutions of decision making problems. Decision making problems are modeled as to minimize or maximize an objective function which represents the quality of the solution under given limitations. Decision variables represent the amount of a resource to use or the level of some activity. There are always certain limitations which are called constraints that one has to satisfy when obtaining the solution of a decision making problem. The optimum solution of a decision making problem identifies the best values of the decision variables such that the objective function in the decision making problem attains its extremum value and the constraints of the problem are all satisfied. Operations research is basically developed to help decision makers in an engineering business, public systems, manufacturing and service industries. The application of the operations research methods to structural design caused emergence of structural optimization. In the mathematical modeling of the structural design process, the decision variables are taken as the cross-sectional properties of structural members and the constraints are the limitations imposed on stresses and displacements that occur in the structure under the applied loads. The objective function is generally considered as to minimize the overall or material cost of the structure.

Prior to such formulation of the structural design problem, designers had to use trial and error method to find the required sections for the members of structural frames. Particularly if the frame is statically indeterminate, in practice most of the time this is the case, the designer has to arbitrarily select the cross-sectional properties of the members so that response of the frame can be determined through the structural analysis. This is due to the fact that the methods available for structural analysis of a rigid frame necessitate data for the cross-sectional properties of its members. This is not an easy task particularly for those who are inexperienced in designing structures. Another difficulty arises when it is required to assign the cross-sections from a discrete set of practically available steel sections. There is a large number of

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combinations of steel profiles available in the steel section list, each of which can be assigned to one member group of the frame. For example, for a steel frame whose members are collected in 10 groups there are 9.536743×10^{23} possible combinations each of which can be assigned to frame member groups in the case where there are 250 different steel profiles available in the steel section list. It may be possible to eliminate some of the combinations by making use of designer's practical experience and engineering intuition. Yet, this reduction will be quite small and remaining large number of combinations requires enormous computational time to determine the optimum combination of steel sections, which is practically not possible. One has to remember that for large-scale real-size frames, the number of member groups becomes even larger which makes the total number of trials so large that no designer has the time to try all these possible combinations. Usually what has been carried is that after few trials, the combination which gives a feasible design according to design code provisions is adopted. It is apparent this combination is generally not the most convenient design so long as the material cost is concerned. Hence the emergence of structural optimization has been welcomed by structural designers because through the use of structural optimization it has become possible to formulate the design process as a decision making problem and obtain its optimum solution using available techniques of mathematical optimization. Several reviews of the mathematical modeling of structural design optimization problem and obtaining its solution by various mathematical optimization techniques are available in the literature [28,3,40,41,43,45,52].

Despite successful applications of metaheuristics in structural optimization, nowadays one can see various articles in the literature; such as Weyland [58] and Sorensen [51], where metaheuristics are criticized rigorously and ruthlessly on account of not having mathematical background and making use of irrelevant or ridiculous metaphors. In one of these articles some of the metaheuristics are claimed to be not being novel; rather being only imitation of other metaheuristics. In the other article, it is even suggested that researchers should be prevented from carrying out research on metaheuristics. The main objective of this paper is to argue validity of such assertions and answer some of the criticisms made against metaheuristics based design optimization in some recent publications. However, before this, historical developments of mathematical optimization techniques and metaheuristics will be overviewed in Sections 2 and 3, respectively with an aim to provide necessary background for traditional and recent methods of structural optimization and to emphasize the extent of developments in this field with the emerge of metaheuristics.

2. Mathematical optimization

Formulation of a structural design problem as a decision making problem and finding its solution through the use of mathematical optimization methods has attracted a lot of attention after its emergence and a large number of research has been carried out on the topic [45]. Mathematical optimization techniques have some features that are later found to be not very much suitable for practical structural design optimization problems. The first one is that mathematical optimization algorithms make the assumption of continuous design variables. This means cross-sectional areas of structural members if selected as design variables can have any real value between their lower and upper bounds. This does not yield practically acceptable results because most of the time in practice the cross-sectional dimensions are integer numbers that lead cross-sectional area values that are not continuous but discrete in a list. Furthermore in the design of steel structures, it is required to select the members from the available list of steel profiles which also has discrete values. The second feature of the mathematical optimization techniques is that most of them require gradient computations of the objective function and constraints. Although this may seem to be straightforward computations to carry out, in some problems constraint functions are not continuous and hence their gradient do not exist, and in some others the constraint functions may be mathematically complex functions such that the computation of their gradients may not be quite easy. Another feature of these techniques is that they do require an initial estimate of the solution vector to start the iterations. The performance of the algorithms is closely related with the quality of this selection. If initial design point is selected far away from the optimum solution and the design problem has several local optimums, it is more likely that the mathematical optimization algorithm will end up with one of the local optimum as the optimum solution. Sometimes if the initial design point is not a good estimate, the convergence difficulties may arise, and no solution can even be obtained. Hence after a vast amount of research works, researchers were able to present the optimum design results only for small size structures using mathematical programming techniques. Later some mathematical programming techniques, such as integer programming and branch and bound techniques have been developed that are able to handle the discrete variables. However these algorithms are cumbersome to code in computers and have similar discrepancies of the general mathematical optimization techniques. A review of the published articles which makes use of mathematical programming techniques in structural optimization literature reveals the fact that the optimum structural design algorithms developed up to the present could only deal with structural frames with few bays and not more than 10-storey. On the other hand researchers were able to design real-size structural steel frames using optimality criteria approaches that were developed later [43,45]. One of the promising features of the optimality criteria approaches was that the number of iterations to reach the optimum design was not related with the number design variables in the design problem. This approach has increased the hope of designing practical structures optimally provided that the continuous design variable assumption is made. In addition to continuous design variable assumption, selection of an appropriate initial design point was also needed for an optimality criteria approach to start its iterations, and the performance of these algorithms was contingent upon the quality of the selected initial design point. Later, some variants of optimality criteria techniques were presented in the literatures which were able to handle discrete design variables as given in the steel sections list. Overall the structural optimization algorithms based on mathematical programming technique or optimality criteria concept were not able to satisfy the needs of designing real-size structural frames under design code provisions that designers face in every day practice. It was only after the emergence of metaheuristic techniques this dream became reality.

3. Metaheuristics

Computational drawbacks of the derivative based mathematical optimization algorithms mentioned above have enforced researchers all over the world to seek approaches which are based on different concepts. This has led to the emergence of a new class of optimization techniques that are called “metaheuristics”. A metaheuristic is formally defined as an iterative generation process which makes use of certain guides in the search process of the design domain. Its goal is to efficiently explore the search space in order to find optimal or near-optimal solutions. Mathematical optimization algorithms progress toward the complete solution by making deterministic decisions. This is why they are also called