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Simultaneous Size And Shape Optimization Of Truss Structure Employing Simulated Annealing With Particle Swarm Optimization

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ABSTRACT

Due to the great diversity of possible configurations, either to overcome a certain span or to resist a certain load, trusses constitute a very fertile field for the use of optimization techniques. With the use of optimization metaheuristics, we seek to quantify the minimum amount of material necessary for the structure to support a given load with due safety. Truss optimization problems are basically classified into three categories: size, shape and topology optimization. The present work presents the hybrid algorithm called Simulated Annealing with Particle Swarm Optimization (SAwPSO) for shape and size optimization of truss structure with natural frequency constraints. The results indicate that SAwPSO produces good results compared to those published in the specialized literature.

Keywords: shape; size, optimization, truss structure.

1. INTRODUCTION

The structures known as trusses have a wide field of application in engineering, being widely used in the construction of bridges (roads and railways), as covering structures (in homes, industries, stadiums, etc.), in power transmission towers, among others. several other uses. They are usually built in wood or steel, being relatively light and especially suitable for overcoming large spans or high loads. In this context, trusses become an economical and practical solution

In the past, many design processes were driven by the designer's experience and intuition rather than intensive application of optimization theory. Recently this way of thinking has changed due to the importance that the field of structural optimization has taken on in design, since through its application it is possible to reduce costs, materials and time in the design processes carried out by engineers. The purpose of applying the concepts of optimal design to structural engineering is to obtain a solution to an engineering problem that meets all the limitations and restrictions imposed, and that at the same time turns out to be the best in terms of one or or several design criteria previously established.

Truss optimization problems are basically divided into three categories: size, shape and topology optimization. In the first situation, the topology and geometry of the structural elements are fixed, and only the characteristics of the cross sections of the bars are dimensioned. In this case, one can work with discrete variables, through a set of pre-defined dimensions for the sections, or continuous variables, when working with section values within a certain range. In shape optimization, it is possible to modify the node coordinates for a pre-defined topology. In this situation, it is also common to allow the modification of the characteristics of the cross sections. In the case of topology optimization, the number of elements and the relative positions of the nodes are idealized with complete freedom of choice. The truss optimization process may have one or more of the following basic constraints: allowable displacement, maximum buckling stress, and maximum axial stress.

The present work aims to optimize simultaneously the size and shape of truss structure using Simulated Annealing With Particle Swarm Optimization (SAwPSO), with constraints of natural frequencies. The validity of SAwPSO is confirmed by testing for two shape and size optimization problems of truss structures. The remainder of this article is structured as follows. Section 2 describes the mathematical formulation of truss optimization. The SAwPSO is briefly presented in Sect. 3. Section 4 presents three benchmark numerical examples to illustrate the efficiency of the SAwPSO. Finally, in Sect. 5, conclusions are presented.

2. PROBLEM DEFINITION

The objective of the structural optimization problem is to minimize the weight of the truss, the optimal nodal coordinates and the optimal cross-sectional areas of the elements, satisfying some constraints of natural frequencies. The mathematical formulation for this problem can be expressed by

$$\text{Find,}\quad X=\{A,NC\},\ \text{where}\quad A=\{A_1,A_2,\dots,A_n\}\ \text{and}\ NC=\{NC_1,NC_2,\dots,NC_m\}$$

$$\text{Minimize}\qquad W(X)=\sum_{i=1}^{n}\rho_i A_i L_i$$

$$\text{Subject to}\quad \begin{cases} f_q - f_q^{min} \geq 0 \\ f_r - f_r^{max} \leq 0 \\ A_i^{min} \leq A_i \leq A_i^{max} \\ NC_j^{min} \leq NC_j \leq NC_j^{max} \end{cases} \qquad (1)$$

where W(X) is the total weight of the minimized truss; n is the total number of structure members; ρ_i, A_i and L_i represent the density of the material, the cross-sectional area and the length of member i, respectively; NC_i are the nodal coordinates (x_j, y_j, z_j) of node j; fq and fr are the natural frequencies of the structure, respectively, and the subscripts "max" and "min" denote the maximum and minimum permitted limits, respectively.

3. SAwPSO ALGORITHM

The basis of the hybrid algorithm is very simple. Each algorithm is working separately, each one evaluating a different function. In the SAwPSO, the SA selects the initial parameters of the PSO (c_1, c_2, N, α), and the PSO is evaluating the objective function (weight optimization of truss structures). In this way, both algorithms perform the optimization work until it meets the established stopping criterion. Figure 1 shows the SAwPSO flowchart.

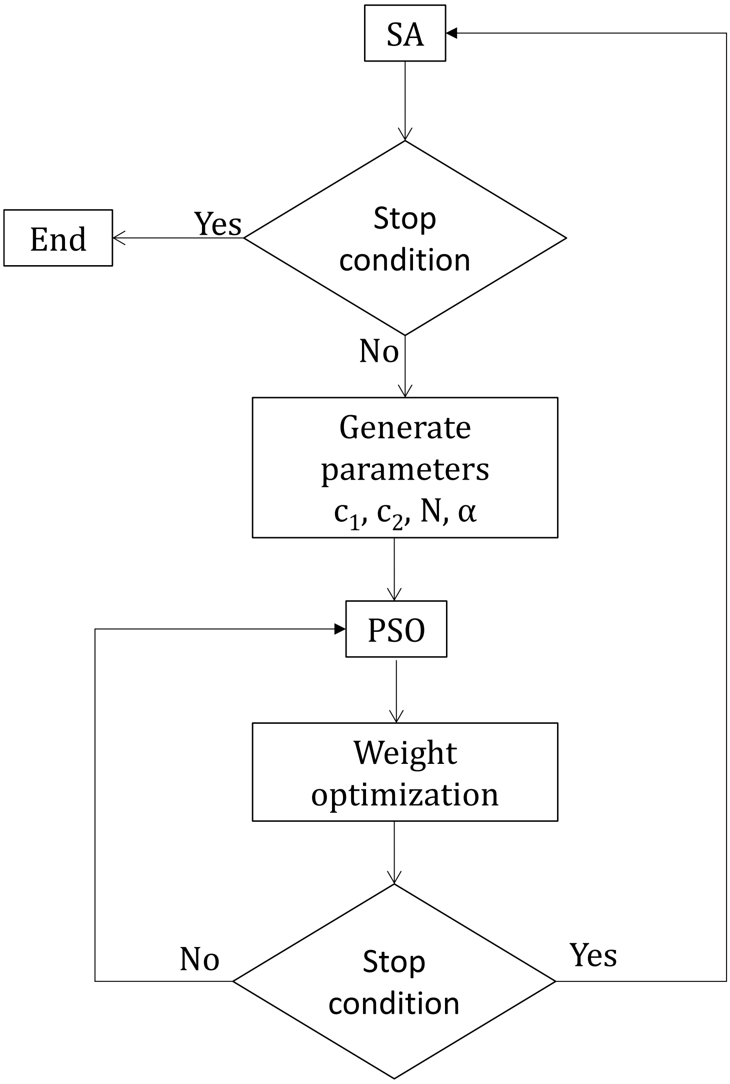

Figure 1. The SAwPSO flowchart.

4. TRUSS PROBLEMS AND DISCUSSIONS

Two trusses with 37 members and 52 members are considered, which are famous trusses in the field of structural optimization. The results are compared with the previous results obtained through various existing metaheuristics. The algorithm was coded in Matlab on an Intel Core-i7 computer with 16 GB of RAM. Each problem was run 50 times and the results in the tables are in terms of minimum weight, mean, standard deviation (SD) and number of iterations (NI). The main input data of the problems are presented in Table 1.

Table 1. Input data for each problem

Problem	**Modules of elasticity E (N/m^2)**	**Weight density ρ (kg/m^3)**	**Size variables (cm^2)**	**Shape variables (m)**	**Frequency constraints (Hz)**
37-bar planar truss	2.1×10^{11}	7800	$0.1 \leq A_i \leq 10$	$0.1 \leq y \leq 3$	$f_1 \geq 20$ $f_2 \geq 40$ $f_3 \geq 60$

52-bar spatial truss	2.1×10^{11}	7800	$0.1 \le A_i \le 10$	All the free nodes can displace±2 m in symmetric manner	$f_1 \le 15.9155$ $f_2 \ge 28.6479$

4.1 37-bar planar truss

The 37-bar planar truss, simply supported bridge, is shown in Figure 2. This problem considers simultaneous size and shape optimization. A mass of 10 kg is added at each lower node, as shown in Figure 2. The lower bars have a fixed and pre-defined cross-sectional area of 0.4 cm^2 (Lieu et al., 2018). Design parameters are given in Table 1. The remaining elements are categorized into 14 groups through the symmetry of the structure in relation to the vertical median plane (using symmetry along the central nodes 10 and 11). Top nodes can move vertically, while bottom nodes are fixed. So this problem has 14 size variables and 5 shape variables.

Table 2 presents a comparison of the best results obtained by SAwPSO and other metaheuristics. The results indicate that SAwPSO gets a weight of 360.51 kg, occupying the sixth place among the compared algorithms.. Regarding the speed of convergence, SAwPSO ranks seventh among the considered metaheuristics. The table also indicates that ASAM is more stable than PSO.

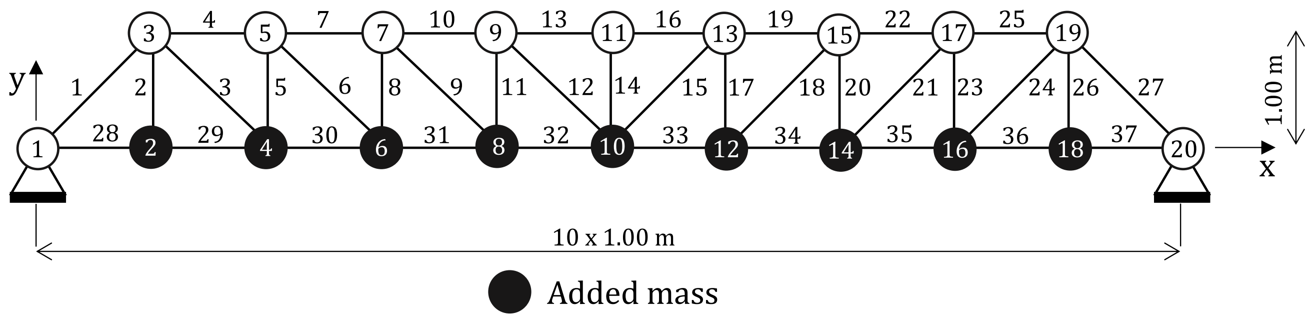

Figure 2. Schematic of the 37-bar planar truss.

Table 2. Optimal design parameters (y coordinates: m; and areas: cm^2) for the 37-bar planar truss by other algorithms

Variables (cm^2)		**Gomes (2011)**	**Kaveh e Zolghadr (2014)**	**Kaveh e Ilchi Ghazaan (2015)**	**Kaveh e Ilchi Ghazaan (2017)**	**Ho-Huu et al. (2018)**	**Tejani et al. (2018)**	**Lieu et al. (2018)**	**SAwPSO**
		PSO	**DPSO**	**HALC-PSO**	**VPS**	**ReDE**	**ISOS**	**AHEFA**	
1	y_3, y_{19}	0.9637	0.9482	0.9750	0.9042	0.9533	0.9257	0.9589	1.0296
2	y_5, y_{17}	1.3978	1.3439	1.3577	1.2850	1.3414	1.3188	1.3450	1.3999
3	y_7, y_{15}	1.5929	1.5043	1.5520	1.5017	1.5319	1.4274	1.5355	1.5878
4	y_9, y_{13}	1.8812	1.6350	1.6920	1.6509	1.6528	1.5806	1.6668	1.7255

5	y_{11}	2.0856	1.7182	1.7688	1.7277	1.7280	1.6548	1.7397	1.8003
6	A_1, A_{27}	2.6797	2.6208	2.9652	3.1306	2.9608	2.6549	2.8210	2.7457
7	A_2, A_{26}	1.1568	1.0397	1.0114	1.0023	1.0052	1.0383	1.0019	1.0000
8	A_3, A_{24}	2.3476	1.0464	1.0090	1.0001	1.0014	1.0000	1.0001	1.0104
9	A_4, A_{25}	1.7182	2.7163	2.4601	2.5883	2.5994	3.0083	2.5308	2.5579
10	A_5, A_{23}	1.2751	1.0252	1.2300	1.1119	1.1949	1.0024	1.2210	1.1710
11	A_6, A_{21}	1.4819	1.5081	1.2064	1.2599	1.2165	1.4499	1.2429	1.2454
12	A_7, A_{22}	4.6850	2.3750	2.4245	2.6743	2.4303	3.1724	2.4718	2.4438
13	A_8, A_{20}	1.1246	1.4498	1.4618	1.3961	1.3644	1.2661	1.4018	1.4537
14	A_9, A_{18}	2.1214	1.4499	1.4328	1.5036	1.5548	1.4659	1.5061	1.4955
15	A_{10}, A_{27}	3.8600	2.5327	2.5000	2.4441	2.5247	2.9013	2.5604	2.1299
16	A_{11}, A_{15}	2.9817	1.2358	1.2319	1.2977	1.1946	1.1537	1.2146	1.1728
17	A_{12}, A_{15}	1.2021	1.3528	1.3669	1.3619	1.3163	1.3465	1.3605	1.4040
18	A_{13}, A_{16}	1.2563	2.9144	2.2801	2.3500	2.4465	2.6850	2.3992	2.4172
19	A_{14}	3.3276	1.0085	1.0011	1.0000	1.0003	1.0000	1.0000	1.0030
Weight (kg)		377.20	360.40	359.93	359.94	359.81	360.74	359.81	360.51
f_1 (Hz)		20.0001	20.0194	20.0216	20.0002	20.0005	20.0119	20.0000	20.0049
f_2 (Hz)		40.0003	40.0113	40.0098	40.0005	40.0004	40.0964	40.0001	40.0147
f_3 (Hz)		60.0001	60.0082	60.0017	60.0000	60.0022	60.0066	60.0002	60.0058
Mean (kg)		381,2	362.21	360.23	360.23	359.99	363.40	359.92	362.98
SD (kg)		4.26	1.68	0.24	0.22	0.15	1.57	0.09	1.83
NI		12500	6000	10000	30000	13740	4000	8640	15000

4.2 52-bar spatial truss

Figure 3 indicates a 52-bar spatial truss structure. Design parameters are given in Table 1. This structure is considered for simultaneous dimensional and shape optimization. A mass of 50 kg is added to all free nodes in the structure. The bars are grouped into eight groups considering symmetry about the z axis, while the free nodes can move ± 2 m in each direction of the vertical plane to keep the dome symmetrical. So there are 13 design variables (8 dimensional and 5 shape).Table 3 compares the SawPSO results with other optimization methods. It can be seen that the design produced by ASAM (196.01 kg) is is better than those reported by PSO and CSS-BBBC. In terms of convergence speed, SAwPSO requires 15000 NI. Regarding SD, SAwPSO ranks second among the considered metaheuristics.

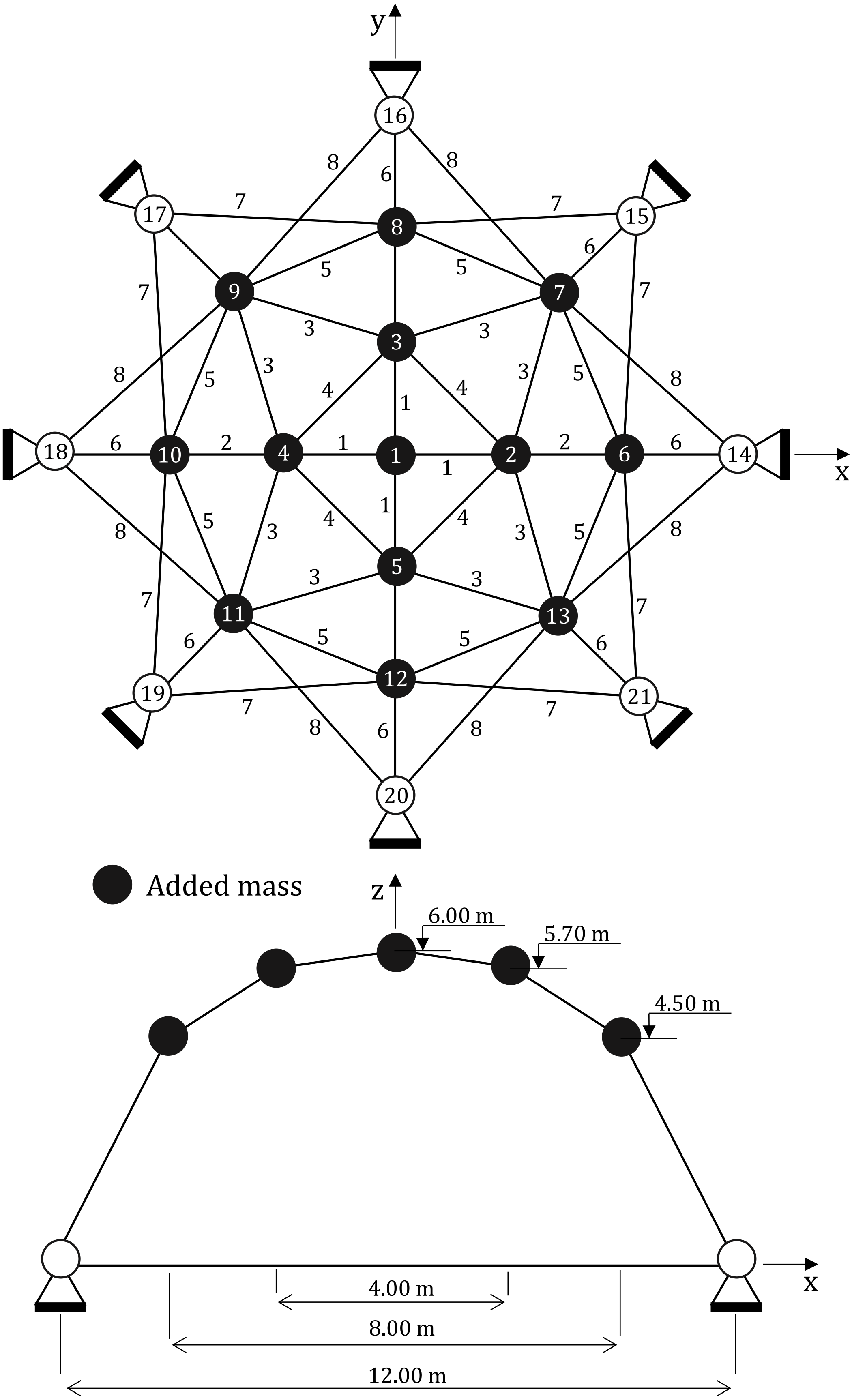

Figure 4. Schematic of the 52-bar spatial truss.

Table 3. Optimal design parameters for the 52-bar spatial truss by other algorithms

Variáveis (cm^2)		Gomes (2011)	Kaveh e Zolghadr (2012)	Kaveh e Ilchi Ghazaan (2015)	Ho-Huu et al. (2018)	Tejani et al. (2018)	Lieu et al. (2018)	SAwPSO
		PSO	**CSS-BBBC**	**HALC-PSO**	**ReDE**	**ISOS**	**AHEFA**	
1	Z_A	5.5344	5.3310	5.9362	6.0188	6.1631	5.9953	5.9267
2	X_B	2.0885	2.1340	2.2416	2.2976	2.4224	2.3062	2.2281
3	Z_B	3.9283	3.7190	3.7309	3.7417	3.8086	3.7308	3.7571
4	X_F	4.0255	3.9350	3.9630	3.9996	4.1080	4.0000	3.9767
5	Z_F	2.4575	2.5000	2.5000	2.5001	2.5018	2.5000	2.5087
6	A_1-A_4	0.3696	1.0000	1.0001	1.0000	1.0074	1.0000	1.0068
7	A_5-A_8	4.1912	1.3056	1.1654	1.0852	1.0003	1.0832	1.1832
8	A_9-A_{16}	1.5123	1.4230	1.2323	1.1968	1.1982	1.2014	1.2801
9	A_{17}-A_{20}	1.5620	1.3851	1.4323	1.4503	1.2787	1.4527	1.4594
10	A_{21}-A_{28}	1.9154	1.4226	1.3901	1.4216	1.4421	1.4212	1.4265
11	A_{29}-A_{36}	1.1315	1.0000	1.0001	1.0001	1.0000	1.0000	1.0001
12	A_{37}-A_{44}	1.8233	1.5562	1.6024	1.5614	1.4886	1.5570	1.5442
13	A_{45}-A_{52}	1.0904	1.4485	1.4131	1.3878	1.4990	1.3904	1.4126
Weight (kg)		228.38	197.31	194.85	193.20	194.75	193.20	196.01
f_1 (Hz)		12.751	12.987	11.4339	11.6107	12.5459	11.6629	11.4953
f_2 (Hz)		28.649	28.648	28.6480	28.6482	28.6518	28.6480	28.6429
Mean (kg)		234.30	–	196.85	195.43	207.55	198.73	198.22
SD (kg)		5.22	–	2.38	3.86	8.74	4.41	3.42
NI		11270	–	7500	16200	4000	12120	15000

5. CONCLUSION

In this work, the SAwPSO algorithm was used to solve simulataneous size and shape optimization of truss structures with natural frequency constraints. The results obtained with SAwPSO show that they are competitive in terms of the mean, best and standard deviation. This indicates that it is a tool that could be used to solve this kind of problems and that it can be used at the undergraduate level to teach metaheuristic methods.

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