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Selection of Sustainable Short-Span Bridge Design in Brazil

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Abstract: Owing to the elevated cost of bridges, especially when compared to the cost of roads, their rational design and material selection are fundamental properties to consider when aiming to reduce the environmental impacts and lengthen the lifespan of the bridge. Especially in developing countries, the construction of new bridges (mainly short spanned) is still a necessity, and it is important that these new structures are designed according to all the sustainability parameters, instead of being based only on the construction cost. Thus, the present work aims to study short-span bridges by integrating environmental assessments into the decision-making process. To achieve this goal, three short-span bridge designs, proposed by public organizations in Brazil, are evaluated: Precast concrete bridge, mixed concrete/steel bridge, and timber bridge. In order to allow comparison, the same location and span are considered. The structures are evaluated considering the following quantitative aspects: Cost of construction, assembly and material transportation, lifespan, and environmental impact (measured by the global warming potential, GWP). In addition, some more subjective factors are considered, such as the architecture (layout and appearance) and the user's sensation of security. The selection is made by the adoption of two multi-criteria decision-making methods (analytic hierarchy process or AHP and Vikor). The results obtained with both methods indicate the mixed concrete/steel bridge as the most adequate alternative. Some additional analysis is performed in order to evaluate the influence of the qualitative aspects, as well as to study the importance of the variations in the costs on the results.

Keywords: cost; sustainability; bridges; design; environmental impact; decision making

1. Introduction

Bridges play a very important role in the infrastructure of a country by reducing distances required to travel and/or enabling the transportation of goods and people. The design and construction of bridges constitute very ancient activities, being the first structures composed of wood and rock [1]. In the last few decades, the development of materials and computational analysis tools have allowed for sophisticated designs, enabling the construction of innovative solutions in view of the spans and aesthetics aspects. In addition, efforts have been made to extend the lifespan of existing bridges through careful maintenance strategies and technologies to identify pathologies more precisely, as well as in the early stages. On the other hand, especially in developing countries, the need for the construction of new bridges (mainly short spanned) is still a necessity. According to [2], there is a need for the construction of nearly a hundred thousand short- and medium-span bridges in Brazil. A characterization of the bridges in Pato Branco, a city located in the southern region of Brazil, was presented in [3], aiming to study the main pathologies. In this study, it was verified that short-span bridges, which are mainly designed for small river crossings, represented 90% of the total, with about 74% being 10 m or less in span. It is supposed that these relations are not very different from those usually found in other countries. For example, based on the data provided in 1982 by the Concrete Reinforcing Steel Institute, it was verified that more than two-thirds of the bridges in the United States had a span below 60 feet or approximately 18.3 m at the time [4].

Besides the need for new bridges in developing countries, owing to the growth of cities and expansion of the road network, a strong deficiency in the maintenance policies is commonly verified. The study developed in [3] observed that according to the apparent conditions of stability as per the procedures of the Transportation Infrastructure National Department (DNIT), 22% of the bridges were in a precarious situation, needing urgent repairs. The ages of the bridges were difficult to obtain when requiring precise data because of the lack of registers maintained by the responsible agencies, however, the information collected allowed the estimation that most bridges were built less than thirty years ago. Another study [5] analyzed 100 Brazilian road bridges, classifying the structures analyzed as potentially problematic (38%), tolerable (35%), and critical, which may suffer structural failure (3%). These studies suggest that in some cases the demolition and substitution of a deteriorating bridge can be an alternative to its rehabilitation.

Several studies can be found on the design alternatives to bridges, relating both the adoption of new materials and to parametric studies to aid structural designers. For example, [6] proposed a modular bridge composed of glue-laminated timber which is reinforced with synthetic straps and steel trusses as a lower cost alternative. In another direction, the number of longitudinal beams in mixed steel/concrete bridges was optimized [7] in order to obtain the design parameters.

Owing to the elevated cost of a bridge in relation to the cost of roads, a rational design and material selection are fundamental, but also with the aim of reducing environmental impacts and extending the lifespan of the bridge. Despite the high social and economic importance of the constructions, the severe impacts on the environment must also be addressed. In Brazil, sustainable practices are still incipient, but the awareness of society on the impacts caused by construction activities is changing this [8].

In order to evaluate alternative designs regarding several criteria, a specific strategy such as multi-criteria decision-making methods (MCDM) needs to be adopted. MCDM have been applied to the design of bridges in several focus areas. Most of these areas are related to the development and improvement of methods [9–13], with very few works directly addressing the problems of the comparison and selection of bridge design alternatives [14,15]. MCDM have also been applied to evaluate multiple performance aspects of multiple bridges in order to rank bridge maintenance activities [16]. An extensive review of the papers related to bridge sustainability evaluation was presented in [17], relating each method to the corresponding life cycle phase.

Despite the growing number of publications on the topic of sustainability in civil engineering and construction building technology [18], in general, there are rather limited studies available on the analysis of bridges, even when focusing only on the environmental aspects. Several studies have been developed related to the relative impact of bridges composed of timber, concrete, and/or steel [19–24]. It was observed that in general their results were not coincident.

In short, a lack of studies was still observed to allow the practical design of short-span bridges considering diverse criteria, materials, and configurations. Based on this, and considering the tremendous need for infrastructure in developed countries, this work aims to study short-span bridges, integrating environmental assessment into the decision-making process. To achieve this goal, three short-span bridge designs proposed by public organizations in Brazil are evaluated: Precast concrete bridge, mixed concrete/steel bridge, and timber bridge. In order to allow comparison, the same location and span are considered. The structures are evaluated considering the following quantitative aspects: Cost of construction, assembly and materials transportation, lifespan, and environmental impact (measured by the global warming potential, GWP). In addition, some subjective factors are considered, namely, the architecture (layout and appearance) and security sensation by the users.

The selection of these factors is made by the adoption of two classical multi-criteria decision-making methods (Analytic Hierarchy Process, or AHP, and Vikor). Some additional analyses are performed in order to evaluate the influence of qualitative aspects, as well as to study the influence of cost variations on the results.

The remainder of this paper is structured as follows: The second section briefly describes multi-criteria decision-making methods, focusing on those applied in this study. The third section presents the adopted methodology, with the results and discussion detailed in the fourth section. Finally, the conclusions and final considerations are presented.

2. Multi-Criteria Decision-Making

The measurement of intangible factors in decisions has for a long time defied human understanding [25]. In addition, especially in the last few decades, the amount of available information has increased the complexity of the decision-making process. In this view, multi-criteria decision-making methods (MCDM) have emerged as effective supporting tools for solving problems in which conflicting criteria exist. These methods provide the user with a ranking of the candidate alternatives to a given problem, considering a set of criteria used to measure the performance of each action.

MCDMs cover a wide range of quite distinct approaches, being classified into two categories: Discrete (multi-attribute decision-making, MADM) and continuous (multi-objective decision-making, MODM) methods. While in MODM the number of possible alternatives is infinite, MADM methods deal with a limited number of predetermined alternatives, allowing the assessment and ranking of these alternatives. Solving a multi-criteria decision-making problem begins with the problem definition, identification of the constraints and criteria, and finally, finding alternatives to be evaluated and selected by the decision-maker. This is achieved by comparing the criteria with the alternatives and final goal. To make the comparisons, a scale of numbers indicates how many times more important or dominant one element is over another with respect to the criterion to which they are being compared. This scale is known as Saaty´s fundamental scale.

In order to solve problems that cover multiple criteria, several methods have been proposed. In this paper, two multi-criteria decision-making methods were adopted: The analytic hierarchy process method, or AHP, and the Vikor method.

The AHP has been found to be the most used technique when dealing with sustainability problems in civil engineering [26]. The method begins with a decomposition of the problem into smaller hierarchically independent problems, followed by the pair-wise comparison of the criteria allocated at the same level. As a consequence, relative weights are attributed to each criterion in each level.

The Vikor method works with the distance concept according to different criteria (e.g., Euclidean distance or metropolitan distance), regarding the best and worst solutions. Initially, the solutions are classified according to each criterion. In the sequence, the sum of the weighted fractional distances of each solution from the best value, S, and maximum weighted fractional distances of each solution from the best value to each solution, R, are calculated. Value Q is determined by R, S and their relative weights, and the alternatives are ranked based on the minimum values of R, S, and Q.

3. Materials and Methods

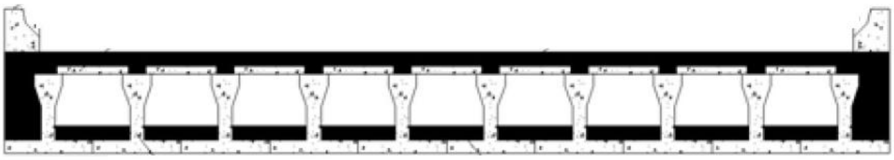
3.1. Bridges Studied

In order to evaluate some design alternatives to short-span bridges, three designs were considered: Precast concrete bridge, mixed concrete/steel bridge, and timber bridge. These were all proposed by public organizations in Brazil. To allow comparison, the same location and span were considered. All the simulations considered simply supported 8 m bridges located in Pato Branco in the southern region of the country. This span was adopted as a representative value for small-span bridges. Similar studies can be made considering the data obtained for other spans [27]. The alternatives studied considered simply the superstructure. All the bridges were designed to allow the crossing of one vehicle at a time.

The precast concrete bridge design was proposed by the Department of Roads of Paraná State (DER-PR). The bridge, ranging in span from 6 to 16 m and with a total width of 4.5 m, is constituted by an assembly of reinforced concrete beams (Figure 1a), with a characteristic strength of 35 MPa, connected by transverse steel bars positioned in the holes (Figure 1b). After this, the precast slabs are positioned over the set, and a coverage of concrete is applied. A transversal view is presented in Figure 1c, where the in-situ cast concrete is printed in black.

(**a**)

(**b**)

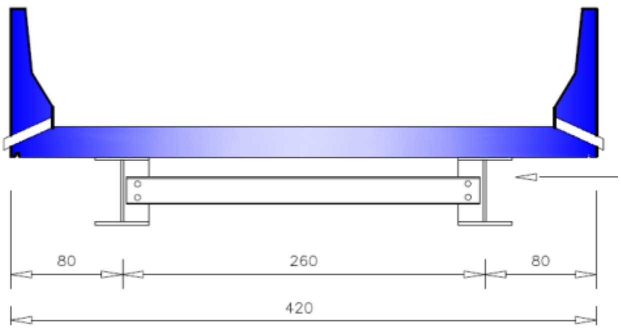


(**c**)

Figure 1. Precast concrete bridge: Isolated beam (**a**), assemblage (**b**), and transversal view (**c**).

The mixed concrete/steel bridge is a project developed by the Department of Roads of Minas Gerais State (DER-MG). It is composed of precast concrete slabs linked to two longitudinal welded steel beams by shear connectors (Figure 2a). A transversal view of the bridge can be seen in Figure 2b. The simply supported bridge is designed for spans ranging from 8 to 18 m.

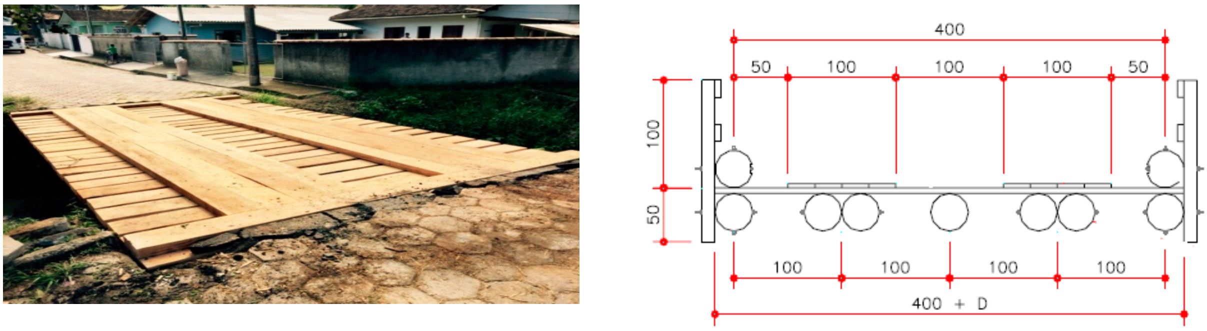
(**a**)



(**b**)

Figure 2. Concrete/steel bridge: Construction (**a**) and transversal view, in cm (**b**).

The timber bridge chosen to be studied was taken from the guidelines of a research group on timber structures from the University of São Paulo, Brazil. Although in the same guidelines several configurations were presented, including glue-laminated timber bridges, the selection was made based on the fact that it is probably the most used configuration in the country, owing to its simplicity [28]. In the guidelines, the bridge spans range from 6 to 10 m. Figure 3a shows the deck of the bridge, with a transversal view shown in Figure 3b, where D is the diameter of the trunk (approximately 20 cm).



(**a**) (**b**)

Figure 3. Timber bridge: Deck (**a**) and transversal view, in cm (**b**).

3.2. Criteria Adopted

The next subsection details the aspects considered in the evaluation of the alternatives. Three of these aspects are quantitative (cost of construction, assembly, and transportation; lifespan; and environmental impact) and two are qualitative (architecture and security sensation). In order to develop the comparisons, the value per square meter of the bridge was considered as the functional unit.

3.2.1. Costs of Construction/Assembly and Transportation

There are several costs to be considered for a structure, such as the costs of design, construction and/or assembly, maintenance (here, included inspection and repairing), or even demolition/recycling. In the present work, just the costs of material transportation, construction, and assembly were considered. The costs of the construction and/or assembly include structural materials, formworks, equipment, and labor costs. The cost of transportation is presented separately in order to emphasize the influence of the distance on the results. This cost considers the extraction of raw materials up to the transportation of the structural elements and processed materials to the construction site, taking into account the distances, weight of the materials, and truck capacity.

Table 1 presents the costs, in US$, used in this work for the comparison of alternatives. It can be observed that precast concrete bridge has a different total area because its total width is 4.5 m, compared to the 4.2 m of other alternatives. According to the table, the mixed steel/concrete bridge is the most expensive option considered, both in terms of the total cost and the unit cost of the construction/assembly. On the other hand, this alternative presents a lower transportation cost, which considers not only the distances but also the weights of the materials. This can be justified based on the strong relationship between the strength and weight of the steel profiles.

Still, based on Table 1, it is interesting to notice that although the timber bridge is the least expensive option for construction and/or assembly, its transportation cost is very high. This is because only reforested species of timber with an appropriate forest management certification can be utilized. In this study, the *Eucaliptus dunnii* species was used, resulting in a transportation distance of 180 km to the construction site.

Table 1. Unit costs of bridges.

Alternative	Total Cost (US$)	Total Area (m^2)	Unit Cost (Construction /Assembly, US$/$m^2$)	Unit Cost (Transportation, US$/$m^2$)	Unit Cost (Construction /Assembly and Transportation, US$/$m^2$)
Precast Concrete	11,326.04	36.00	312.07	2.54	314.61
Mixed Steel/concrete	11,831.53	33.60	350,42	1.71	352.13
Timber	8,419.84	33.60	238.24	12.35	250.59

3.2.2. Lifespan

Sustainable bridge construction refers to the reduction of emissions and environmental impacts during bridge construction. However, it is also important to design durable bridges with a minimum serviceability, in accordance with the design standards [29].

The service lifetime is not consistent for the different standards, varying from 75 [30] to 120 years [31]. A period of 100 years has been used for the major European bridge and tunnel projects since the early 1990s, being adopted by European standards [32].

According to [33], in modern applications, it is seldom practical or economical to cover timber bridges to avoid direct exposure to the elements (this procedure was adopted during the 19th century to lengthen the lifespan of bridges). In contrast, modern treatments can effectively protect wood from deterioration for periods of 50 years or longer. In addition, treated wood requires less maintenance and painting [2]. In the present study, a lifespan of 50 years was considered for timber bridges.

3.2.3. Environmental Impact

In order to evaluate the environmental impact of each alternative, a life cycle analysis (LCA) was performed. The impacts were evaluated with the Simapro software, with the ReCiPe midpoint approach and the Ecoinvent database. In this study, the following phases were considered: Extraction and production of aggregates, cement production, concrete production at the mixing station, steel production, extraction and processing of wood, production of pre-cast elements, transport, and construction of the bridge.

The materials considered in the 35 MPa concrete production were cement, water, coarse aggregate, natural sand, and additives. The service of the mixing plant included the infrastructure area (buildings, roads, etc.), energy, and machines used to produce the concrete. The rebar production process included the extraction and processing of raw materials, such as coal and iron ore, as well as the recycling of steel scrap and hot rolling. The production of steel beams included the infrastructure of the metallurgical plant, production of rolled steel (beams and plates), electricity consumption, and transportation of the elements to the construction and welding site. Regarding wood, all the processes related to cultivation, harvesting, sawing, machines, energy consumption, and transport were considered.

The energy consumption was adopted from Ecoivent, and the dataset also included the infrastructure (poles, cables, etc.) of the electricity transmission network and high-to-medium voltage transformation stations. For the transport in the production phase of the materials, the average market distances were considered. For the construction, a distance of 20 km from the city to the construction site was adopted. In addition, truck EURO 3 was selected, owing to its similarity with Brazilian national vehicles.

Although several impact categories can be obtained by the LCA, only the GWP was included in this study. The corresponding results, in $kgCO_2eq/m^2$, are summarized in Table 2. It can be noticed that the precast concrete bridge generates, by far, the most major impacts when compared to the other alternatives. This is because cement (and more precisely, the clinker) is among the list of materials that decisively contribute to the total emissions [34]. On the other hand, a timber bridge, although consuming a large quantity of water and needing chemical treatments to improve its durability, is still a more environmentally friendly option than concrete. Wood is considered as an ecologically green material, and its use in construction is usually encouraged, because it requires minimum energy consumption during the whole life cycle, from production to final disposal [35]. It is important to emphasize that to countries that need to import wood its sustainability performance can vary dramatically, owing to differences in the production process, energy structure, and transportation distances. High humidity also makes timber bridges prone to fungi growth and faster deterioration, demanding chemical treatment [36]. It is important to emphasize that the cost and impact of the wood treatments are not considered in the present study.

Table 2. Unit environmental impacts.

Alternative	GWP (kgCO_2eq/m^2)
Precast Concrete	296.00
Mixed Steel/concrete	194.00
Timber	174.00

3.2.4. Architecture and Security Sensation

These criteria are focused together in this subsection of the paper because they represent qualitative aspects, and so a pairwise methodology is well suited. According to this methodology, the behavior of each alternative to each criterion needs to be addressed.

The architecture criterion refers to the layout and appearance of the structure. Although it must not be considered at the same level of importance as the quantitative criteria, it must be emphasized that because bridges are designed to have a long lifespan, they also will be a part of the environment for a very long period. Owing to its simplicity, the timber bridge is evaluated as slightly worse when compared to the other two solutions, whereas the same values are attributed to the precast concrete bridge and the mixed steel/concrete bridge. Table 3 presents the matrix constructed according to Saaty´s fundamental scale, based on the considerations described above.

Table 3. Architecture.

	Precast Concrete	Mixed Steel/Concrete	Timber
Precast Concrete	1	1	3
Mixed Steel/concrete	1	1	3
Timber	0.3333	0.3333	1

The security sensation to a user, a measure of sensitive acceptance, is considered according to Table 4. The attributed importance, from best to worst, is as follows: Mixed steel/concrete bridge, precast concrete bridge, and timber bridge. The main factors considered here are the robustness appearance and height of the guardrails.

Table 4. Security sensation.

	Precast Concrete	Mixed Steel/Concrete	Timber
Precast Concrete	1	0.3333	3
Mixed Steel/concrete	3	1	5
Timber	0.3333	0.2	1

The consistency index (CI) of each matrix was verified, resulting in 0 and 0.019, respectively. Considering a random consistency index of 0.58, the consistency of the results is demonstrated.

4. Results and Discussion

Based on former considerations, the alternatives presented were evaluated according to the adopted criteria. Table 5 summarizes the information about each alternative regarding each criterion.

The last two columns, corresponding to the qualitative criteria, present the weights obtained by the application of the AHP methodology. In the table, values in bold indicate the best alternative when considering each criterion. The second line of the table indicates if the criteria must be minimized (min) or maximized (max).

Table 5. Alternatives and criteria.

Alternative	Cost (US$/m^2)	Lifespan (Years)	Environmental Impact (kgCO_2eq/m^2)	Architecture	Security Sensation
	Min	**Max**	**Min**	**Max**	**Max**
Precast Concrete	314.61	**100**	296.00	**0.4286**	0.2583
Mixed Steel/concrete	352.13	**100**	194.00	**0.4286**	**0.6370**
Timber	**250.59**	50	**174.00**	0.1429	0.1047

In bold: best alternative to each criterion.

Following the application of the AHP, a pairwise comparison was made regarding the criteria. The same relative importance was attributed to the first three criteria and a lower importance to the others. This resulted in weights of 0.273 and 0.091, respectively, with consistency index of 0.

Table 6 summarizes the weight of each criterion, where the final score of each alternative is presented in the last column.

Table 6. Weights of criteria.

Alternative	Cost	Lifespan	Environmental Impact	Architecture	Security Sensation	Final
Precast Concrete	0.318	**0.400**	0.237	**0.4286**	0.2583	0.3232
Mixed Steel/concrete	0.284	**0.400**	0.361	**0.4286**	**0.6370**	**0.3823**
Timber	**0.399**	0.200	**0.402**	0.1429	0.1047	0.2958

In bold: best alternative to each criterion.

A similar analysis was made by usage of the Vikor method. Table 7 presents normalized distances r_{ij}', and Table 8 presents the obtained values of metrics S_j (metropolitan) and R_j (infinite). It can be observed from the analysis performed that both the AHP and Vikor methods identified the mixed steel/concrete bridge as the best option among those presented, despite having the highest final cost. On the other hand, timber bridge is considered as the worst alternative. This poor performance can be attributed to the evaluation of the architecture and security sensation, as well transportation distances. It can be emphasized that even by halving the transportation distance, the cost of transportation will not significantly change, owing to the weight of wood. In addition, because transport corresponds to less than 3% of the total impact of the timber bridges, the impact reduction will also be negligible.

Table 7. Normalized distances (Vikor).

Alternative	Cost	Lifespan	Impact	Architecture	Security Sensation
Precast Concrete	0.128	**0.000**	0.030	**0.000**	0.297
Mixed Steel/concrete	0.204	**0.000**	0.005	**0.000**	**0.000**
Timber	**0.000**	0.306	**0.000**	0.043	0.417

In bold: best alternative to each criterion.

Table 8. Distances S_j and R_j.

Alternative	Sj	Rj
Precast Concrete	0.455	0.297
Mixed Steel/concrete	**0.209**	**0.204**
Timber	0.767	0.417

In bold: best alternative to each criterion.

Aiming to study the effects of aspects such as the relative cost variations and subjective criteria, two additional simulations were performed: Attribution of the same importance (same weight) to all the alternatives regarding the architecture and security, and an increase of 20% in the cost of the construction/assembly of the mixed steel/concrete bridge. The corresponding results, obtained with the AHP method, are presented in Table 9, named as variations 1 and 2, respectively, together with the original result. When considering the same weight for all the alternatives for the subjective criteria (architecture and security sensation), the results are similar for all the alternatives, because although the cost and impact of timber bridges are lower, their reduced lifespan is a clear disadvantage. The last column shows that even for the cost variation (an increase of 20%), the mixed steel/concrete bridge remains the best alternative.

Table 9. Final weights (original and variations).

Alternative	Original	Variation 1	Variation 2
Precast Concrete	0.3232	0.3213	0.3273
Mixed Steel/concrete	**0.3823**	**0.3459**	**0.3725**
Timber	0.2958	0.3339	0.3010

In bold: best alternative to each criterion.

The results presented in this study tried to take into consideration the influence of subjective aspects and the relative weights attributed to them. On the other hand, it is also important to stress that even measurable factors can be subjected to significant variations due to local factors and other specific considerations. For example, according to the National Ready Mixed Concrete Association [37], concrete emissions of carbon dioxide can vary from 100 to 300 $kgCO_2/m^3$ of concrete, depending on the composition of the concrete. These values consider only the construction material, not the whole structure as result of its application. In addition, some studies on bridges of different configurations and materials, although considering a square meter of the structure as a functional unit, compare bridges of different lengths or bridges submitted to different traffic loads, which is a questionable procedure. Neglecting this limitation, it is understandable that the extraction of generic recommendations for an environmentally friendly bridge design may be difficult because the studies were carried out under different assumptions [23].

5. Conclusions and Final Considerations

The aim of this work was to study sustainable design alternatives for short-span bridges in Brazil. Because bridges are designed to have a long lifespan, it is important to consider other criteria instead of just the cost of construction. Based on this fact, the structures were evaluated considering quantitative aspects (cost of construction, assembly, materials transportation, lifespan, and environmental impact) and qualitative aspects (architecture and security sensation to the user). The application of multi-criteria decision-making methods to this kind of problem allows the consideration of several criteria, reducing the subjectivity implicit in the decision-making process. In this work, two multi-criteria decision-making methods were adopted: The analytic hierarchy process, or AHP, and the Vikor method.

Regarding the problem studied, some important results can be emphasized:

- Much work has been done regarding the application of MCDM methods to bridges, especially focusing on maintenance. Alternatively, more efforts could be made to design small-span bridges to fulfill the needs of infrastructure, especially in developing countries. It is important that these new structures not only have the least cost but also consider other important aspects, such as their impact on the environment.
- Both the MCDM methods considered led to similar results, identifying the mixed steel/concrete bridge as the most suitable option, despite its higher construction and assembly cost. Even when considering the impact caused by the production of steel, its elevated relation between the

strength and own weight led to a relatively low transportation cost. Precast concrete bridges presented the worst results when considering the environmental impacts.

- Although less expensive, timber bridges cannot be considered a good alternative, owing to their transportation cost, architecture, security sensation, and lifespan. It is important to stress that the costs and impacts needed to guarantee the durability of timber were not considered. A study including the treatment and maintenance aspects of timber bridges could be a possible direction in future works.
- Among several possible configurations, the timber bridge selected was one of the most used in Brazil. Its simplicity explained the worst evaluation in terms of the architecture and security sensation. The consideration of other alternatives, such as glue-laminated timber bridges, can allow the construction of more aesthetically pleasant (but more expensive) bridges. In this sense, the evaluation of other timber bridge configurations could be interesting.
- Aiming to study the influence of several aspects such as relative cost variations and the weights of the subjective criteria on the results, additional simulations were performed. It was seen that these considerations did not alter the final weights significantly.

Wood is considered as an ecological green material, and its use in construction is usually encouraged. However, when considering other factors, as in the present work, this advantage can be strongly reduced or even disappear. In addition, in countries that need to import wood, the sustainability performance can vary dramatically, owing to differences in the production process, energy structure, and transportation distances.

Although based on local aspects and practices, the methodology adopted in this paper can be applied to other countries and structural configurations. Additional studies must be done in order to generalize the results presented here.

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