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SIZE AND SHAPE OPTIMIZATION OF STRUCTURES BY HARMONY SEARCH

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Abstract. *Structural optimization is a relatively new area that has been increasingly exploited. There are many classical methods, and newer is emerging to compete on efficiency, reliability and speed in obtaining an optimal result. The algorithms are classified into deterministic algorithms, which use the gradient information, i.e., use the values of the functions and their derivatives, and meta-heuristic algorithms, random optimization methods which are probabilistic methods not based on gradient, i.e., they use only objective function evaluation. A relatively recent meta-heuristic algorithm is presented, Harmony Search, that is a music-based metaheuristic optimization algorithm, which is inspired by musician's improvisation process. Some benchmarks of2-D and 3-D trusses, considering size and shape optimization with stress, displacement, and natural frequency constraints are presented to demonstrate the effectiveness of the method. The results are compared to the other authors using different methods found in the literature. The results indicate that optimization algorithms studied in this paper are better than or as efficient as others. Finally, the methods are applied to the structure of an adapted design.*

Keywords: *structural optimization, meta-heuristic algorithms, Harmony Search, truss structures*

1. INTRODUCTION

The optimization is everywhere. In almost all activities involving optimization, one tries to achieve certain goals or optimize something like profit, quality or time. As resources, time and money are always limited in real-world applications, solutions must be found to make use of these valuable resources optimally on several constraints. Optimization is the study of such problems of planning and design using mathematical tools. Currently, computer simulations become an indispensable tool for solving optimization problems with several efficient search algorithms.

The field of structural optimization is still a relatively new area, subject to rapid changes in its methods and goals. Until recently, there was a large imbalance between the huge amount of literature on the subject, and the lack of applications in practical design problems. This imbalance is being corrected gradually, because there are many applications of methods for structural optimization in the automotive, aerospace, civil engineering, design engineer and other engineering fields. As a result the growth rate of these applications, studies on structural optimization methods are increasingly being driven by real problems.

The current need for greater efficiency and competitiveness has forced those responsible for the design of structures to take great interest in the economics of their designs.

In this context, the area of optimization is gaining more prominence and will therefore be the subject of this paper.

The optimization methods based on probabilistic algorithms use only the evaluation of the objective function and introduce the process of data optimization and stochastic parameters. They are considered zero-order methods for not using the derivative of the objective function. The best known are: Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), Ant Colony Search (ACS), Simulated Annealing (SA), Harmony Search (HS), Firefly Algorithm (FA), Bat Algorithm (BA), Cuckoo Search (CS), among others.

Meta-heuristic algorithms represent a way by trial and error to produce acceptable solutions to complex problems in a reasonable time. There is no guarantee that the best solutions are found, and not even if the algorithm work and why they work. The idea is to have an efficient algorithm, but practical that works most of the time, is capable of producing good quality solutions and, among these, some that are close to the optimal.

The main advantages of probabilistic algorithms in relation to deterministic ones are:

- The objective function and the constraints need not necessarily have a mathematical representation;
- Do not require that the objective function is continuous and differentiable;
- They work properly with both discrete and continuous parameters, or a combination of them;
- They not require complex formulations or reformulation of the problem;
- There is no restriction as to the starting point in the search space of the solution;

- They perform simultaneous searches in the space of possible solutions through a population of individuals, therefore, are candidates for use of parallelization on computers;
- Optimize a large number of variables, since the evaluation of the objective function does not have a too high computational cost.

The biggest disadvantage of probabilistic methods in relation to deterministic methods is the computational cost. Thus, probabilistic methods generally require a high processing time when used in sequential processing machines.

2. HARMONY SEARCH

Harmony Search is a relatively new heuristic optimization algorithm and it was first developed by Z. W. Geem, J. H. Kim and G. V. Loganathan [Geem et al., 2001]. Harmony search is a music-based metaheuristic optimization algorithm. It is inspired by the observation that the aim of music is to search for a perfect state of harmony. This harmony in music is analogous to find the optimality in an optimization process. The search process in optimization can be compared to a musician's improvisation process.

Music harmony is a combination of sounds considered pleasing from an aesthetic point of view. Harmony in nature is a special relationship between several sound waves that have different frequencies.

Musical performances seek a best state (fantastic harmony) determined by aesthetic estimation, as the optimization algorithms seek a best state (global optimum – minimum cost or maximum benefit or efficiency) determined by objective function evaluation. Aesthetic estimation is determined by the set of the sounds played by joined instruments, just as objective function evaluation is determined by the set of the values produced by component variables; the sounds for better aesthetic estimation can be improved through practice after practice, just as the values for better objective function evaluation can be improved iteration by iteration. A brief presentation of these observations is shown in Tab. 1.

Table 1. Comparison between Optimization and Musical Performance

COMPARISON FACTOR	OPTIMIZATION PROCESS	PERFORMANCE PROCESS
Best state	Global Optimum	Fantastic Harmony
Estimated by	Objective Function	Aesthetic Standard
Estimated with	Values of Variables	Pitches of Instruments
Process unit	Each Iteration	Each Practice

Source: adapted from Geem et al., 2001

The steps in the procedure of HS proposed by Geem et al., 2001, are as follows:

- Step 1: Initialize a Harmony Memory (HM).
- Step 2: Improvise a new harmony from HM.
- Step 3: If the new harmony is better than minimum harmony in HM, include the new harmony in HM, and exclude the minimum harmony from HM.
- Step 4: If stopping criteria are not satisfied, go to Step 2.

This perfectly pleasing harmony is determined by the audio aesthetic standard. The aesthetic quality of a musical instrument is essentially determined by its pitch (or frequency), timbre (or sound quality), and amplitude (or or loudness).

Geem et al., 2001, observed when musicians are improvising, they have three possible choices: (1) play any famous piece of music (a series of pitches in harmony) exactly from their memory; (2) play something similar to a known piece (thus adjusting the pitch slightly); or (3) compose new or random notes. If we formalize these three options for optimization, we have three corresponding components: usage of harmony memory, pitch adjusting, and randomization.

The use of harmony memory will ensure that the best harmonies will be carried over to the new harmony memory. It is reached through the use of a parameter called Harmony Memory Considering Rate (HMCR), $0 \leq HMCR \leq 1$. So, if this parameter is too low, only few best harmonies are selected and it may converge too slowly. On the other hand, if this parameter is extremely high (near 1), almost all the harmonies are used in the harmony memory, then other harmonies are not explored well, leading to potentially wrong solutions. Therefore, this parameter usually assumes values between 0.7 up to 0.95 [Yang, 2008].

The second component is the pitch adjustment determined by a pitch bandwidth range (bw) and a pitch adjusting rate (PAR). In HS pitch adjustment corresponds to generate a slightly different solution. The PAR is used to control the degree of the adjustment. Thus, a low PAR with a narrow bandwidth can slow down the convergence of HS because the limitation in the exploration of only a small subspace of the whole search space. On the other hand, a very high PAR with a wide bandwidth may cause the solution to scatter around some potential optima as in a random search. So, this parameter usually assumes values between 0.1 up to 0.5 in most simulations [Yang, 2008].

The third component is the randomization, which is to increase the diversity of the solutions. Although adjusting pitch has a similar role, but it is limited to certain local pitch adjustment and thus corresponds to a local search. The use of

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randomization can drive the system further to explore various diverse solutions so as to find the global optimality [Yang, 2008]. The three components in HS can be summarized as the pseudo code shown in Fig. 1 [Yang, 2008].

```
begin
    Objective function f(x), x = (x1, ..., xp)^T
    Generate initial harmonics (real number arrays)
    Define pitch adjusting rate and pitch limits
    Define harmony memory accepting rate
    while (t < Max number of iterations)
        Generate new harmonics by accepting best harmonics
        Adjust pitch to get new harmonics (solutions)
        if (rand > HMCR), choose an existing harmonic randomly
        else if (rand > PAR), adjust the pitch randomly within limits
        else generate new harmonics via randomization
        end if
        Accept the new harmonics (solutions) if better
    end while
    Find the current best estimates
end
```

Figure 1. Pseudo code of Harmony Search. Source: adapted from Yang, 2008.

Finally, according to Yang, 2008, HS could be more efficient than Genetic Algorithms (GA), for instance, because HS does not use binary encoding and decoding, but it does have multiple solution vectors. Therefore, HS is faster during each iteration. Besides, the implementation of HS algorithm is also easier. In addition, there is evidence to suggest that HS is less sensitive to the chosen parameters, which means that it is not necessary to fine-tune these parameters to get quality solutions.

3. BENCHMARKS EXAMPLES

Harmony Search was implemented in MATLAB code, as well as, the subroutines of truss analysis developed by the author. The method change the cross sectional areas (A_i) and nodal coordinates (l_i), which are the design variables, looking for the minimum structural mass (M_{min}), subject to stresses (σ_i), displacements (δ_i) and natural frequencies (f_i) constraints. Thus, the mathematical relationships that led to the numerical results are:

Minimize

$$M_{min} = \sum_{i=1}^{n} \rho_i l_i A_i$$

Subjected to

$$|\sigma_i| - \sigma_i^{max} \leq 0,\ i = 1, \dots, m$$
$$|\delta_j| - \delta_j^{max} \leq 0,\ j = 1, \dots, q$$
$$f_k - f^{max} \leq 0;\ f^{min} - f_k \leq 0,\ k = specific\ freq.$$
$$A_i^{min} \leq A_i \leq A_i^{max}, i = 1, \dots, n$$

in which M_{min} is the minimum structural mass, m is the number of members in the current design, q is the number of nodes in the current design, ρ_i is the specific mass of the material of each bar, l_i is the length of each bar, σ_i and σ_i^{max} are the stress and maximum allowed stress of the i^{th} bar, respectively, δ_j and δ_j^{max} are the displacement and maximum allowed displacement at node j, respectively, and finally, A_i^{min} and A_i^{max} are, respectively, the lower and upper bounds of the cross sectional area of the i^{th} bar. The design variables are considered as continuous.

The input parameters of the HS were defined by Yang, 2008, and used for all problems: HMS = 6; HMCR = 0.9; PAR_{min} = 0.4; PAR_{max} = 0.9; bw_{min} = 0.0001; bw_{max} = 1.0.

3.1 37-bar plane truss

The first standard test problem is the simply supported 37-bar plane truss with initial configuration shown in Fig. 2. Both size and shape optimizations are performed on the same problem. The design variables are the areas of cross sections of the bars and the coordinates of the nodes. The truss is subject to multiple natural frequency constraints. The material properties of the truss are shown in Tab. 2.

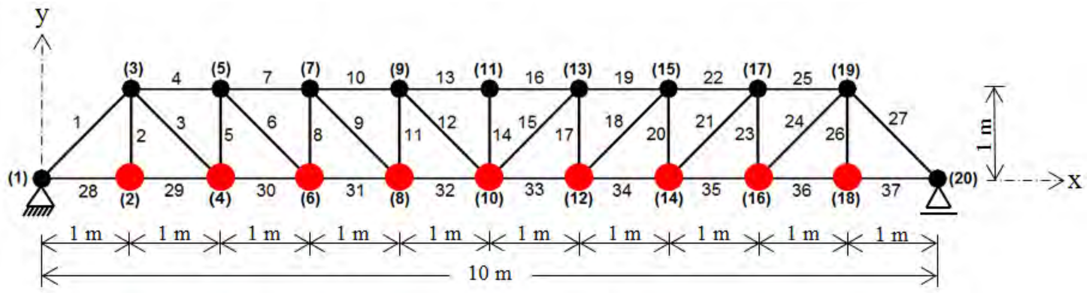

Figure 2. Initial configuration design for the simply supported 37 bar truss

Table 2. Material properties for the simply supported 37 bar truss

Property	**Value**	**Unit**
Material	Steel	–
E – Young's modulus	210x 10^9	N/m^2
ρ – Specific mass	7800	kg/m^3

As can be seen in Fig. 4, non-structural mass equal to 10 kg is attached at each of nodes on the lower chord, which remain fixed during the design process (2, 4, 6, 8, 10, 12, 14, 16, 18). Nodal coordinates in the upper chord and member areas are regarded as design variables. All members on the lower chord (numbers 28–37) have fixed cross section areas of 4 x 10^{-3} m^2 and the others have initial cross section areas of 1 x 10^{-4} m^2. In the optimization process, nodes on the upper chord can be shifted vertically. In addition, nodal coordinates and member areas are linked to maintain the structural symmetry. Thus, only five shape variables (nodes) and fourteen sizing variables (areas) will be redesigned for optimization, as shown on Tab. 3. The natural frequency constraints are $f_1 \geq 20$ Hz, $f_2 \geq 40$ Hz e $f_3 \geq 60$ Hz. The allowable minimum area of the cross sectional is 1 x 10^{-4} m^2.

Table 3. Nodal coordinates and bar groups of the simply supported 37 bar truss

Design Variables	
Node Coordinates	
Y3 = Y19	
Y5 = Y17	
Y7 = Y15	
Y9 = Y13	
Y11	
Cross Section Areas	**Elements**
Group 1	A1 = A27
Group 2	A2 = A26
Group 3	A3 = A24
Group 4	A4 = A25
Group 5	A5 = A23
Group 6	A6 = A21
Group 7	A7 = A22
Group 8	A8 = A20
Group 9	A9 = A18
Group 10	A10 = A19
Group 11	A11 = A17
Group 12	A12 = A15
Group 13	A13 = A16
Group 14	A14

Figure 3 shows the convergence curve for this problem subject to many natural frequency constraints. A total of twenty thousand iterations is used.

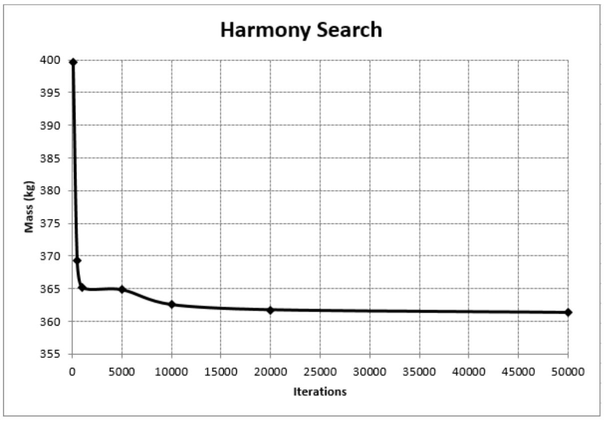

Figure 3. Convergence curve for the simply supported 37 bar truss

Wang et al., 2004, also studied this problem, using the *Evolutionary Node Shift Method*; Lingyun et al., 2005, using the *Niche Hybrid Genetic Algorithm* (*NHGA*); and Gomes, 2011, using the *Particle Swarm Optimization* (*PSO*). In this paper, *Harmony Search* (*HS*) is used to solve size and shape optimization with multiple natural frequency constraints.

The optimal design obtained in this paper and the comparison with results of the other authors cited above are shown in Tab. 4. The result obtained by the HS was the best of all the methods proposed in the literature, followed by Wang et al., 2004; Lingyun et al., 2005; and Gomes, 2011. Note that the structural masses obtained by all algorithms in this example are worse than the initial one. It must be emphasized that this occurs because the initial design is not in accordance with the constraints.

Table 4. Optimum design for the simply supported 37 bar truss from various methods

ALGORITHM			**Initial**	***Evolutionary Node Shift***	***NHGA***	***PSO***	***Harmony Search***
AUTHOR				**Wang et al. (2004)**	**Lingyun et al. (2005)**	**Gomes (2011)**	**Present paper**
Design Variables	Nodal coordinates (m)	Y3, Y19	1.0	1.2086	1.1998	0.9637	0.9561
		Y5, Y17	1.0	1.5788	1.6553	1.3978	1.3331
		Y7, Y15	1.0	1.6719	1.9652	1.5929	1.5716
		Y9, Y13	1.0	1.7703	2.0737	1.8812	1.7741
		Y11	1.0	1.8502	2.3050	2.0856	1.8569
	Cross sectional areas (cm^2)	Group 1	1.0	3.2508	2.8932	2.6797	2.7878
		Group 2	1.0	1.2364	1.1201	1.1568	1.1194
		Group 3	1.0	1.0000	1.0000	2.3476	1.1428
		Group 4	1.0	2.5386	1.8655	1.7182	2.2458
		Group 5	1.0	1.3714	1.5962	1.2751	1.1426
		Group 6	1.0	1.3681	1.2642	1.4819	1.1541
		Group 7	1.0	2.4290	1.8254	4.6850	1.9163
		Group 8	1.0	1.6522	2.0009	1.1246	1.4539
		Group 9	1.0	1.8257	1.9526	2.1214	1.5773
		Group 10	1.0	2.3022	1.9705	3.8600	2.5871
		Group 11	1.0	1.3103	1.8294	2.9817	1.6016
		Group 12	1.0	1.4067	1.2358	1.2021	1.5072
		Group 13	1.0	2.1896	1.4049	1.2563	2.4911
		Group 14	1.0	1.0000	1.0000	3.3276	1.1166
Mass (kg)			**336.9**	**366.5**	**368.84**	**377.20**	**361.35**

It is important to point out that using HS none of the natural frequency constraints were violated, as may be seen in Tab. 5.

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Table 5. Optimum design of natural frequencies (Hz) for the simply supported 37 bar truss from various methods

ALGORITHM			***Evolutionary Node Shift***	***NHGA***	***PSO***	***Harmony Search***
AUTHOR		**Initial**	**Wang et al. (2004)**	**Lingyun et al. (2005)**	**Gomes (2011)**	**Present paper**
Natural frequencies (Hz)	1	8.8778	20.0850	20.0013	200001	20.0003
	2	29.2135	42.0743	40.0305	40.0003	40.0683
	3	48.5539	62.9383	60.0000	60.0001	60.0253
	4	67.7487	74.4539	73.0444	73.0440	77.8438
	5	84.2484	90.0576	89.8244	89.8240	100.0876

The statistical results of five independent simulations, presented in Tab. 6, show a small standard deviation from the mean value, showing that the method is efficient in solving the size and shape optimization of this structure with multiple natural frequency constraints.

Figure 4 shows the final configuration obtained in this paper.

Table 6. Statistical results for the simply supported 37 bar truss for 5 independent runs

Mean mass (kg)	**Standard deviation (kg)**	**Coefficient of variation (%)**	**Number of searches**
362.6273	0.9291	0.26	20000

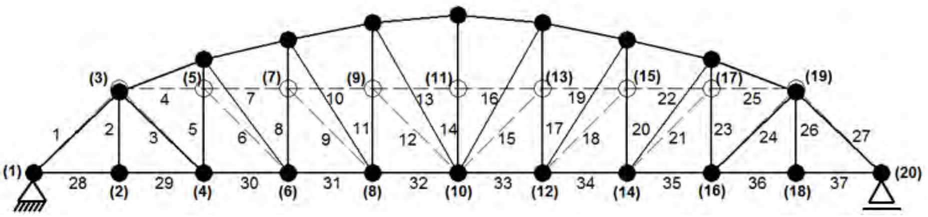

Figure 4. Final configuration design optimized by the present paper

3.2 25-bar space truss

The second case is the 25-bar space truss, shown in Fig. 5. In this example is performed size optimization, where the design variables are the areas of cross sections of the bars. The constraints are the stresses and displacements. The material properties are showed in Tab. 6.

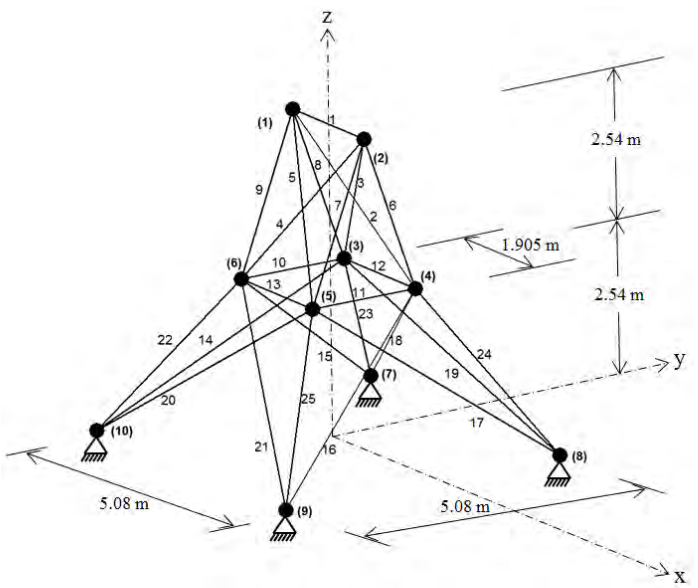

Figure 5. Configuration of 25-bar space truss

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Table 6. Material properties for the 25-bar space truss

Property	**Value**	**Unit**
Material	Aluminum	–
E – Young's modulus	68.95×10^9	N/m^2
ρ – Specific mass	2767.99	kg/m^3

The truss is subjected to two distinct loading conditions and has eight independent design variables after linking, as indicated in Tab. 7. The loadings, allowable and optimum design are shown in Tab. 8 to 10, respectively.

Table 7. Member linking detail for the 25 bar truss

Group	**Elements**
1	1
2	2 – 5
3	6 – 9
4	10 – 11
5	12 – 13
6	14 – 17
7	18 – 21
8	22 – 25

Table 8. Nodal load components for 25 bar truss

Load (kN)				
Case	**Node**	**x**	**y**	**z**
1	1	4.4482	44.482	-22.241
	2	0	44.482	-22.241
	3	2.2241	0	0
	6	2.2241	0	0
2	1	0	88.964	-22.241
	2	0	-88.964	-22.241

Table 9. Allowable for the 25-bar space truss

Constraints	
Stress (MPa)	
Tension stress for all members	275,79
Compression stress for Group 1	-241,95
Compression stress for Group 2	-79,91
Compression stress for Group 3	-119,31
Compression stress for Group 4	-241,95
Compression stress for Group 5	-241,95
Compression stress for Group 6	-46,60
Compression stress for Group 7	-47,98
Compression stress for Group 8	-76,41
Displacements	
±8,89 mm in x, y and z directions for 1 and 2 nodes	
Range of the design variables	
$6.45\ mm^2 \leq A_i \leq 2000\ mm^2$	

Figure 6 shows the convergence curve for this problem subject to stress and displacement constraints. A total of fifty thousand iterations were performed.

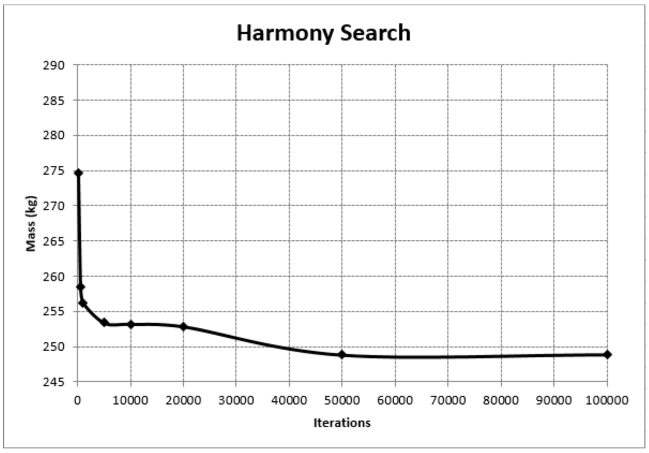

Figure 6. Convergence curve for the 25-bar space truss

This problem was also studied by Lee and Geem, 2004, using the *Harmony Search* (*HS*); Farshi and Alinia-ziazi, 2010, using the *Method of Centers and Force Formulation*; Sonmez, 2011, using the *Artificial Bee Colony* (*ABS-AP*) and Degertekin, 2012, using the *Self Adaptive Harmony Search* (*SAHS*). In this paper, *Harmony Search* (*HS*) is used to solve size optimization with stress and displacement constraints. The optimal design obtained in this paper and the comparison with results of the other authors cited above are shown in Tab. 5. The result obtained by Lee and Geem, 2004, was the best of all the methods proposed in the literature, followed by Degertekin, 2012, Sonmez, 2011, and Farshi and Alinia-ziazi, 2010. HS obtained the worst results. Note that the result obtained in this paper is compared with another author who also uses the same algorithm (Lee and Geem, 2004), but the results obtained by the first author are not as good as the ones obtained by the second ones. This occurs because the optimization methods are based on probabilistic algorithms and not deterministic ones.

Table 10. Optimum design for the 25-bar space truss

ALGORITHM			***HS***	***Method of Centers***	***ABS-AP***	***SAHS***	***Harmony Search***
AUTHOR			**Lee and Geem (2004)**	**Farshi and Alinia-ziazi (2010)**	**Sonmez (2011)**	**Degertekin (2012)**	**Present paper**
Design Variables	Cross Sectional Areas (cm^2)	G1	0.3032	0.0645	0.0710	0.0645	0.2007
		G2	13.0459	12.8917	12.7685	13.3814	12.4090
		G3	19.0334	19.2450	19.3754	19.1044	19.6250
		G4	0.0645	0.0645	0.0645	0.0645	0.0808
		G5	0.0903	0.0645	0.0645	0.0645	0.5158
		G6	4.4390	4.4112	4.4519	4.4583	4.7427
		G7	10.6910	10.8071	10.8329	10.4329	11.0650
		G8	17.1817	17.2062	17.1107	17.2526	16.8040
Mass (kg)			**246.9266**	**247.3757**	**247.2954**	**247.2623**	**248.82**

And it is important to point out that using HS, none of the stress and displacement constraints were violated.

The statistical results of five independent simulations, presented in Tab. 7, show a small standard deviation from the mean value, showing that the method is efficient in solving the size optimization of this structure with stress and displacement constraints.

Table 11. Statistical results for the 25-bar space truss for 5 independent runs

Mean mass (kg)	**Standard deviation (kg)**	**Coefficient of variation (%)**	**Number of searches**
249.0766	0.3556	0.14	50000

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3.3 Adapted Design

Based on the results obtained previously, confirming the efficiency of the studied algorithm, is made an innovation proposing the optimization of a new structure, *i.e.*, the HS will now be applied to the structure optimization of a configuration different from those found in the literature, a structure of an adapted realistic design.

The structure is the simply supported 124-bar space truss with initial configuration shown in Fig. 7. Size and shape optimizations are performed to minimize its mass, where the design variables are the areas of cross sections of the bars and the coordinates of the nodes that can move. The design constraints are the stresses, displacements, buckling and natural frequencies. The material properties of the truss are shown in Tab. 12.

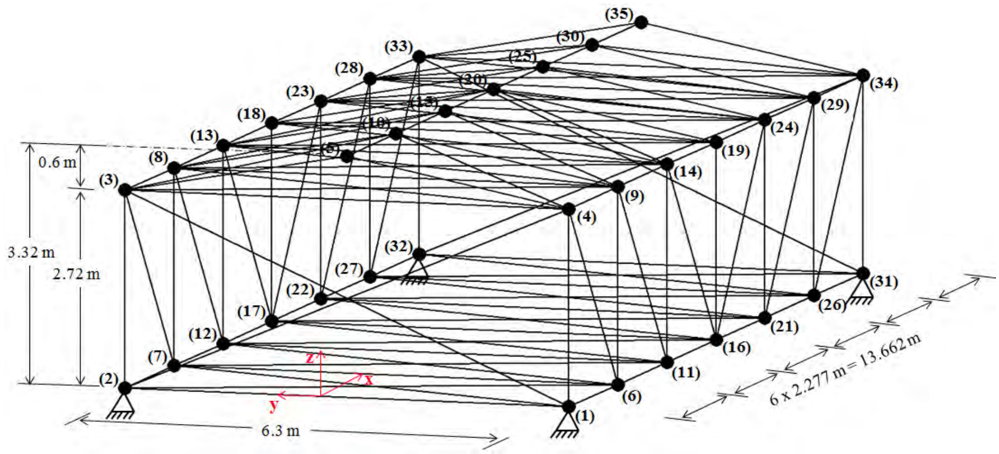

Figure 7. 124-bar space truss

Table12. Material properties for 124-bar space truss

Property	Value	Unit
Material	Steel A36	–
E – Young's modulus	210 x 10^9	N/m^2
ρ – Specific mass	7800	kg/m^3

All the nodes of the structure receive vertical loads (z) and transversal horizontal loads (y), and no load is applied to the longitudinal horizontal direction (x). Load values correspond to the critical combination of design, from the self-weight loads, wind, attached elements and equipment. The bars are arranged in fifteen groups and nodal coordinates are grouped in five groups, to ensure symmetry of the structure. For the size variables, the area of each group corresponds to an independent variable; for shape variables, the coordinates of the nodes in each group are equivalent to an independent variable. The nodes of the upper chords (3, 8, 13, 18, 23, 28, 33, 4, 9, 14, 19, 24, 29, 34) can move both in vertical direction (z) and in the cross horizontal direction (y), while the central nodes (5, 10, 15, 20, 25, 30, 35) can move only in the vertical direction (z).So, in total there are twenty design variables in the problem, fifteen size variables relating to the areas of cross sections of bars groups, and five shape variables, corresponding to the coordinates of node groups.

The way that the limits for the shape variables were defined is illustrated in Fig. 8. The nodes of the upper chords, left and right, when they represent a displacement in the cross horizontal direction (y), can move at most 1 m. When the displacement is in the vertical direction (z), these same nodes as well as the central nodes of the upper chord, are limited to a height of 1.75 m. These values were defined in terms of equipment and movement of persons within the structure.

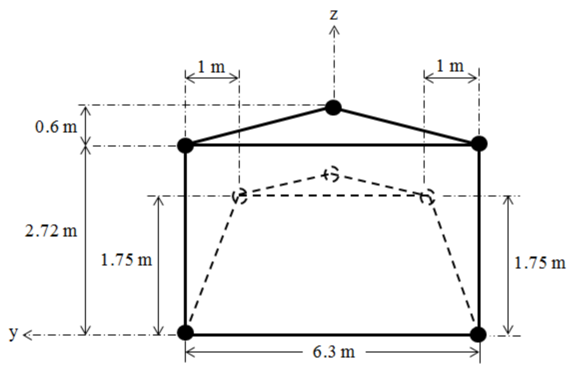

Figure 8. Limits for the nodal coordinates (front view)

For the stress constraint, all groups have the same limit for the tensile stress and the compressive stress, which is the yield stress for the ASTM A36 steel. For displacement constraint, all nodes of the structure are restricted in the directions ±x, ±y and ±z. The used limit is the factor L/300, where L is the span length between supports of the truss. The minimum area permitted for the cross section of the bar is 100 mm^2, value obtained from a catalog of commercial profiles. The buckling constraint is implemented according to Euler's equation, used by Lee and Geem, 2005. For the natural frequency constraint was used a range of values in which a particular equipment installed in the structure will operate, *i.e.*, we must avoid that the structure presents values of natural frequencies within the frequency band that the equipment will operate. Therefore, in total there are 246 constraints.

The load components used are specified in Tab. 13; the group of size and shape variables and the bars connectivities are shown in Tab. 14; and the allowable values for the stress, displacement and frequency constraints, as well as the lower and higher limits for the design variables can be seen in Tab. 15.

Table 13. Load components for 124-bar space truss

Node	**Load (kN)**		
	x	**y**	**z**
1, 6, 11, 16, 21, 26, 31	0	10	-30
2, 7, 12, 17, 22, 27, 32	0	0	-30
3, 8, 13, 18, 23, 28, 33	0	0	-20
4, 9, 14, 19, 24, 29, 34, 5, 10, 15, 20, 25, 30, 35	0	10	-20

Table 14. Nodal coordinates and bars groups, and element connectivities

Design variables		
Nodal coordinates		
Y3 = Y8 = Y13 = Y18 = Y23 = Y28 = Y33 = Y4 = Y9 = Y14 = Y19 = Y24 = Y29 = Y34		
Z3 = Z33 = Z4 = Z34		
Z8 = Z28 = Z9 = Z29		
Z13 = Z23 = Z14 = Z24		
Z18 = Z19 = Z20		
Cross sectional areas	**Elements**	**Connectivities**
Group 1	1:4	1-4, 2-3, 31-34, 32-33
Group 2	5:6	2-1, 32-31
Group 3	7:8	3-4, 33-34
Group 4	9:20	1-6, 6-11, 11-16, 16-21, 21-26, 26-31, 2-7, 7-12,12-17,17-22, 22-27, 27-32
Group 5	21:32	3-8, 8-13, 13-18, 18-23, 23-28, 28-33, 4-9, 9-14, 14-19,19-24, 24-29, 29-34
Group 6	33:37	7-6, 12-11, 17-16, 22-21, 27-26
Group 7	38:42	8-9, 13-14, 18-19, 23-24, 28-29
Group 8	43:52	7-8, 12-13,17-18,22-23, 27-28, 6-9, 11-14, 16-19, 21-24,26-29
Group 9	53:64	2-6, 1-7,7-11, 6-12, 12-16, 11-17, 17-21, 16-22, 22-26, 21-27,27-31, 26-32
Group 10	65:76	3-9, 4-8, 8-14, 9-13, 13-19, 14-18, 18-24, 19-23, 23-29,24-28, 28-34, 29-33
Group 11	77:88	3-7, 8-12, 13-17, 17-23, 22-28, 27-33, 4-6, 9-11, 14-16,16-24, 21-29, 26-34
Group 12	89:92	1-3, 2-4, 31-33, 32-34
Group 13	93:106	3-5, 5-4, 8-10, 10-9, 13-15, 15-14, 18-20, 20-19, 23-25, 25-24, 28-30, 30-29, 33-35, 35-34
Group 14	107:112	5-10, 10-15, 15-20, 20-25, 25-30, 30-35
Group 15	113:124	3-10, 10-4, 8-15, 15-9, 13-20, 20-14, 23-20, 20-24, 28-25,25-29, 33-30, 30-34

Table 15. Stress, displacement and natural frequencies constraints

Constraints	
Stress	
Group	**Value**
All groups	±250 MPa
Displacement	
Node	**Value**
All nodes	±45.54mm (x, y e z)
Natural frequency	
$f_1 \leq 15.00$ Hz; $f_2 \geq 20.00$ Hz	
Range of the design variables	
$100\ mm^2 \leq A_i \leq 10000\ mm^2$	

Figure 9 shows the convergence curve for this problem subject to the constraints of stress, displacement, buckling, and natural frequency. Ten thousand iterations were used.

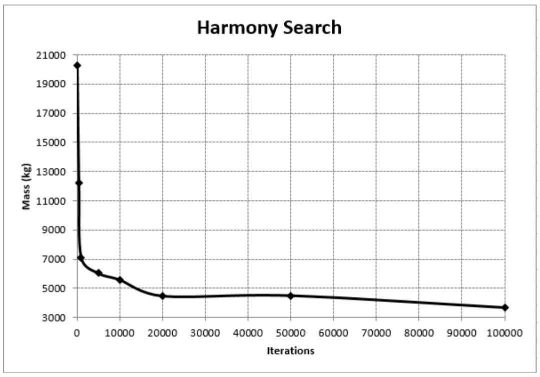

Figure 9. Convergence curve for the 124-bar space truss

The optimal design obtained is shown in Tab. 16. The initial structure has a mass value of 9347.49 kg. The algorithm was able to optimize the structure of significant manner, of which about 42% of the mass of the initial structure.

Table 16. Optimum design for the 124-bar space truss from various methods

ALGORITHM			Initial	*Harmony Search*
Design variables	Nodal coordinates (m)	Z3	2.720	1.8376
		Z8	2.720	1.8618
		Z13	2.720	1.9081
		Z18	2.720	2.6674
		Y3	3.150	2.9859
	Cross sectional areas (cm^2)	G1	101.20	9.8550
		G2	36.60	5.7118
		G3	36.60	1.0775
		G4	23.40	10.6810
		G5	23.40	19.1050
		G6	36.60	13.1120
		G7	23.40	3.2661
		G8	23.40	10.0130
		G9	18.58	13.5970
		G10	18.58	5.4041
		G11	15.34	11.3480
		G12	15.34	10.1720
		G13	23.40	9.9998
		G14	23.40	27.7490
		G15	15.34	8.0196
Mass (kg)			**9347.49**	**3938.85**

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Table 17. Optimum design of natural frequencies (Hz) for the 124-bar space truss.

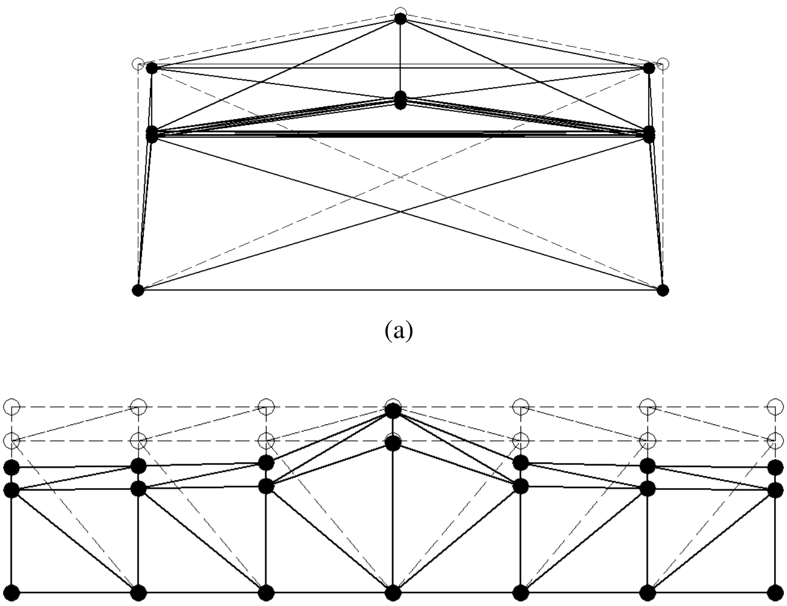
ALGORITHM		Initial	*Harmony Search*
Natural frequencies (Hz)	1	17.8808	14.5099
	2	19.3012	20.4853
	3	26.2337	21.0175
	4	31.0374	26.0924
	5	35.7826	26.4399

The statistical results of three independent simulations show a value of standard deviation to average value larger than in benchmarks examples of 28.27%.

Table 18 – Statistical results for the 124-bar space truss for 3 independent runs of HS

Mean mass (kg)	**Standard deviation (kg)**	**Coefficient of variation (%)**	**Number of searches**
4774.4	1349.8	28.27	100000

Figure 10 shows the final configuration of the 124-bar space truss optimized in this paper.



(a)

(b)

Figure 10. Final configuration of 124-bar space truss: (a) frontal view; (b) lateral view

4. CONCLUSIONS

This paper studied one of the most modern and broadcast meta-heuristic algorithms, random optimization algorithms that are non-gradient probabilistic methods. They use only the evaluation of the objective function. This method is the Harmony Search Algorithm (HS), which is a music-based metaheuristic optimization algorithm, in the musician's improvisation process.

In order to prove the efficiency of the method, it was applied to benchmarks, used as a reference for comparison with results of other authors and methods already established in the literature. Plane and space trusses were analyzed. Size and shape optimization were performed, subject to the constraints of stress, displacement, buckling, natural frequency and minimum and maximum areas. The design variables were the areas of cross sections of the bars and the position of the nodes. Finally, the method was applied to optimization of a structure adapted from a realistic design, designed and built without the use of optimization techniques. The results obtained in relation to the problems patterns showed that the method is better or as good as the algorithms proposed by other authors, if not overcome them, the results are very similar, with small differences compared to the best results. The convergence curves showed that the algorithm converges to an optimal solution, and statistical analysis proved small standard deviations and coefficients of variation. The results for the adapted structure showed a significant result in reducing its mass. In all problems analyzed the restrictions were respected. Therefore, the Harmony Search represents a powerful tool for solving size and shape optimization problems, applied to different plane and space truss structures, and with different types of constraints, imposed separately or simultaneously.

5. ACKNOWLEDGEMENTS

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7. RESPONSIBILITY NOTICE

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