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MULTICRITERIA DECISION-MAKING METHOD APPLIED TO OPTIMIZED REINFORCED CONCRETE, STEEL, AND WOOD BEAMS

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ABSTRACT

Optimization techniques have been increasingly used to obtain structures of lower cost or weight. However, the result obtained depends on the choice of materials. This can be based on factors such as cost, performance, and environmental impacts, as well as subjective aspects such as the cultural issue. This work adopts a multicriteria decision method to compare optimized reinforced concrete, steel, and wood beams to subsidize the choice of the best material. The criteria adopted were weight, height, cost, environmental impact, and culture. For this analysis, beams of the three materials were optimized to minimize cost and impact, considering the same loading and spans. The results were evaluated using the Analytical Hierarchical Decision Method (AHP). It was observed a great influence of cost and culture in the choice of a material favoring the wooden beam for the smallest span and the reinforced concrete beam for the largest span studied.

Keywords: Structures. Beams. Optimization. Decision making. AHP method.

1. INTRODUCTION

Optimization techniques have been increasingly used to obtain structures of lower cost or weight. However, the result obtained is directly dependent on the choice of materials, which must precede the structural design. This choice may be based on tangible factors such as cost, performance, and possible environmental impacts produced, as well as aspects of greater subjectivity such as the dominant culture in the region. In this sense, a way of selecting the best alternative based on several criteria can be the use of decision-making techniques (Variani & Kripka, 2021).

Dimensioning with the aid of optimization, in structural engineering, means looking for a structure that presents the best performance through the rational use of available resources. The engineer's choices directly influence the general expenses of the work, the expenses with raw materials, excessive losses, and also a consequent negative environmental impact.

The practical use of optimization is usually carried out considering a single objective, taking into account design practices and regulatory restrictions. Considering that different objectives and criteria can lead to conflicting solutions, the association of optimization techniques with Multicriteria Decision Making Methods (DMM) can lead to interesting and nonconventional results.

The present work aimed, at first, to optimize beams made of reinforced concrete, steel, and wood, seeking to minimize costs and environmental impact, separately. Afterward, the same structures were confronted regarding the criteria weight, height, cost, environmental impact, and culture, with the aid of the Analytical Hierarchical Method (AHP), aiming to subsidize the choice of the best material among the established criteria.

Several studies can be found in the technical literature related to the optimization of beams made of reinforced concrete (Garcia-Segura et al., 2014; Rahmanian et al., 2014; Kripka et al., 2014; Santoro & Kripka, 2020), steel (Drehmer, 2005) or mixed steel-concrete (Tormen et al, 2020). However, to the best of the authors' knowledge, few studies have been developed comparing the results of the optimized design of structures composed of different materials. Merta et al. (2008), compared reinforced concrete and steel beams, considering their selfweight, height, and cost. Ozimboski et al (2020) developed a similar study, considering more than one characteristic strength of concrete. Zula and Kravanja (2018) compared a beam optimized for concrete, steel, and wood, aiming to minimize the cost and environmental impact, in isolation. The use of multicriteria decision methods (AHP and TOPSIS) was carried out by Kripka et al (2019) for the selection of reinforced concrete bridge designs, precast concrete, and mixed steel-concrete structures. Finally, Variani and Kripka (2021) compared a cubic meter of concrete, steel, and wood according to criteria such as cost, strength, self-weigh, and culture, evaluating the alternatives with the aid of the AHP method. However, as the amount of material (and, consequently, the cost) is directly dependent on the strength, it is understood that a valid comparison must be associated with the optimization of the structural elements.

The present work is structured as follows. The first section presents the motivation for the study and the objectives of the work. The second section describes some concepts related to multicriteria analysis, with emphasis on the AHP method, in addition to basic concepts of structural optimization. The third section presents the formulations for the optimization problems, as well as the data and the optimization results for the considered objectives. In the fourth section, the multicriteria decision method is applied. The results of the sensitivity analysis are also presented, considering scenarios arising from the disregard of the cultural criterion, the variation in the characteristic strength of concrete, and the possible use of glue-laminated beams to replace sawn wood. Finally, the last item lists the main conclusions obtained in the study.

2. BASIC CONCEPTS

2.1. *Analytic Hierarchy Process* (AHP)

The measurement of intangible factors consists of a big challenge (Saaty, 2008). In this sense, multicriteria decision methods can be a valuable tool, especially in the presence of conflicting objectives. The Analytic Hierarchy Process (AHP) is one of the most popular multicriteria decision methods (Lee et al, 2020; Neves et al, 2022), and has been applied to several distinct objectives (Spak et al., 2022). Its objective is to select the best alternative among a group of alternatives that compete with each other, based on predefined criteria.

The AHP Method, created in 1980 by Thomas Saaty, allows the use of both quantitative and qualitative criteria, decomposing the problem into hierarchical levels and making a paired comparison, to express the importance of one over criterion the other and, finally, evaluating the relative superiority of one alternative.

The application of the method can be decomposed into three distinct steps, starting with the hierarchical construction, passing through the construction of decision matrices based on the fundamental scale, and ending with the verification of the consistency ratio.

-Hierarchical Construction: this step comprises a hierarchical structure separated into three distinct levels, the first level being the preferable alternative, that is, the objective of the problem, the second corresponding to the presented alternatives, and the third to the criteria established for comparison.

-Construction of Decision Matrices: in this step, a matrix for data analysis and comparison is created, including the criteria that must be compared in pairs, and to which relative importance is attributed according to the *Fundamental Saaty Scale*. In this scale, which varies from 1 to 9, intensity 1 indicates the same importance for both criteria, and 9 is the maximum value of importance that one criterion can have over another, from the decision-makers point of view. With the help of the matrix, it is possible to assign relative importance values to all criteria.

-Obtention of the Consistency Ratio (RC): the consistency ratio is responsible for evaluating whether the comparison among criteria or alternatives was performed consistently by the decision-maker, without presenting nonconformity or inconsistency in values.

2.2. Structural optimization

Optimization consists of obtaining the best solution for a mathematically defined problem, which is often the modeling of a physical problem, satisfying certain conditions. In the field of structures, optimization is usually applied to find the minimum cost or weight of beams, columns, slabs, frames, or trusses. The conditions to be met, known as constraints, are defined by standards that govern the practice of structural design, including limits on stresses and displacements and constructive limitations.

The formulation of the problem, in which the objective, variables, and constraints are defined, constitutes a fundamental step of the process, once only with the construction of an adequate model is it possible to represent the real behavior of the considered system.

Thus, an optimization problem can, in general, be described as the minimization (or maximization) of an objective function (Eq. 1), subject to inequality, equality, or lateral constraints (Eq. 2 to 4, respectively):

$$f(x_i), \quad i = 1, n \tag{1}$$

$$g_j(x_i) \leq 0, \qquad j = 1, m \tag{2}$$

$$h_k(x_i) = 0, \qquad k = 1, l \tag{3}$$

$$x_i^l \leq x_i \leq x_i^u \tag{4}$$

In the previous equations, x = (x_1, x_2,... x_n)^T designates the vector of the design variables. These variables can be discrete or continuous. The functions involved in the problem can contain the design variables explicitly or not, and both the objective function and the constraint functions can be linear or non-linear.

The algorithms used to solve an optimization problem can be classified as deterministic or probabilistic. Deterministic optimization methods, also called classical methods, generally employ derivatives of functions or their approximations. For more complex problems, these methods may have some limitations, such as difficulty in identifying global optimal solutions, and working with discrete variables, or with non-differentiable functions. Probabilistic methods, once do not employ the calculus of derivatives, are not so easily tied to local extremes, and use strategies to escape local minimum (or maximum) points known as global optimization algorithms. However, they require a large number of evaluations of the value of the objective function, which is considered computationally expensive. Thus, despite the tendency to use probabilistic methods due to their greater versatility (Dede et al, 2019), it is interesting that the choice of the optimization method is made depending on the characteristics of the formulated problem.

Regarding structures, optimization problems are usually classified as section optimization, geometric optimization, and topological optimization. Section optimization seeks the lowest weight or cost for the structure by determining the dimensions of the cross-section. The geometric optimization considers the variation in the length of the elements by the change in the nodal coordinates. Finally, topological optimization aims at the optimal arrangement of elements, by changing their number and position in the structure.

3. OPTIMIZATION OF REINFORCED CONCRETE, STEEL, AND WOOD BEAMS

To identify the best structural material for beams, formulations were proposed to minimize the cost of these structures according to the adopted material. For the formulations of reinforced concrete, steel, and wood, beams, the objective was to minimize the total cost of materials and labor, taking into account the constraints and limits imposed by the corresponding standards. The adopted formulations were developed by the authors or under their guidance (Medeiros & Kripka, 2013; Magnan, 2019; Ozimboski et al, 2020). These formulations were implemented in the Excel Solver, using the generalized reduced gradient (GRG) method, and considering the variables as continuous.

The reinforced concrete beams were dimensioned by Brazilian standard NBR 6118:2014, aiming to minimize the cost composed of steel, concrete, and forms. The beam height is the only design variable, with the steel area being determined from the concrete section. The constraints considered are related to the ultimate and service limit states, in addition to constructive provisions. The detailed formulation can be found in Pagnussat and Kripka (2010) and in Medeiros and Kripka (2013).

The value of the characteristic strength of concrete to compression (fck, or Feature Compression Know) was initially adopted as 30 MPa, with nominal coverage of 30 mm. The costs considered, in Brazilian currency (Reais, or R$), were 395.08 R$/m³ for C30 concrete, 74.31 R$/m² for formwork, and 7.71 R$/Kg for CA-50 steel, and 10.02 R$/Kg for CA-60 steel. The base width was fixed as 15 cm, a dimension often used for embedding the beam in the wall.

The steel beam was dimensioned following Brazilian standard NBR 8800:2008 for the design of steel structures and composite steel and concrete structures for buildings. A double symmetry welded I-profile cross-section was considered (steel ASTM A36). The variables of the cost minimization problem (equivalent to weight minimization) were profile height, flange width, and web and flange thicknesses (Ozimboski et al, 2020). The unit cost considered was 7.72 R$/Kg.

The objective function to the search for the optimal dimensioning of the wooden beams was established aiming to minimize the total cost of the structure, taking as a design variable the height of the cross-section. The wooden beam was dimensioned according to standard NBR 7190:2012, for the Design of Wooden Structures. pinewood species chosen was the C30 conifer, which served as the basis for obtaining the other material properties through tables provided by the standard. The constraints are related to ultimate and service limit states, in addition to dimensional restrictions such as a minimum cross-sectional area of 50 cm² and minimum thickness of 5 cm. The unit cost considered corresponds to undressed pine sawn wood, being 1,044.06 R$/m³.

For the analysis of the beams according to the three materials, the optimization was performed for two different spans, being 4m and 8m. The applied load was considered as the average of the values used in the study by Pagnussat and Kripka (2010), resulting in 13 kN/m for permanent loads and 4.5 kN/m live loads, both uniformly distributed along the length of the beam. The own weight was computed automatically and added to the permanent loading.

Table 1 shows the final costs corresponding to the beams optimized for 4m and 8m spans, respectively. It can be observed that considering only costs, wooden beams were significantly cheaper, with reductions of around 43 and 60% compared to reinforced concrete, which represented the second most economical option.

Cost (R$) - Span 4 m		**Cost (R$) - Span 8 m**	
Reinforced concrete beam	533.26	**Reinforced concrete beam**	2209.43
Steel beam	693.29	**Steel beam**	2969.01
Wood beam	213.84	**Wood beam**	1274.28

Table 1 – Optimum cost of beams

Tables 2 and 3 show the total weight and height of the optimized beams, respectively. Despite being the most expensive option, based on these values, a significant advantage can be seen in the use of steel beams, both in terms of own weight and in the lower height of the section.

Weight (Kg) - Span 4 m		**Weight (Kg) - Span 8 m**	
Reinforced concrete beam	678.60	**Reinforced concrete beam**	3091.80
Steel beam	89.80	**Steel beam**	384.59
Wood beam	122.89	**Wood beam**	732.30

Table 2 – Weight of beams corresponding to optimized costs

Height (m) - Span 4 m	**Height (m) - Span 8 m**

Reinforced concrete beam	0.45	**Reinforced concrete beam**	1.03
Steel beam	0.24	**Steel beam**	0.53
Wood beam	0.48	**Wood beam**	0.79

Table 3 – Height of beams corresponding to optimized costs

By adapting the objective function, the same structures were optimized to minimize the environmental impact, measured in terms of carbon dioxide emission. Unit values for emissions were taken from the studies by Santoro and Kripka (2016) for the south of Brazil. These values consider the emissions in the stages of extraction, production, and transport of materials (known as "cradle to gate"). The values used were: 157.65 KgCO2/m3 for concrete, 8,242.50 KgCO2/m3 for steel (or 1.05 KgCO2/kg) and 74.63 KgCO2/m3 for wood (1.78 KgCO2/m2). Table 4 summarizes the results obtained for the minimization of the environmental impact, through which the lower impact produced by wooden structures is evident, regardless of the span considered.

Environmental Impact ($KgCO_2$) - Span 4 m		**Environmental Impact (KgCO2) - Span 8 m**	
Reinforced concrete beam	64.93	**Reinforced concrete beam**	278.76
Steel beam	94.29	**Steel beam**	403.82
Wood beam	15.29	**Wood beam**	91.09

Table 4 – Minimum Environmental Impact of beams

4. APPLICATION OF AHP TO OPTIMIZED BEAMS

After minimizing the beams in terms of cost and environmental impact, the results were evaluated with the multicriteria decision-making method Analytical Hierarchical Process

(AHP). With this objective, criteria for comparison between beams were first defined, namely: weight, height, cost, environmental impact, and culture. Based on this, it was possible to generate the hierarchical structure (Figure 1) of the method, which illustratively presents the pairwise comparison between criteria and between alternatives, enabling a comprehensive view of the study and the relationships among its components.

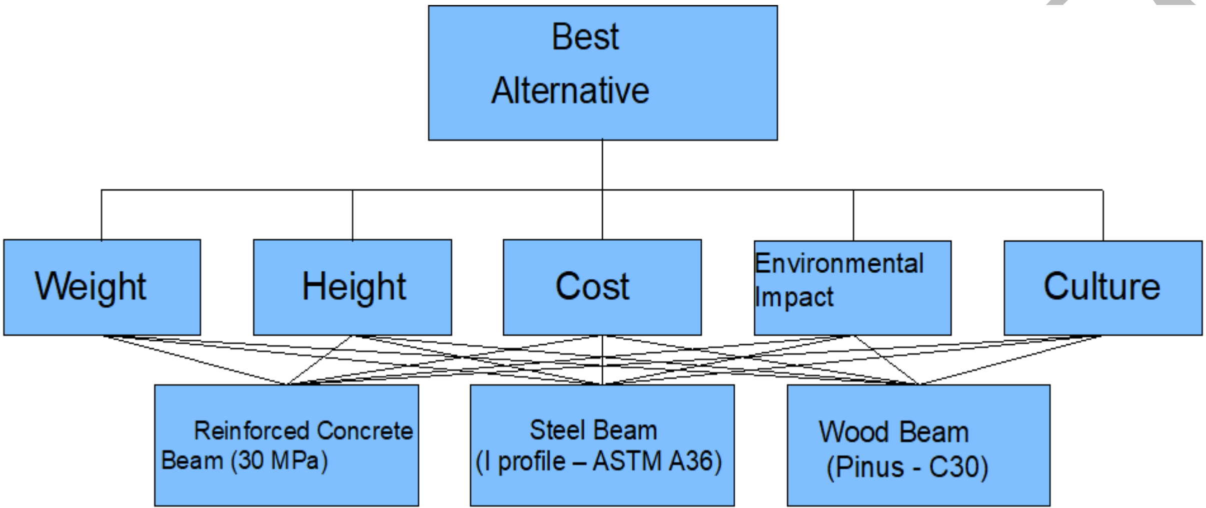


Figure 1 – Hierarchical Structure

To assign relative importance among the criteria for the creation of the pairwise comparison matrix, it was decided to carry out a survey with professionals and Civil Engineering students, to increase the representativeness of the results. In the survey, prepared with the help of the Google Forms survey administration application, participants were asked to assign preferences for pairwise comparison between the criteria provided. In this attribution, the values used by the respondents were based on the Saaty Fundamental Scale, identified within the form.

For the elaboration of the pairwise comparison matrix, the values were obtained through the answers that were most present among the values resulting from the research. However, some of the responses generated needed small changes to comply with the limit value for the consistency ratio (CR). The final result can be seen in Table 5. It was observed that cost was considered the most important of the criteria, while the environmental impact was the least important criterion in all comparisons. It is worth noting that some recent studies point to greater weight for the environmental criterion, suggesting that the weights attributed by experts must be influenced by the current situation owing to the coronavirus disease pandemic (Hoose et al, 2021).

Pairwise Criteria Comparison	**Weight**	**Height**	**Cost**	**Environmental Impact**	**Culture**
Weight	1	3	1/5	5	1/3
Height	1/3	1	1/5	3	1/5
Cost	5	5	1	7	3
Environmental Impact	1/5	1/3	1/7	1	1/5
Culture	3	5	1/3	5	1

Table 5 - pairwise comparison matrix of criteria

Once the peer comparison matrix of the criteria was completed, the elaboration of the peer comparison matrix of the alternatives was performed, where the alternatives reinforced concrete, steel, and wood beams, are compared to a given criterion separately. As a consequence, local average priorities (PML's) were obtained, which helps in determining the most preferable material within the evaluated criteria.

Regarding the weight, height, cost, and environmental impact criteria, these comparisons were made by using the magnitudes obtained through the optimization. Cultural criterion, as a qualitative criterion, had its magnitude obtained from the survey previously described. In that survey respondents were asked to compare the alternatives indicating which had a greater regional cultural impact or, in other words, which material was more likely to be chosen in the region of study. The results, illustrated in Table 6, clearly show the respondents' preference for reinforced concrete, followed by steel, and finally wood. This poor assessment of the wood, globally, can be justified by the preoccupation about its durability (Viholainen et al 2020).

Culture	**Steel**	**Reinforced Concrete**	**Wood**
Steel	1	1/5	3
Reinforced Concrete	5	1	7

Wood	1/3	1/7	1

Table 6 – Pairwise comparison matrix of the cultural aspects

5. RESULTS AND DISCUSSION

The choice of the best structure according to the considered criteria was made using a specific calculator, developed through excel software. The relative importance of the criteria, obtained from the pairwise comparison matrix, is summarized in Figure 2.

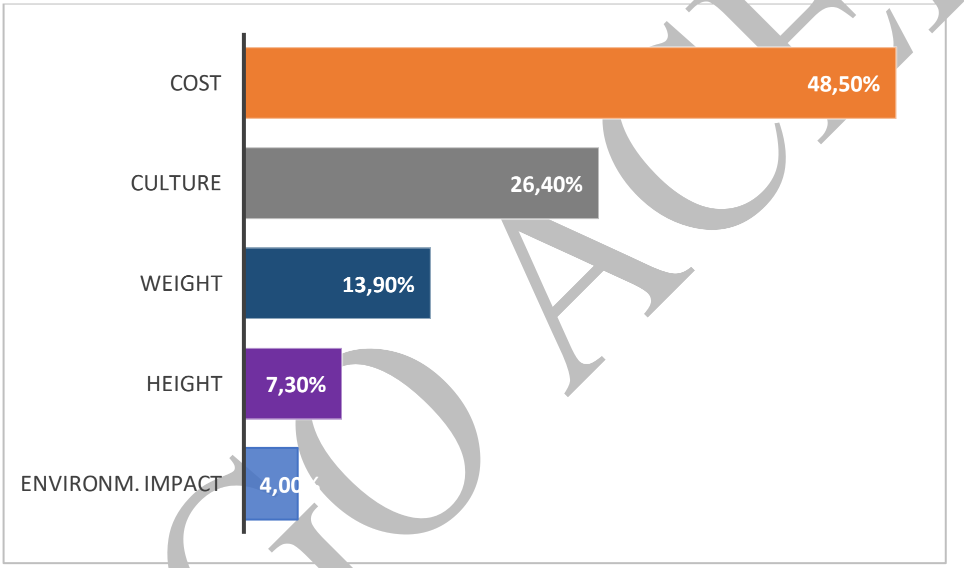
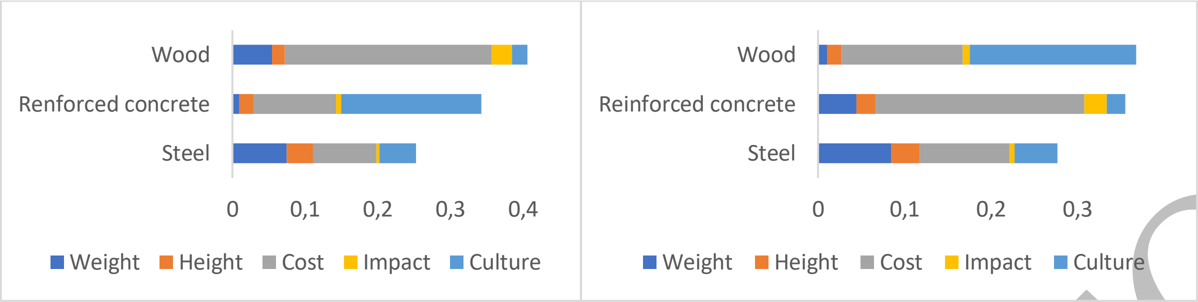


Figure 2 – Importance of criteria

As expected, the criterion referring to cost was more relevant when compared to the others, accounting for almost 50% of the weight of the choice. Associated with the cultural issue, it represents approximately 75% of the reason for the choice.

For the relative weights and importance, it was possible to compare reinforced concrete, steel, and wooden beams for spans of 4m and 8m. The final result, together with the decomposition of the importance of each criterion in the analyzed alternative, is shown in Figure 3.

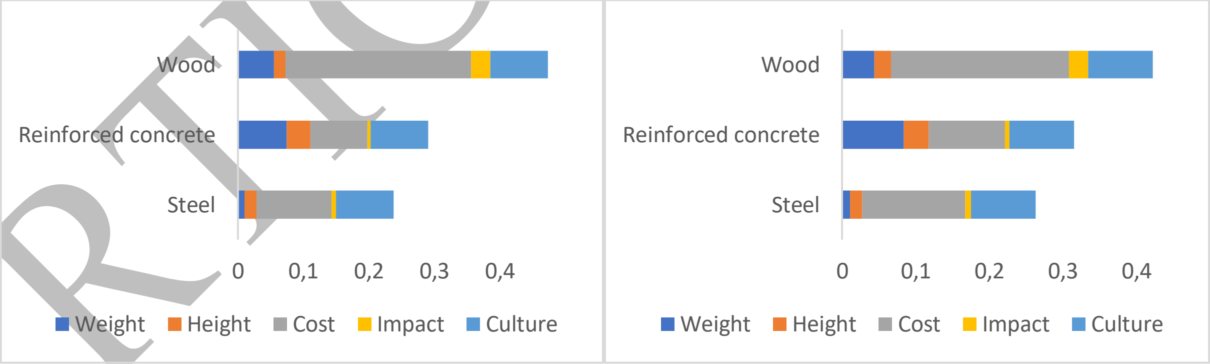


(a) (b)

Figure 3 – Best alternative and criteria importance to beams of 4 m (a) e 8 m (b).

Despite the importance of the cultural criterion, and the fact that wood was the last option in this regard, the wooden beam proved to be preferable among the beams with a 4m span, with a 40.62% priority. This fact is mainly explained by the low cost of this material. For the 8m spans, the reinforced concrete beam was the preferred one with 36.84% of priority, with great influence on the cultural criterion.

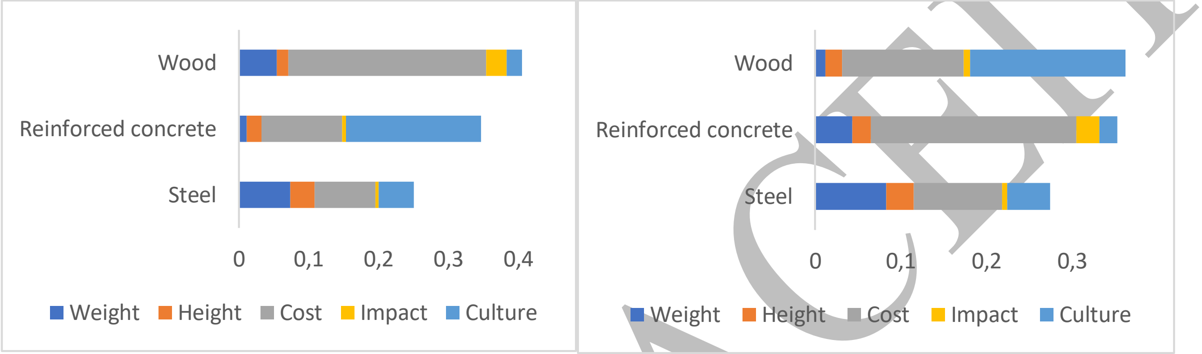
Given the subjectivity of the criteria and the particularity of regional aspects, additional studies were carried out to obtain a greater coverage of results and comparisons. First, it was sought to disregard culture as an effect of confrontation between the beams. In this sense, all structural alternatives received equal importance in this regard. The results, shown in Figure 4, now point to a clear advantage for wood for both spans analyzed. In addition, the lower weight and height of the steel beam make this option better than reinforced concrete beams.



(a) (b)

Figure 4 – Best alternative and criteria importance to beams of 4 m (a) e 8 m (b) disregarding culture.

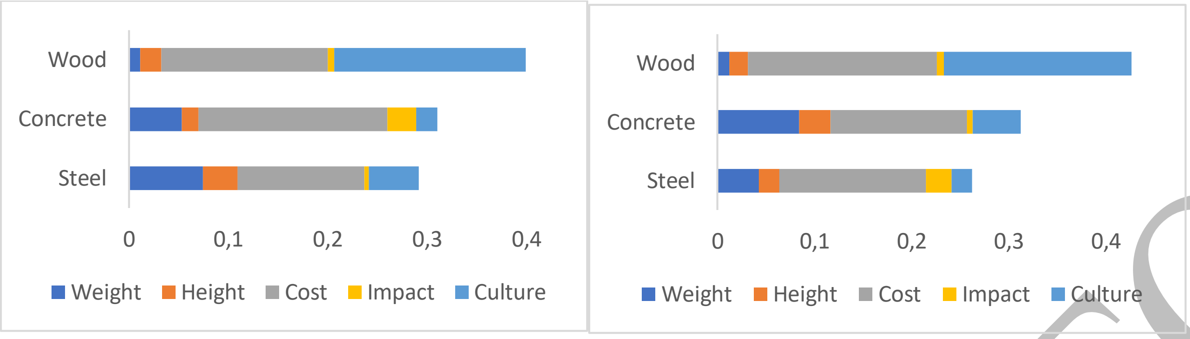
For a second comparison, the concrete had its characteristic strength modified from 30 to 50 MPa. For such a comparison to be possible, a new optimization was necessary, both for cost and for environmental impact. The unit cost considered was now 508.20 R$/m³, an increase of 28.7% about the C30 concrete used initially. As for the environmental impact, due to its greater amount of cement, the CO2 emission obtained by Santoro and Kripka (2016) to C50 is approximately 16 KgCO2/m³ bigger than for C30 concrete, equivalent to 225.78 KgCO2/ m³. Compared to beams optimized with C30 concrete, C50 concrete resulted in lower cost, weight, and height, but in greater impact. These changes, however, did not decisively influence the results, as illustrated in Figure 5.



(a) (b)

Figure 5 – Best alternative and criteria importance to beams of 4 m (a) e 8 m (b) to concrete C50.

Finally, the lumber beam was replaced by a glue-laminated wooden timber (Glulam) beam. Due to its better mechanical characteristics and aesthetic quality, this wood has a significantly higher price than solid wood. This price, obtained from the research carried out by Magnan (2014), regarding the optimization of biaxial bending of elements in Glulam, resulted in the value of 2,265.20 R$/m³. In the comparison, the reinforced concrete beam with characteristic strength of 50 MPa was maintained. Due to the high cost of glue-laminated wood, the reinforced concrete beam took on a significant advantage among the alternatives, as shown in Figure 6.



(a) (b)

Figure 6 – Best alternative and criteria importance to beams of 4 m (a) e 8 m (b) considering Glulam beam

6. CONCLUSIONS

The development of the present study aimed to present a methodology for the selection of structural material considering several criteria. In this sense, the optimization allowed the beams to be dimensioned, in an equivalent way, within their specific material properties, and the multicriteria decision-making method AHP provided the consideration of both conflicting criteria and intangible factors.

The results demonstrated the strong influence that cost and culture have when choosing a structural material. Together, they represent almost 75% of the weight, consequently dictating the preference for structures that are more economically viable or culturally more employed.

This was the case for wooden beams for the 4m spans and for reinforced concrete beams for the 8m spans. However, when the culture is disregarded, the wooden beam presented itself as the best option for both spans analyzed, mainly due to its low cost. Other factors such as lower environmental impact contributed to this result.

When the characteristics of the component materials of the beams were modified, the first change from the initial concrete to a higher strength concrete did not cause significant changes in the results. Regarding the use of glue-laminated wood, due to its higher cost, the advantage of reinforced concrete structures became even more relevant. It is noteworthy that, due to the production process, it produces a greater impact than the lumber beam, but this factor was not considered in the analysis.

This study considered costs and environmental impact obtained to the south region of Brazil and is based on Brazilian Standards. Due to this, similar studies developed in other regions or countries can present variations in regard to those obtained here. On the other hand, it is supposed that the conclusions are not affected by regional particularities.

In this work, optimized results for reinforced concrete, wood, and steel beams were presented. Other structural elements, models, materials, and decision-making methods can be investigated in future studies to generalize the conclusions obtained here.

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