XLI CILAMCE
XLI Ibero-Latin American Congress on Computational Methods in Engineering
16-19 November, 2020 FOZ DO IGUAÇU PARANÁ - BRAZIL

DEVELOPMENT OF A WOODEN TRUSS OPTIMIZATION SOFTWARE BY THE HARMONY SEARCH METHOD

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Abstract. The optimization algorithms are efficient tools for structural design, reaching optimal solutions for a given problem through a systematic search method. In this way, the engineer is able to design technically viable structures that have the lowest cost, regardless of their previous experience. The Harmony Search method is a heuristic that makes an analogy to the musical improvisation of jazz, where musicians generate from their own memory new combinations of notes among instruments, looking for the perfect harmony. This paper shows the development of a software in C# that perform the structural analysis of isostatic plane trusses and, thereafter, the parametric optimization of the structure, using the Harmonic Search process. In order to reduce the cost, the objective function is the truss weight, which should be minimized by determining the optimum base dimensions and height of the cross section. To ensure that the solution is feasible, the constraints imposed by the revision version of Brazilian code ABNT NBR 7190/2013 must be met. The parameters of the optimization algorithm were studied, seeking a better calibration to the specific problem of this research. To validate the program, wooden gable roof structures are tested.

Keywords: Software, Plane trusses, Wood, Optimization, Harmony search.

1 Introduction

Wood is one of the oldest building materials used in civil construction and has a wide range of applications due to its mechanical characteristics, abundance in nature, versatility, ease of handling and great durability when correctly treated. Its structural uses can vary from wood frame houses and roofs to bridges, and due to its characteristics, the structures in which it is applied are usually trusses, allowing it to overcome large spans and withstand heavy loads with a low self-weight. Besides that, Zubizarreta et al [1] shows that timber is a renewable, recyclable and its production process is energetically efficient, making it an environmentally friendly construction material.

When designing a structure, the engineer seeks for the cheapest one while bearing the loads, which is done by a slow trial and error method, based on the previous experiences of the designer. For the same project situation, there are many possible solutions, and this number grows as the complexity of the problem increases. In these cases, structural optimization algorithms can be a powerful tool, finding the best solution in a more efficient way. The optimization methods can be mathematical or heuristic, the second being best with engineering problems, as the functions involved usually are discontinuous, not convex and have several local minimum or maximum points.

Among the heuristics, the Harmony Search is one of the methods that have been bringing good results. Originally proposed by Geem, Kim and Loganathan [2], the algorithm is inspired by the jazz musical improvisation process, where the musicians propose a new combination between notes of each instrument seeking for the best harmony, through repeated attempts or from their previous knowledge. In this analogy, the instruments represent the problem variables that, when combined in the best possible way, takes to the perfect harmony, which is the global optimum point.

This paper presents the implementation of constraints imposed by the revision version of Brazilian code ABNT NBR 7190/2013 [3] in a previously developed software, which performs the structural analysis of plane trusses and optimizes them with the Improved Harmony Search algorithm. The code was written in C# language, and it has a graphic interface where the user inputs the coordinates of nodes, material and section properties of bars, loads and supports.

In order to verify its efficiency, a wooden roof truss was optimized and the results were manually calculated in order to make sure it was a feasible solution, meeting the problem constraints. Two parameters of the method, the harmony memory size (HMS) and the harmony memory consideration rate (HMCR) were studied to determine the values that results in better solutions to the problem of this paper.

2 Improved Harmony Search Method

The original algorithm of the Harmony Search is an iterative process where an initial set of solution is proposed and then is compared with the new solution generated in each iteration, discarding the worst and keeping the best, until the stopping criterion is met. As Medeiros [4] shows, it can be described in five steps, as it follows.

1. Problem and parameters startup: is characterized by the definition of the objective function, restraints and parameters of the algorithm. The main ones are the harmony memory size (HMS), harmony memory consideration rate (HMCR), pitch adjustment rate (PAR), bandwidth (bw) and the maximum number of improvisations (MI).

2. Harmony memory initialization: it is where the first solution is created, whether randomly between an interval or given by the user. The harmony memory (HM) is a matrix where each line represents a solution vector, with the number of lines equal to HMS and the number of columns equal to the number of variables (N).

3. New harmony improvisation: this step is based on the HMCR and PAR. A random number between 0 and 1 is generated and, if it is higher than HMCR, the new solution will be generated randomly. If it is lower, another random number will be generated and, if it is lower than PAR, the new harmony will be created from a solution in HM, applying a fine adjustment based on bw.

4. Harmony memory update: in this step, the new harmonies are compared with those already in HM. It will replace the worst solution in the HM if it is better.

5. Checking the stopping criterion: After each iteration, the stopping criterion is checked. If it is true, the algorithm is finished, otherwise, the third and fourth steps are repeated, until the criterion is meet. In the case of the present paper, this criterion is the limit of improvisations, which is equals to MI.

Since its publication, many suggestions for changes to the method have been proposed in order to improve is results. Mahdavi, Fesanghary e Damangir [5] proposed the Improved Harmony Search, where the PAR and bw parameters dynamically over the generation, within a maximum and minimum limit. While PAR is linearly increased with the iterations, bw decreases exponentially, as shown in Figure 1.

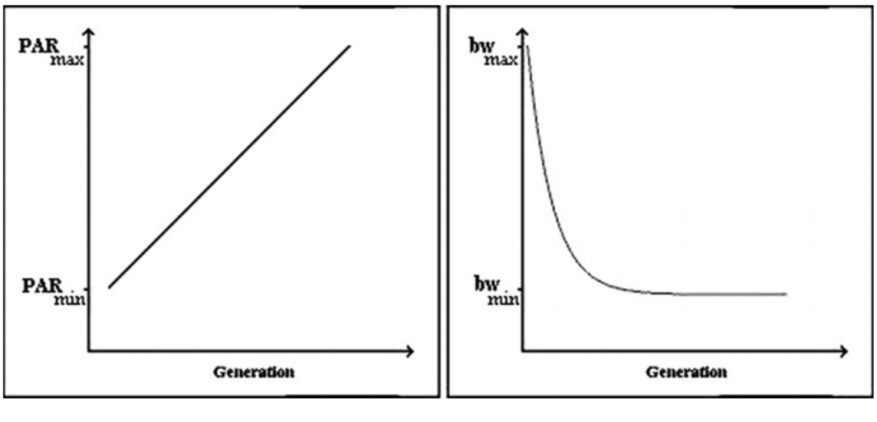

Figure 1. Variation of PAR and bw versus generation number (Mahdavi, Fesanghary and Damangir [5])

The method efficiency and popularity are attested in several recent optimization papers. Kaveh and Ghafari [6] optimized the geometry of steel roofing structures using nine different heuristic methods, where the Harmony Search was among the three that presented the best results. Vargas [7] used the method to optimize roof trusses, considering different topologies. It is worth mentioning other recent works that used the Harmony Search algorithm and its improved version to optimize trusses, such as Ouedraogo [8], Kayabekir et al [9], Mirza [10] and Marafi [11].

3 Problem Description

Initially, in order to obtain the stresses acting on the structure, the software under development performs the structural analysis using the displacement. Due to the possibility of applying this method in a matrix form, its implementation as a computer algorithm is done in an easy way, calculating the stresses of the bars from a linear plastic analysis.

For the purpose to achieve the structure with the lowest cost, the objective function is the truss self-weight, which should be minimized. It can be represented mathematically as minimize

$$f(x) = W = \sum_{i=1}^{n} \rho_i A_i L_i, \tag{1}$$

where W is the structure weight, ρ_i is the specific weight of bar material, A_i is the cross-section area and L_i represents the bar length. The variables used in the problem were the base and height dimensions of the bars cross section, later used to determine the area of the elements.

The problem constraints are those imposed by the Brazilian code ABNT NBR 7190/2013 [3], and to ensure that the solution is feasible, they must be strictly met. When the bar is under tensile stress, the following inequation must be true:

$$1 - \frac{\sigma_{t0,d}}{f_{t0,d}} \geq 0, \tag{2}$$

where $\sigma_{t0,d}$ is the tensile stress in the bar and $f_{t0,d}$ is the admissible tensile stress, calculated according to the same rule. To compressed bars, the constraint is

$$\frac{\sigma_{c0,d}}{k_c \cdot f_{c0,d}} + \frac{\sigma_{Md}}{f_{c0,d}} \geq 0, \tag{3}$$

where $\sigma_{c0,d}$ is the compressive stress, k_c is a coefficient calculated from the bar relative slenderness, $f_{c0,d}$ is the admissible compressive stress and σ_{Md} represents the bending stress created by accidental eccentricity.

Beyond that, there are also minimum cross-section area and slenderness constraints as shown in eq. (4) and eq. (5), respectively:

$$A_i \geq 50cm^2 \tag{4}$$

$$\lambda_{x,y} = \frac{L_i}{r_{x,y}} \leq 140, \tag{5}$$

where $\lambda_{x,y}$ is the slenderness and $r_{x,y}$ is the radius of gyration, both for x and y axis.

The truss to be optimized is a gable roof structure of a fictional industrial shed, 14 meters wide and 33 meters long, with 15° roof slope. The loads applied were calculated according to ABNT NBR 6120/2019 [12], ABNT NBR 8681/2003 [13], and the wind action was determined using ABNT NBR 6123/1988 [14]. It was used the critical load combination, which happens to the suction generated by the wind load acting at 0° to the building. Figure 2 shows the structure and the loads, as well as the numeration of the bars used.

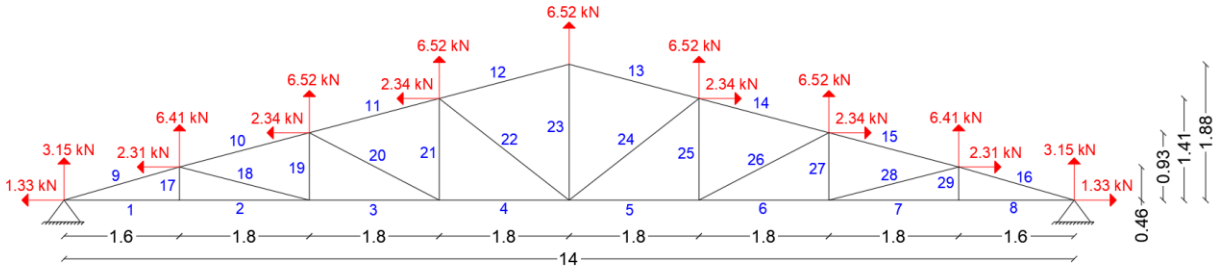

Figure 2. Gable roof structure to be optimized

The optimization algorithm is executed until the limit of improvisations is reached. The value of it and some others parameters of the Improved Harmony Search used in this paper are shown in Tab. 1. Another two of them, HMS and HMCR, were part of a study to calibrate parameters, as described in the results and discussion chapter. The first parameter tested was HMS, and after finding the value that led to best results and fixing it, the same was done with HMCR. The values that base and height dimensions can assume were predetermined from a database that starts with 5 cm and goes up to 30 cm, varying every 2.5 cm.

Table1. Parameters values

Parameter	Value
MI	7,500
$bw_{mín}$	2
$bw_{máx}$	5
$PAR_{mín}$	0.5
$PAR_{máx}$	0.9

4 Results and Discussion

After setting the HMS and HMCR parameters at 5 and 0.9 respectively, the problem was optimized again running 5 more tests. Thus, the final result was reached, with a total self-weight of 386.84 kgf and dimensions as presented in Tab. 2. As may be observed, even though the geometry and the loads of the structure are symmetrical, the sections of symmetrical bars do not have the same dimensions. This indicates that the result could still be improved by increasing MI or calibrating the method’s parameters. Another possible solution to this could be the grouping of symmetric bars in the optimization algorithm, assigning them the same dimensions, which would also reduce the number of variables of the problem. Another important point to take notice is that the joints between adjacent bars would become extremely difficult or even impossible to implement in practice. Thus, it is clear the importance of taking into account these aspects in order to obtain a viable structure.

Table 2. Dimensions of the best solution

Bar	Base (cm)	Height (cm)
1	5	22.5
2	7.5	17.5
3	7.5	10
4	5	27.5
5	7.5	30
6	7.5	12.5
7	12.5	12.5
8	5	30
9	10	22.5
10	5	25
11	7.5	17.5
12	5	25
13	5	20
14	7.5	22.5
15	15	15
16	7.5	25
17	7.5	15
18	7.5	7.5
19	5	12.5
20	7.5	27.5
21	5	15
22	10	10
23	15	17.5
24	10	12.5
25	7.5	10
26	7.5	10
27	5	12.5
28	5	10
29	7.5	30

The parameter adjustment study of the Harmony Search optimization method for the problem developed is described in the sequence.

The first parameter studied was HMS, one of the most influential in the method effectiveness. The tested values were 5, 10, 20, 50 and 100. For each one, the optimization was run 5 times, and the medians of the results were used for comparison. For this initial test, the value adopted for HMCR was 0.9. Figure 3 shows the results for each, where HMS = 5 was the best for this problem. It is also possible to notice the great variation in the weight of the structure for each value, with a difference of 95.01 kgf, representing 18.33%.

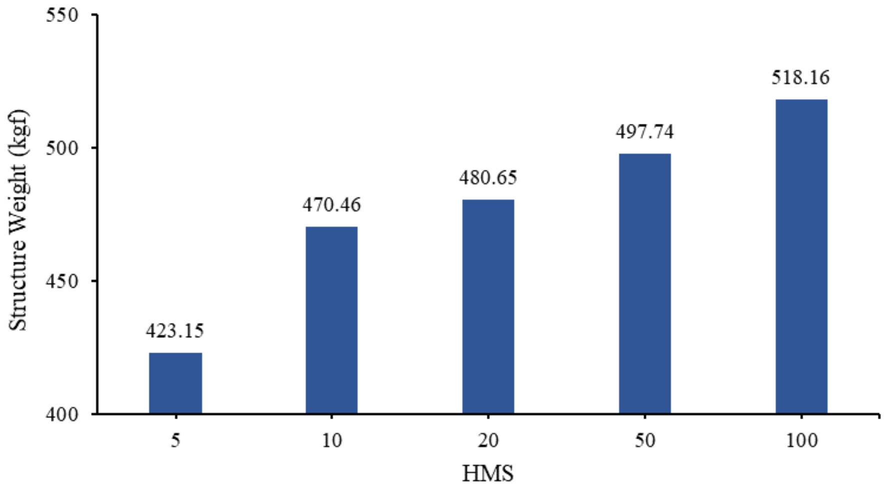

Figure 3. Structure weight for each HMS value

Using HMS = 5, the same procedure was done to the HMCR. It was used 0.5, 0.6, 0.7, 0.8 and 0.9 as possible values for it. The results are shown in Fig. 4, where HMCR = 0.9 achieved the best results. Again, the variation in weight is noticeable, with a difference of 141.41 kgf, or 25.22%.

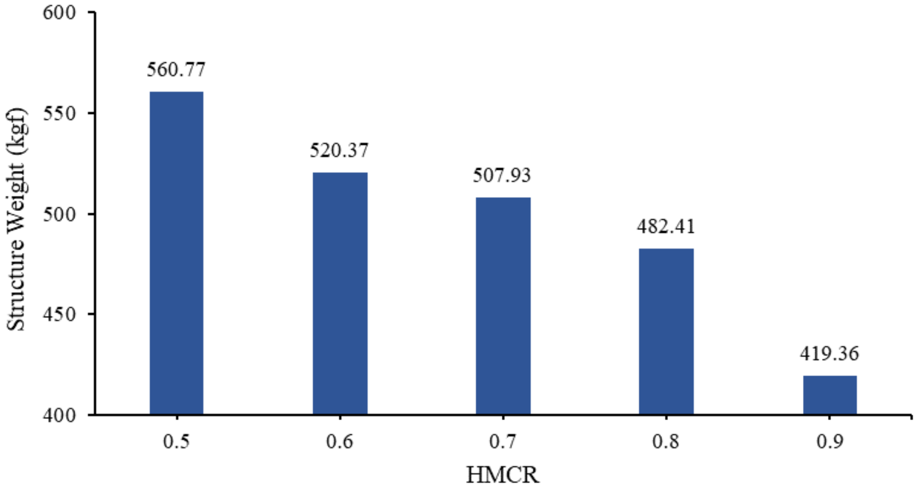

Figure 4. Structure weight for each HMCR value

5 Conclusions

The developed software was able to achieve feasible solutions using structural optimization by the Improved Harmony Search algorithm, reaching results that meet the constraints of the Brazilian code ABNT NBR 7190/2013 [3]. From the model tested, it was possible to study and adjust some of the important parameters of the method, which have a great influence on the solutions obtained and, consequently, on the efficiency of the method. The obtained results showed that the variation in the values of the objective function for each value of the studied parameters can be very significant, showing the importance in their correct calibration. For the specific problem of this paper, the best values for harmony memory size (HMS) and harmony memory consideration rate (HMCR) are 5 and 0.9, respectively. Using these values, it was possible to reach a weight of 386.84 kgf for the structure. However, the result could be improved by increasing the maximum number of improvisations (MI) and calibrating the remaining parameters.

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References

[1] M. Zubizarreta et al, “Modeling the environmental sustainability of timber structures: a case study”. *Environmental Impact Assessment Review*, vol. 78, 2019.
[2] K. S. Lee, Z. W. Geem and G. V. Loganathan, “A new heuristic optimization algorithm: Harmony Search”. *Simulation*, vol. 76, n. 2, pp. 60-68, 2001.
[3] ABNT, NBR 7190. *Projeto de estruturas de madeira*. Rio de Janeiro, 2013.
[4] G. F. Medeiros. *Método da busca harmônica aplicado na otimização de seções de pilares retangulares em concreto armado considerando custos econômicos e ambientais*. Master’s thesis, Universidade de Passo Fundo, 2012.
[5] M. Mahdavi, M. Fesanghary and E. Damangir, “An improved harmony search algorithm for solving optimization problems”. *Applied Mathematics and Computation*, vol. 188, n.2, p. 1567-1579, 2007.
[6] A. Kaveh and M. H. Ghafari, “Geometry and sizing optimization of steel pitched roof frames with tapered members using nine metaheuristics”, *Iranian Journal of Science and Technology, Transactions of Civil Engineering*, vol. 43, pp. 1-8, 2019.
[7] G. D. Vargas. *Otimização de treliças metálicas empregadas em galpões através do algorítmo harmony search*. Undergraduate thesis, Universidade Federal do Rio Grande do Sul, 2018.
[8] P. J. De D. Ouedraogo. *Artificial bee colony (ABC), harmony search (HS) and particle swarm optimization (PSO) based discrete and continuous optimum design of steel trusses*. Master’s thesis, Karadeniz Technical University, 2018.

[9] A. E. Kayabekir et al, "A novel hybrid harmony search approach for the analysis of plane stress systems via total potential optimization". *Applied Sciences*, vol. 10, 2020.
[10] M. Mirza. *Optimization of truss structures using harmony search algorithm*. Master's thesis, Temple University, 2020.
[11] A. Marafi. *Optimization of steel moment frame using harmony search algorithm.* Temple University, 2020.
[12] ABNT, NBR 6120. *Cargas para o cálculo de estruturas de edificações*. Rio de Janeiro, 2019.
[13] ABNT, NBR 8681. *Ações e segurança nas estruturas - procedimento*. Rio de Janeiro, 2003.
[14] ABNT, NBR 6123. *Forças devidas ao vento em edificações*. Rio de Janeiro, 1988.