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Analytic Network Process-Based Sustainability Life Cycle Assessment of Concrete Bridges in Coastal Regions

Ignacio J. Navarro , José V. Martí and Víctor Yepes *

ICITECH, Department of Construction Engineering, Universitat Politècnica de València, 46022 Valencia, Spain
* Correspondence: vyepesp@cst.upv.es

Abstract: Since establishing the Sustainable Development Goals in 2015, the assessment of the sustainability performance of existing and future infrastructures has been in the spotlight of the scientific community. This is because the construction sector is essential for promoting the social welfare and economic development of countries, but is also one of the main environmental stressors existing to date. However, assessing infrastructure sustainability throughout its life cycle remains a significant challenge, as the criteria involved in sustainable design are often complex and conflicting. The Analytic Network Process (ANP) is recognized as a powerful decision-making tool to model such problems. Here, the life cycle sustainability performance of different design alternatives for a concrete bridge near the shore is evaluated using ANP. The obtained results are compared with those obtained using the conventional Analytical Hierarchy Process (AHP). The results obtained using ANP are more reliable than those derived from the conventional AHP in terms of the expert's consistency and the number of comparisons made.

Keywords: sustainability; Analytic Network Process; bridge design; life cycle assessment; TOPSIS; multi-criteria decision making

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1. Introduction

The construction sector is one of the main stressors for the environment and is responsible for a significant amount of the annual budget expenditure of almost any nation. At the same time, however, the development and construction of infrastructure is a very effective way of increasing the social and economic well-being of countries insofar as it enables territorial structuring, access to services of all kinds, or the development of commercial activities, among other things. This is why assessing the contribution of infrastructure to sustainability has attracted much interest since the recent establishment of the Sustainable Development Goals (SDGs) in 2015 [1].

Designing infrastructures that effectively contribute to the sustainable future demanded by our society is becoming a priority and a major challenge for engineers and architects, who are now faced with the responsibility of balancing the positive and negative life cycle-related effects generated by the infrastructures they design. As a result, research has been conducted in recent times in the assessment of infrastructures focusing on their economic, environmental, and social impacts. Although interest has arisen on the sustainability assessment of a wide variety of infrastructure types, such as pavements [2,3], buildings [4–6], earth retaining walls [7–9], railway tracks [10], dams [11], and others, much consideration has always been given to the sustainable design of bridges in particular.

Bridges are key elements of transport infrastructure systems. Although essential for providing terrestrial accessibility, bridges consume a significant share of the budget for road projects. They are also quite demanding in using materials with high embodied energy, such as concrete or structural steel. Recently, studies have been conducted to optimize the economic costs associated with the construction and maintenance of bridges [12–14].

Studies have also been undertaken to assess the environmental life cycle of these infrastructures [15–18], usually combining the analysis of this dimension with the economic one [19,20]. Recent attention has also been given to assessing the social impacts of bridge life cycle construction and maintenance phases [21,22].

Assessing the sustainability inherent to infrastructure requires the simultaneous consideration of every one of its three dimensions. Multi-criteria decision-making (MCDM) procedures have emerged as a powerful and widely accepted tool to face such complex assessments, where various and often conflicting criteria are involved. These methods consist of several steps, the first and most relevant of which is usually the determination of the weight that each criterion will have in the final decision making. These weights are generally based on the decision-maker's experience and view of the problem to be evaluated. The most commonly used method to derive those relevancies is the so-called Analytic Hierarchy Process (AHP), developed by Thomas L. Saaty [23]. The criteria weights resulting from applying the AHP technique are obtained by letting the decision maker (DM) compare pairwise how much more relevant each criterion is concerning the rest. Due to the simplicity of this methodology, it has been widely used in a variety of decision-making problems, such as transport management [24], software selection [25], or the flood risk assessment of regions [26], to cite some recent studies.

The AHP method is based on a strict hierarchization of the criteria involved in the decision-making problem, considering only the relations between elements belonging to a particular hierarchical level and those elements on the immediate lower level. In other words, AHP is based on one-directional hierarchical relationships. Consequently, AHP is limited when assessing problems whose decision criteria are complexly related. Such is the case of sustainability-related problems, where many criteria of very different natures are usually involved and are complexly interrelated. Although AHP is a popular technique for sustainability-related decision-making problems due to its ease of application [27–30], other methods exist that allow for the capturing of non-hierarchical relations in complex problems more accurately and reasonably. The Analytic Network Process (ANP) was presented by Saaty [31] as a generalization of the AHP, allowing for the consideration of interdependent criteria relations, thus resulting in decision-making models that fall closer to reality [32].

On the other hand, there is widespread concern about the credibility of criteria relevancies that result from applying the AHP technique when the decision-making problem involves a significant number of criteria. Being decisive and conditioned in the final decision, the weights resulting from using judgment-based techniques such as AHP are entirely subjective. This implies that the objectivity of the resulting decision may be limited by so-called non-probabilistic uncertainties associated with the decision maker's ability to consistently reflect his or her view of the problem when making a pairwise comparison. This may be particularly an issue regarding the sustainable design of infrastructures, where the consequences of an inadequate design-related decision might be severe for society. In this context, minimizing the unavoidable subjectivity inherent in decision-making problems is essential. It is well known that the greater the number of criteria or the more complex the relationships between them, the less able the decision maker is to make coherent and accurate judgments [33]. Therefore, research has been conducted in recent decades to effectively capture the decision maker's view of the problem and reflect it in the most accurate weighting of criteria. One way to minimize non-probabilistic uncertainties consists in reducing the complexity of the problem to increase the consistency of the decision. This might be achieved through an adequate reduction in the number of judgments required by the decision maker to complete the decision-making process. ANP can allow for such a reduction if applied to quantitative criteria-based decision-making problems.

So, the AHP technique is valid for decision-making problems that can be structured hierarchically, i.e., problems where the relationship between criteria and sub-criteria can be structured in levels where the dependencies flow in only one direction. However, the ANP procedure allows for modelling more complex decision-making problems. The relationship between criteria and sub-criteria cannot be assumed to be hierarchical except where relationships of any kind may exist between them. In addition, ANP-based problems where every criterion can be derived quantitatively allow for a reduction in the number of comparisons required by the expert, thus leading to more consistent results.

The present paper proposes applying the ANP technique for designing a bridge in a coastal environment based on sustainability-related criteria. To the authors, no study has been conducted on the sustainability assessment of bridges using ANP. In this case, nine sustainability-related criteria are used to determine the design alternative for a given bridge that contributes most to sustainability. The infrastructure chosen for this study is a concrete bridge close to the coast and is exposed to a harsh environment that will entail significant maintenance. The sustainability and life cycle performance of five different alternative designs is analyzed using the ANP technique. The results are then compared with those derived from the determination of the weights using the conventional AHP technique. In addition, as ANP provides both the criteria weights and the scoring of each alternative, the ANP results are compared with an AHP-TOPSIS decision-making process.

2. Materials and Methods

2.1. The Analytic Hierarchy Process and the Consistency Measure

The AHP methodology is a multi-criteria decision-making tool developed by Saaty in the 1980s [23]. This method is used to determine the relative importance of each criterion or alternative involved in a given decision-making problem based on paired comparisons. These comparisons are expressed in the so-called Saaty Fundamental Scale, which allows a closed set of 9 semantic values to be converted into 9 numerical integers ranging from 1 to 9. These semantic values express different levels of how relevant one criterion A is considered to be when compared to another criterion B, with 1 being equivalent to the judgment "A and B are equally important", and 9 being equivalent to the judgment "A is extremely more important than B". The remaining intermediate values between 1 and 9 express intermediate levels of comparison. Thus, the experts involved in the decision-making process are asked to compare the importance of the criteria or alternatives by choosing only one of the nine semantic alternatives of the fundamental scale for each comparison.

By doing so, a so-called comparison matrix can be constructed, where rows and columns stand for each of the criteria involved, and each position a_{ij} shall contain the expert's judgment in relation to the relative comparison between criteria i and j, expressed in terms of Saaty's fundamental scale. It is important to note that inverse values of Saaty's scale can also be used when filling the comparison matrix. This is in fact essential, as if criterion i is considered to be much more relevant than criterion j, then criterion j should be considered to be less relevant than i to the same extent. As a result of that, AHP comparison matrices are always reciprocal matrices, i.e., if $a_{ij} = x$, then $a_{ji} = 1/x$.

Once the comparison matrix has been constructed, the AHP method allows for deriving the weight of each criterion as the values of the eigenvector corresponding to the largest eigenvalue of the comparison matrix. For the resulting weights to be mathematically acceptable, the comparison matrix is required to be consistent. Saaty [23] suggested a method to analytically determine if the comparison matrix is sufficiently consistent or not. This method consists in determining the so-called Consistency Index (CI), which is calculated as:

$$CI = (\lambda_{max} - n)/(n - 1), \tag{1}$$

where λ_{max} is the maximum eigenvalue corresponding to the eigenvector of the comparison matrix, and n is the number of criteria involved. If n criteria are involved in the decision-making problem, the comparison matrix will be a square nxn matrix. A Consistency Ratio (CR) can be obtained from the CI value obtained by dividing $CI/RI = CR$, where the Random Index RI is an index expressing the consistency derived from a completely random comparison matrix. The RI value depends on the number of criteria involved in the process (Table 1). If the CI result of a given comparison matrix is close to RI, it means that the matrix has been filled in a totally random way, thus expressing an absolute inconsistency and lack of knowledge of the involved expert when evaluating the problem to be solved. Conversely, a low consistency indicates that the decision-maker has a clear view of the problem. It is widely accepted that CI/RI that is less than 10% indicates sufficiently consistent comparison matrices. However, the authors consider it more appropriate to be less permissible when the problem involves fewer criteria, as in those cases, the expert should be more capable of making coherent judgments. Table 1 includes the limiting CR considered in this research.

Table 1. Values of the Random Index associated to different numbers of criteria and limiting *CR* values.

Number of Criteria *n*	Random Index (*RI*)	Maximum Acceptable *CR*
2	0	0%
3	0.58	5%
4	0.90	9%
5	1.12	10%
6	1.24	10%
7	1.32	10%
8	1.41	10%
9	1.45	10%
10	1.49	10%

Although AHP allows for both the obtention of criteria weights and criteria relevancies, AHP is usually considered for the obtention of criteria weightings, leaving the determination of alternative scoring to the complementary use of other advanced MCDM techniques such as TOPSIS, which will be described below. The described procedure is summarized in the flowchart in Figure 1.

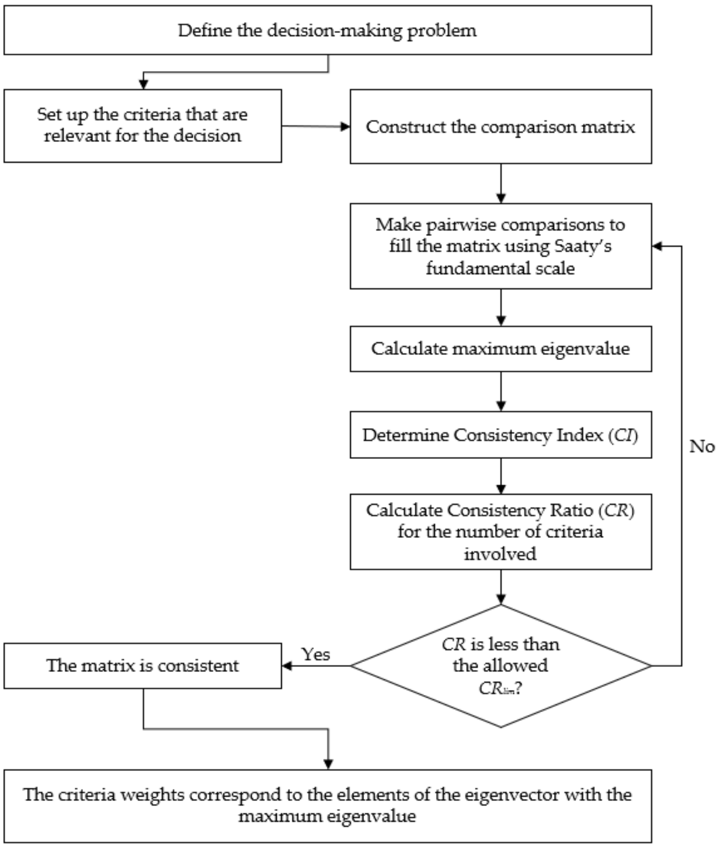

Figure 1. Flowchart representing the AHP procedure.

2.2. The Analytic Network Process

As discussed above, in an AHP-based decision model, criteria, sub-criteria, and alternatives are structured hierarchically, i.e., there is a linear and unidirectional relationship between these levels. ANP, on the other hand, allows a much broader definition of the relationships between the components, which are now structured as a network. The different elements of the model, be they criteria, sub-criteria, or alternatives, are grouped into so-called clusters. ANP allows for a bidirectional relationship between clusters, which means that some or all of the elements of one cluster may depend on some or all of the elements of another cluster, and vice versa. In addition, ANP allows for considering elements of a cluster that rely on elements contained in that cluster. Both dependencies are called external and internal, respectively, and both can be unidirectional or bidirectional. The construction of the decision model network is an essential step in the ANP technique. The decision maker needs, first of all, to determine the criteria, sub-criteria, and alternatives to be included in the decision problem, as well as to properly define which elements are going to be part of each cluster and to establish the relationships between them, always according to his/her vision of the problem. These network relationships are presented in the form of a so-called supermatrix, a matrix that includes all the elements of the network (criteria, sub-criteria, and alternatives).

Each element s_{ij} of this supermatrix is then filled with 0 or 1. Here, 0 means that element j is not influenced by element i, and 1 means that there is influence. It shall be noted that, in contrast with the comparison matrices associated with AHP methodology, ANP supermatrices are not reciprocal, i.e., element i can be influenced by element j, but element j must not necessarily be affected by element i. Once the supermatrix has been constructed, the decision maker must determine the influence that each element belonging to each cluster has on any other element. For each cluster, only the non-zero components of the matrix should be considered. That influence is obtained using the conventional application of the AHP procedure. The decision maker should fill in the comparison matrices, as usual, using Saaty's fundamental scale to fill in a consistent comparison matrix that assesses the influence that the elements i exert on the element j. In doing so, for each element of the supermatrix, a so-called unweighted supermatrix will be constructed, in which the elements of the initial supermatrix filled in with ones are now replaced by the corresponding AHP-derived weights.

To proceed with the ANP methodology, it is essential that the obtained unweighted supermatrix becomes stochastic, which means that every column sums 1. To do so, the values of the unweighted supermatrix must be multiplied by the weight of the cluster they belong to. The weighting of each cluster is again obtained conventionally using the AHP methodology. The resulting supermatrix is then called a weighted stochastic supermatrix. Once this matrix has been obtained, the last step of the ANP methodology consists in powering this supermatrix as often as required to make every column converge to the same values. This resulting supermatrix is called the limiting supermatrix, in which every column is the same. The values of the different elements of these columns correspond to the weights of the criteria, given the case they are criteria elements, or to the final scoring of the alternatives, given the case they belong to the alternatives cluster. Figure 2 shows the flowchart representing the ANP procedure described in the present section.

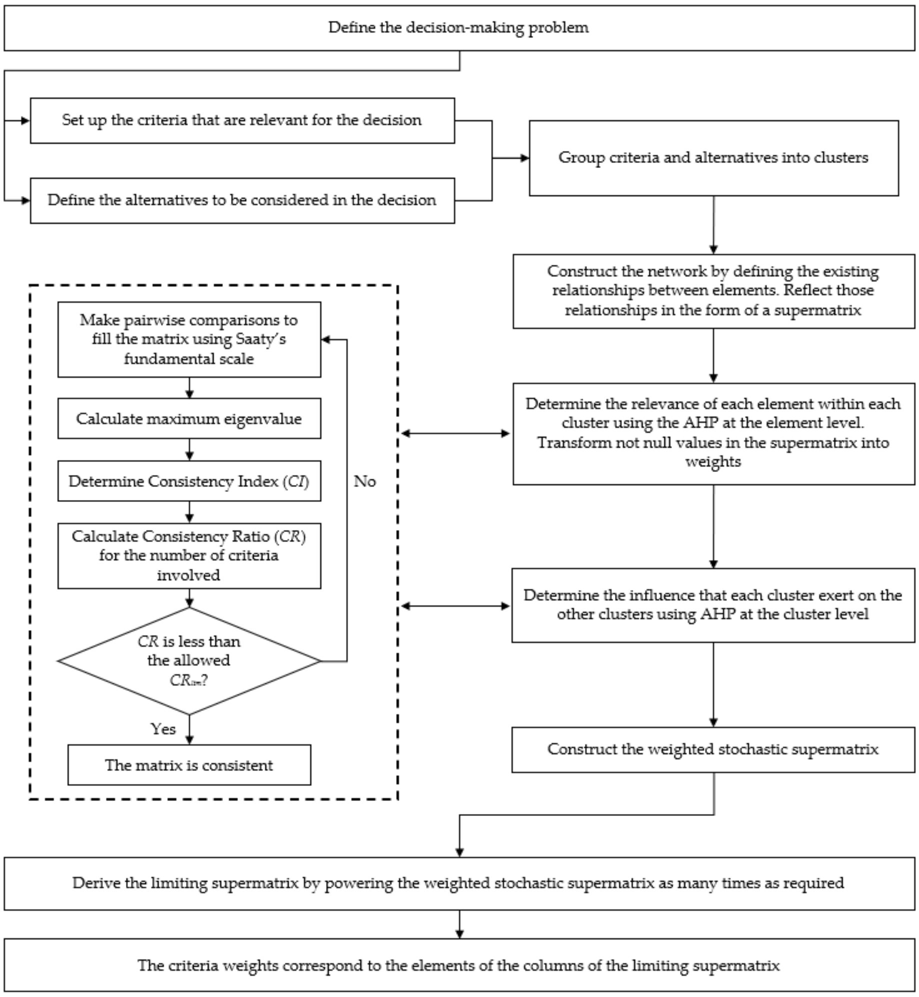

Figure 2. Flowchart representing the ANP procedure.

2.3. TOPSIS Technique

TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is an MCDM methodology widely used in the sustainability assessment of bridges [34], usually combined with AHP. This method, initially developed by Hwang and Yoon in 1981 [35], bases the search for the best alternative on determining the one that simultaneously has the shortest distance to the ideal solution and the longest distance to the worst one. To find such an alternative, the method requires several steps. The first step involves building an evaluation matrix $(p_{ij})_{mxn}$, including the m alternatives and n criteria. Then, the scores p_{ij} that each alternative i has regarding the different criteria j need to be normalized as:

$$p'_{ij} = p_{ij} / \sqrt{\sum_{j=1}^{m} p_{ij}^2}, \tag{2}$$

The normalized scores p'_{ij} are then transformed into the normalized weighted scores v_{ij} by multiplying them by the corresponding criteria weights w_j. These weights are usually obtained using the classical AHP method as a previous step. Then, the hypothetical best and worst alternatives are obtained as the ones constructed by the best (v_{bj}) and worst (v_{wj}) possible normalized weighted scores for each criterion. Then, the distance of each alternative to those hypothetical extreme alternatives is calculated as:

$$D_i^+ = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_{bj}\right)^2}, \tag{3}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_{wj}\right)^2}, \tag{4}$$

Finally, the scoring of each alternative is calculated as the similarity to the worst condition as:

$$S_{iw} = D_i^- / \left(D_i^- + D_i^+\right), \tag{5}$$

The closest the index S_{iw} falls to 1, the closest the corresponding alternative is to the ideal solution and the farthest to the worst one.

3. Case Study

In coastal environments, concrete structures are particularly exposed to highly aggressive deterioration from chlorides penetrating the concrete cover and triggering corrosion processes in the outermost rebars. Research has been conducted recently that studies the consequences of reinforcement corrosion in coastal bridges [36,37]. Consequently, such structures are highly prone to significant maintenance needs, thus leading to important impacts of every kind along their life cycle derived from maintenance operations. Although the outermost steel rebars belong to the shear reinforcement, for simplicity's sake, the present case study considers corrosion acting only on the longitudinal rebars, which will be critical for the bridge sections close to the center of the span. In the present study, the ANP procedure will be used to investigate which of five possible design alternatives for a concrete bridge in a coastal zone is most suitable in terms of sustainability.

To that end, in addition to a conventional design that will serve as the basis for the study (hereafter referred to as REF), four design alternatives are evaluated to avoid the corrosion of the reinforcement due to environmental chlorides. Two alternatives include adding 10% silica fume (alternative SF10) or 10% fly ash (FA10) to the baseline mix. By doing so, the resulting concrete will be less porous and, therefore, present higher resistance to the diffusivity of chlorides through the concrete cover of the rebars. Another alternative is a surface treatment with a sealant (alternative SEAL), which is intended to prevent chlorides from getting in touch with concrete. At last, an alternative considering high corrosion resistant galvanized steel rebars (hereafter as GALV) instead of the conventional carbon steel reinforcement rebars is also included in the present research. The concrete mixes associated with each alternative are presented in Table 2. The concrete cover assumed for every alternative is 40 mm.

Table 2. Concrete mixes considered for the life cycle assessment of the alternatives analyzed (based on [38]).

Component	Baseline (REF)	10% Silica Fume (SF10)	10% Fly Ash (FA10)	Sealant (SEAL)	Galvanized Steel (GALV)
Water (l/m^3)	140	140	140	140	140
Cement (kg/m^3)	350	280	339.5	350	350
Fine aggregates (kg/m^3)	1068	1129	1077	1068	1068
Coarse aggregates (kg/m^3)	1017	1017	1017	1017	1017
Silica fume (kg/m^3)	-	35	-	-	-
Fly ash (kg/m^3)	-	-	35	-	-
Plasticizer (kg/m^3)	5.3	4.2	5.1	5.3	5.3

To analyze the life cycle impacts in the economic, environmental, and social fields, a functional unit has been chosen that consists of a 1 m long bridge deck section with a total width of 12 m constructed near the shore, designed to provide terrestrial connection along a lifespan of 100 years. Every impact or other results presented in this paper are referred to as this functional unit. The maintenance required by each alternative over its life cycle is different depending on its durability against chloride attack. For each alternative, a periodic maintenance interval is chosen so that the probability of failure in the year preventive maintenance is carried out is less than 10% [39]. Here, failure is assumed to occur when the content of chlorides at the rebar depth exceeds the reinforcement's critical chloride threshold (C_0). Consequently, it is assumed that the maintenance operation will consist in replacing the concrete cover depth for which this threshold is exceeded, which will vary depending on the year of maintenance chosen for each alternative. Such depth x (in mm) has been obtained considering Fick's second law of diffusion as suggested in Fib Bulletin 34 [40]:

$$C(x,y,t) = C_s \cdot \left\{ 1 - erf\left(\frac{x}{2\sqrt{D_0 \cdot \left(\frac{t_0}{t}\right)^{\alpha} \cdot t}} \right) \right\}, \quad (6)$$

where t is the time when maintenance is held (in years), D_0 is the diffusion coefficient of concrete (in mm^2/year), C_s is the surface concentration of chlorides (in wt%/binder), and $erf(\cdot)$ stands for the Gauss error function. C_s is assumed to be C_s = 0.0329 and the age factor α is taken as 0.5, following the recommendations of the Spanish code for the structural design of concrete structures [41].

The parameters for assessing the durability of each design option are presented in Table 3. Table 3 shows the mean values of the diffusion coefficient (D_0) and the critical chloride content (C_{cr}), as well as the value of the standard deviation of each parameter in brackets.

Table 3. Durability parameters considered for the life cycle assessment of the alternatives analyzed.

Parameter	Baseline (REF)	10% Silica Fume (SF10)	10% Fly Ash (FA10)	Sealant (SEAL)	Galvanized Steel (GALV)
D_0 (m^2/s)	8.9×10^{-12} (0.9×10^{-12})	1.2×10^{-12} (0.2×10^{-12})	5.5×10^{-12} (0.4×10^{-12})	4.3×10^{-12} (0.3×10^{-12})	8.9×10^{-12} (0.9×10^{-12})
C_{cr} (%)	0.6 (0.1)	0.6 (0.03)	0.6 (0.1)	0.6 (0.1)	1.2 (0.2)

Given that sustainability relies on three dimensions (economy, environment, and society), a set of indicators has been chosen to represent the main impacts that the life cycle of a bridge can generate for each of them. In this case, to assess the sustainability of each alternative throughout its life cycle, a set of nine criteria is considered, each of which corresponds to a specific type of impact. To quantify the effects on the economic dimension of sustainability, the following two criteria/impacts are considered: on the one hand, the costs derived from the construction of the functional unit for each design alternative, and on the other, the costs derived from periodic maintenance. It is worth mentioning that, as this case study is oriented toward sustainability assessment, the costs of the maintenance phase have been calculated considering a social discount rate of d = 2%, which is lower than the usual financial discount rates for private projects.

The social impacts derived from the construction and maintenance of each considered alternative are based on a set of quantitative indicators proposed by Navarro [42]. These are then grouped into four impact categories, each corresponding to one of the four social decision criteria in the present analysis. The first category considers the positive social impact resulting from the generation of employment. Aspects such as unemployment, gender equity, fair salary, or accidentality are considered to evaluate the absolute amount of employment generated and its quality [43,44]. The second decision criteria considered here is the contribution of each alternative to the economic development of the regions affected by the construction and maintenance of each option. The contribution of the bridge's functionality is not considered here as every alternative shall provide the same according to the functional unit described. The third social impact considers the positive effect that the absence of maintenance has on the infrastructure users, such as less impact on accessibility and less risk of accidents [45]. The last social impact included in this study is the positive effect that the absence of maintenance has on public opinion. The less maintenance required, the fewer externalities due to the lack of vibrations, noise, dust, or loss of aesthetics due to maintenance operations [46], thus affecting less negatively the opinion the community might have on the infrastructure.

To assess the impact of each alternative on the environment, three types of impacts are considered. On the one hand, the damage that the emissions derived from the production, transport, and installation of the materials have on human health, both in the construction phase and in the maintenance phase. Likewise, the damage that these emissions cause to ecosystems is also considered independently. Finally, the impact of the extraction of raw materials involved in the life cycle of the functional unit on the availability of natural resources is assessed. These three impacts correspond to the endpoint indicators of the ReCiPe life cycle analysis methodology. These three indicators have been widely used in environmental life cycle analyses of products due to the simplicity of their interpretation and ease of integration into decision-making processes [47,48].

The economic, environmental, and social impacts have been calculated for each alternative, considering the criteria described above and resulting in the values provided in Table 4. It is important to note that the present assessment results have been obtained from the research conducted by Navarro et al. [38]. To find more specific information regarding the assumed product system, inventory data, and economic information, please refer to [38].

Table 4. Impact assessment of each of the alternatives, based on Navarro et al. [38].

	Criterion	**Baseline (REF)**	**10% Silica Fume (SF10)**	**10% Fly Ash (FA10)**	**Sealant (SEAL)**	**Galvanized Steel (GALV)**
Economic criteria	Construction costs	1296.4	1566.6	1387.1	1557.9	2707.7
	Maintenance costs	5511.3	258.2	2208.4	492.8	2121.3
Social criteria	Employment generation	0.671	0.507	0.570	0.611	0.574
	Econ. development of regions	0.637	0.395	0.471	0.519	0.801
	Users	0.060	0.526	0.160	0.156	0.157
	Public opinion	0.057	0.523	0.157	0.153	0.153
Environmental criteria	Human health	270.6	62.8	138.4	50.7	151.8
	Ecosystems	139.9	29.9	70.8	25.4	75.8
	Scarcity of resources	302.5	118.1	176.5	100.2	190.6

4. Results and Discussion

4.1. Analytic Network Process Results

The first step consists of the ANP methodology, which involves constructing the network of relationships between criteria and alternatives. First, the elements of the model must be grouped into decision-relevant clusters. A first cluster with the five design alternatives (REF, SF10, FA10, SEAL, and GALV) is considered in this case. On the other hand, the criteria are grouped into the following three separated clusters: one including the two economic criteria, one comprising the three environmental criteria, and one including the four social criteria described above. As a result, a network with four clusters is assumed. The division into these clusters is not rigid, as it would also be possible to work with a more significant number of clusters (in fact, as many as the number of criteria), making the problem more precise. Still, it would complicate it enormously and harm the consistency of the decision maker's judgments, which is precisely what we are trying to avoid.

Once it has been decided which elements will conform to the decision model and how they are grouped, the relations existing between them are evaluated. As the first step for this, an initial supermatrix is constructed where it is stated whether a relation between elements exists or not. For the present problem, it is assumed that the sustainability performance of each alternative does not influence the performance of the rest. As a result, the first 5x5 quadrant of the supermatrix is filled with zero values. As usual in ANP decision-making problems, it is assumed that there exists a relation between every criterion and every alternative, and vice-versa. Consequently, the quadrants adjacent to the 5x5 alternatives quadrant of the supermatrix are filled with ones. The decision maker is then left with the decision of how the criteria are related. For the present decision-making problem, an expert with 19 years of experience in the structural design of bridges was involved. Figure 3 shows the supermatrix of the resulting network model.

	REF	SF10	FA10	SEAL	GALV	C.C.	M.C.	H.H.	Eco.	Res.	Empl.	E.D.	Us.	Ext.
REF	0	0	0	0	0	1	1	1	1	1	1	1	1	1
SF10	0	0	0	0	0	1	1	1	1	1	1	1	1	1
FA10	0	0	0	0	0	1	1	1	1	1	1	1	1	1
SEAL	0	0	0	0	0	1	1	1	1	1	1	1	1	1
GALV	0	0	0	0	0	1	1	1	1	1	1	1	1	1
C.C.	1	1	1	1	1	0	0	0	0	0	0	1	0	0
M.C.	1	1	1	1	1	0	0	0	0	0	0	1	0	0
H.H.	1	1	1	1	1	0	0	0	1	0	0	0	0	0
Eco.	1	1	1	1	1	0	0	1	0	0	0	0	0	0
Res.	1	1	1	1	1	1	1	0	1	0	0	0	0	0
Empl.	1	1	1	1	1	1	1	0	0	0	0	1	0	0
E.D.	1	1	1	1	1	0	0	0	0	0	0	0	0	0
Us.	1	1	1	1	1	0	0	1	0	0	0	0	0	1
Ext.	1	1	1	1	1	0	0	1	0	0	0	0	1	0

Figure 3. Supermatrix of the resulting network model showing the inner and outer relations between elements (C.C. = Construction costs; M.C. = Maintenance costs; H.H. = Human health; Eco. = Ecosystems; Res. = Resources; Empl. = Employment generation; E.D. = Economic development of regions; Us. = Users; Ext. = Externalities).

The next step consists of determining the relevance of each of the selected relations. When, as in this case, the decision-making problem considers exclusively quantitative criteria, the expert only needs to complete the relationships that, according to his or her vision of the problem, may exist between the criteria, since the relationships between the criteria and alternatives can be deduced automatically from the values of the impacts of each alternative. The life cycle assessment results presented in Table 4 are considered to that end. On the other hand, the relationships that do not involve the alternatives, i.e., those existing only between the criteria, can be now quantified by means of the conventional AHP procedure. Figure 4 shows the resulting unweighted supermatrix.

	REF	SF10	FA10	SEAL	GALV	C.C.	M.C.	H.H.	Eco.	Res.	Empl.	E.D.	Us.	Ext.
REF	0	0	0	0	0	0.25	0.03	0.07	0.07	0.10	0.23	0.23	0.06	0.05
SF10	0	0	0	0	0	0.20	0.55	0.30	0.31	0.26	0.17	0.14	0.50	0.50
FA10	0	0	0	0	0	0.23	0.06	0.14	0.13	0.17	0.19	0.17	0.15	0.15
SEAL	0	0	0	0	0	0.20	0.29	0.37	0.37	0.31	0.21	0.18	0.15	0.15
GALV	0	0	0	0	0	0.12	0.07	0.12	0.12	0.16	0.20	0.28	0.15	0.15
C.C.	0.81	0.14	0.61	0.24	0.44	0	0	0	0	0	0	0.2	0	0
M.C.	0.19	0.86	0.39	0.76	0.56	0	0	0	0	0	0	0.8	0	0
H.H.	0.26	0.28	0.27	0.29	0.26	0	0	0	0.5	0	0	0	0	0
Eco.	0.51	0.58	0.52	0.57	0.53	0	0	1	0	0	0	0	0	0
Res.	0.23	0.15	0.21	0.14	0.21	1	1	0	0.5	0	0	0	0	0
Empl.	0.47	0.26	0.42	0.42	0.34	1	1	0	0	0	0	0	0	0
E.D.	0.45	0.20	0.35	0.36	0.48	0	0	0	0	0	0	0	0	0
Us.	0.04	0.27	0.12	0.11	0.09	0	0	0.25	0	0	0	0	0	1
Ext.	0.04	0.27	0.12	0.11	0.09	0	0	0.75	0	0	0	0	1	0

Figure 4. Unweighted supermatrix of the resulting network model.

As can be observed in Figure 4, the columns of this supermatrix do not sum up to one. To obtain a stochastic, weighted supermatrix, the decision maker must now determine the weight of the influence that each of the clusters that have been defined in the network model exerts on the others. To that end, the AHP procedure is used. It should be noted that, in order to carry out these paired comparisons, only the clusters involved need to be considered. This fact significantly reduces the number of comparisons to be completed, thus increasing the consistency of the decision maker and, consequently, the reliability of the decision finally adopted. Figure 5 shows each cluster's relevance to the rest according to the expert's vision of the decision problem. It should be noted that the most significant dimension of the AHP comparison matrix required to fill this cluster matrix is, in this case, 4x4, corresponding to the determination of the clusters' influence on the economic criteria. Figure 5 shows the consistency ratios (*CR*) derived from each AHP comparison matrix and the coefficient CR/CR_{lim}. It can be observed that in no case does the value of the obtained *CR* exceed 50% of the limiting *CR*, which corresponds to highly consistent judgments.

	Alternatives	Economic Criteria	Environmental Criteria	Social Criteria
Alternatives	0.000	0.423	0.117	0.669
Economic Criteria	0.075	0.122	0.000	0.088
Environmental Criteria	0.592	0.227	0.683	0.000
Social Criteria	0.333	0.227	0.200	0.243
AHP dimension	3x3	4x4	3x3	3x3
CR	0.013	0.004	0.023	0.007
CR/CR_{lim}	0.270	0.043	0.468	0.134

Figure 5. Relevance of each of the clusters in relation to the rest.

A stochastic, weighted supermatrix is obtained by multiplying the values of the supermatrix presented in Figure 6 by the weights of the cluster to which each of its elements belongs. Figure 4 presents this supermatrix.

	REF	SF10	FA10	SEAL	GALV	C.C.	M.C.	H.H.	Eco.	Res.	Empl.	E.D.	Us.	Ext.
REF	0	0	0	0	0	0.10	0.01	0.01	0.01	0.01	0.15	0.15	0.04	0.04
SF10	0	0	0	0	0	0.09	0.23	0.04	0.04	0.03	0.12	0.09	0.33	0.34
FA10	0	0	0	0	0	0.10	0.03	0.02	0.02	0.02	0.13	0.11	0.10	0.10
SEAL	0	0	0	0	0	0.09	0.12	0.04	0.04	0.04	0.14	0.12	0.10	0.10
GALV	0	0	0	0	0	0.05	0.03	0.01	0.01	0.02	0.13	0.19	0.10	0.10
C.C.	0.06	0.01	0.05	0.02	0.03	0	0	0	0	0	0	0.01759	0	0
M.C.	0.01	0.06	0.03	0.06	0.04	0	0	0	0	0	0	0.07036	0	0
H.H.	0.15	0.16	0.16	0.17	0.16	0	0	0	0.34167	0	0	0	0	0
Eco.	0.30	0.34	0.31	0.34	0.31	0	0	0.68334	0	0	0	0	0	0
Res.	0.14	0.09	0.12	0.09	0.12	0.22735	0.22735	0	0.34167	0	0	0	0	0
Empl.	0.16	0.09	0.14	0.14	0.11	0.22735	0.22735	0	0	0	0	0	0	0
E.D.	0.15	0.07	0.12	0.12	0.16	0	0	0	0	0	0	0	0	0
Us.	0.01	0.09	0.04	0.04	0.03	0	0	0.04995	0	0	0	0	0	0.24264
Ext.	0.01	0.09	0.04	0.04	0.03	0	0	0.14986	0	0	0	0	0.24264	0

Figure 6. Stochastic and weighted supermatrix.

Lastly, the limiting supermatrix is obtained by successively powering the stochastic weighted supermatrix. The number of times the previous supermatrix should be powered is ideally infinity. However, convergence is usually found, depending on the problem, after powering the weighted stochastic supermatrix between 10 and 20 times. Figure 7 shows the resulting limiting supermatrix for the present decision problem.

	REF	SF10	FA10	SEAL	GALV	C.C.	M.C.	H.H.	Eco.	Res.	Empl.	E.D.	Us.	Ext.
REF	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039
SF10	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096	0.096
FA10	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054	0.054
SEAL	0.085	0.084	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085	0.085
GALV	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055	0.055
C.C.	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010
M.C.	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019	0.019
H.H.	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139	0.139
Eco.	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202	0.202
Res.	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128	0.128
Empl.	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048
E.D.	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
Us.	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
Ext.	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046	0.046

Figure 7. Limiting supermatrix.

4.2. AHP-TOPSIS

In this section, the same decision problem will be addressed through a conventional AHP-TOPSIS approach, in which AHP is used to determine the relevance of each decision criterion. Then, those weights are used as an input for applying the MCDM technique, TOPSIS, described above. To derive the weights of each criterion, the expert must fill a 9x9 comparison matrix including every one of the criteria involved in the decision-making problem. Figure 8 shows the AHP comparison matrix completed by the expert, as usual, considering the values of Saaty's fundamental scale. It shall be noted that the same expert was involved in the ANP approach.

	C.C.	M.C.	H.H.	Eco.	Res.	Empl.	E.D.	Us.	Ext.
C.C.	1	6	1/5	1/6	1/5	4	1	1/4	1/3
M.C.	1/6	1	1/7	1/7	1/6	1/3	1/3	1/6	1/7
H.H.	5	7	1	1/2	1	5	5	2	2
Eco.	6	7	2	1	1	7	6	2	5
Res.	5	6	1	1	1	5	4	1	1
Empl.	1/4	3	1/5	1/7	1/5	1	1/4	1/6	1/6
E.D.	1	3	1/5	1/6	1/4	4	1	1/5	1/3
Us.	4	6	1/2	1/2	1	6	5	1	2
Ext.	3	7	1/2	1/5	1	6	3	1/2	1

Figure 8. AHP comparison matrix.

The Consistency Ratio that results from the AHP comparison matrix presented above is $CR = 0.059$, which is below the limiting CR. The ratio CR/CR_{lim} is, in this case, 59.5%. The resulting criteria weights are presented in Table 5.

Table 5. Criteria weights according to conventional AHP procedure.

Criterion	AHP-Derived Weights
Construction costs	4.92%
Maintenance costs	1.79%
Employment generation	2.50%
Econ. development of regions	4.56%
Users	15.30%
Public opinion	11.03%
Human health	18.24%
Ecosystems	25.46%
Scarcity of resources	16.19%

Considering these criteria weights, the TOPSIS procedure is applied to obtain the best sustainable alternative, in accordance with the results of the life cycle assessment presented in Table 4. Table 6 presents the results after applying the TOPSIS technique.

Table 6. Sustainability-related performance results of the alternatives after applying AHP-TOPSIS.

Criterion	Baseline (REF)	10% Silica Fume (SF10)	10% Fly Ash (FA10)	Sealant (SEAL)	Galvanized Steel (GALV)
Distance to ideal positive D_i^+	0.2606	0.0187	0.1442	0.1180	0.1524
Distance to ideal negative D_i^-	0.0197	0.2522	0.1347	0.2170	0.1234
TOPSIS Score S_{iw}	0.0702	0.9310	0.4829	0.6478	0.4474

4.3. ANP vs. AHP-TOPSIS Results

After presenting the results obtained following the ANP approach and the AHP-TOPSIS approach, these will be compared and discussed in the present section. Paying attention to the performance results of each alternative, it is observed that the preferred alternative, irrespective of the approach followed, is the alternative based on the addition of 10% silica fume to the baseline concrete mix (SF10), followed in both cases by the alternative consisting of the application of a surface sealing treatment (SEAL). The silica fume-based solution's good performance relies on the fact that it requires less maintenance than the rest, thus scoring positively in the social affection of users and public opinion. However, considering that the most critical decision criteria have proven to be the environmental ones (Table 5), the good sustainability performance might be explained by the fact that silica fume-based mixes allow for the partial substitution of the required cement to achieve a concrete that works the same than the baseline design. In addition, this solution implies giving use to a co-product of the metallurgic industry, namely silica fume, that would remain as a solid waste otherwise. On the other hand, the worst performing solution for the ANP- and AHP-based approaches is the baseline alternative (REF). Although the results lead to the same conclusions regarding the decision, it is noteworthy that the difference in scoring between SF10 and SEAL alternatives following the ANP procedure is quite reduced (13.7% difference), while for the AHP-TOPSIS approach, this difference is much greater (43.7% difference).

If attention is paid to the criteria weights that result from each of both approaches, it is observed that, in general terms, the results are quite similar (Figure 9). This is consistent with the fact that the expert involved in both decision-making procedures is the same. It is observed that the greatest relevance is given in both approaches to the three environmental criteria, taking an absolute relevance between 60% and 70% if compared to the remaining criteria. However, it should be noted that the AHP-derived weights for the environmental criteria are slightly reduced if compared to those obtained from the ANP approach. However, the main difference between both assessments can be found in the relevance given to the criteria involving the affection for the users. While the ANP-based assessment resulted in a weighting to users of about 5.3%, the AHP-based assessment resulted in a weighting of about three times the previous one (15.3%). Similar results can be derived when it comes to the criterion involving employment generation, for which the relevance derived from ANP is, in this case, three times greater than the weight resulting from the AHP approach. Such differences can be explained by the fact that social valuation is more sensitive to the subjectivity of the expert, being a dimension of sustainability whose quantification is still in a very incipient process of development.

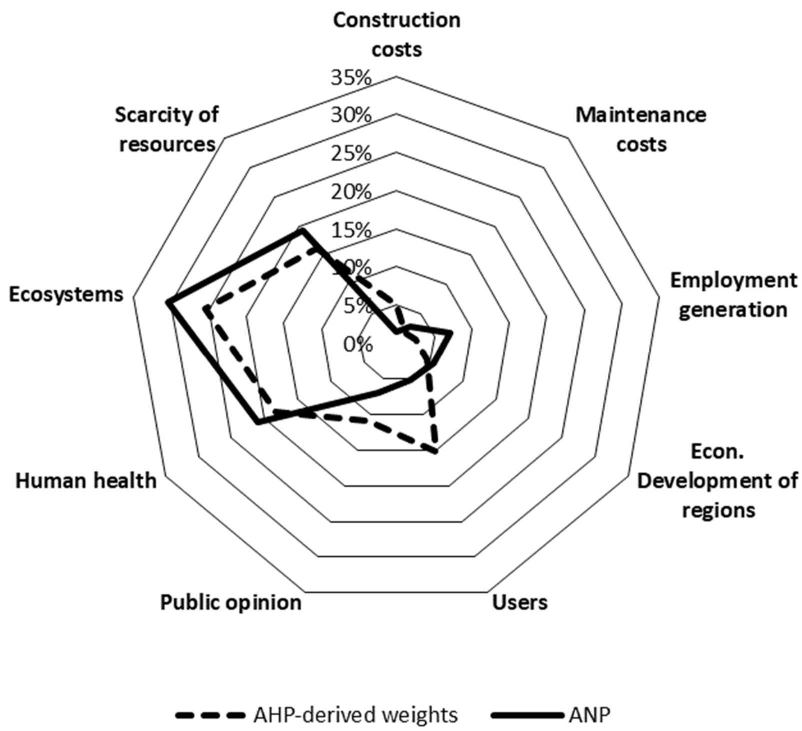

Figure 9. Comparison ANP- vs. AHP-derived criteria weights.

These differences do not provide any information regarding which one of both procedures is more adequate in complex decision-making problems such as the one presented here. They only state the fact that, although the main conclusions might be the same, intermediate results should be carefully interpreted, whether one approach is followed or the other. To understand which of both approaches is more reliable, attention should be paid to the consistency of the assessments that lie behind each of them. As previously shown in Figure 5, the consistency of the ANP-based assessments is quite high. On average, the consistency is about 22% of the limiting *CR*, while the worst case does not exceed 50% of the limiting *CR*. These consistency results apply only for cluster weighting. However, when it comes to the comparison of the criteria, it should be noted that only 2×2 comparison matrices have been required to construct the supermatrix shown in Figure 4. Please observe that the consistency of 2×2 comparison matrices is always and by definition perfect ($CR = 0$). Indeed, the good consistency of an ANP based on quantitative criteria is based on the fact that, in general, it requires filling lower order comparison matrices, thus making it easier for the expert to make consistent judgments. On the contrary, the consistency obtained for the AHP-TOPSIS approach is $CR = 0.059$, which is acceptable but takes 59% of the limiting *CR*. The evaluation of the inner consistencies from both methods led to the conclusion that the ANP assessment based on quantitative criteria results in more consistent and consequently reliable results if compared to conventional AHP-based approaches.

5. Conclusions

This paper aims to analyze the sustainability of five different design alternatives for a concrete bridge in a marine environment using the ANP technique. From the obtained results, case-specific and general conclusions can be drawn. Regarding the case-specific findings:

- The use of concrete with silica fume additions was shown to offer the best response throughout its life cycle when the structure is exposed to chloride environments. This is due to its high durability and to the fact that this alternative replaces part of the cement of a conventional design with silica fume, allowing it to reduce part of the environmental impact associated with cement production and also allowing the reuse of residual by-products of the metallurgical industry, namely the silica fume.
- The least preferred solution in terms of its life cycle sustainability performance corresponded to the design based on conventional materials. The highly aggressive environment associated with coastal spaces and the reduced durability of such designs results in excessively high maintenance needs. This leads to equally high economic and environmental costs in the maintenance phase, making this solution the least successful.
- Conventional designs, although associated with the lowest construction costs and greatest employment generation, lead to maintenance costs that are two to twenty times greater than those corresponding to durable materials.
- The use of corrosion-resistant materials, such as the ones considered in the present research, leads to environmental impacts along their life cycle that can be up to 20% of those corresponding to conventional designs.

Regarding the general findings associated with the performance of the ANP technique in the evaluation of sustainability-related decision-making problems:

- Compared to the AHP approach, the ANP technique further models the complex relationships between the different criteria, making it possible for the expert to reflect his/her vision of the problem more flexibly and accurately.
- The use of this technique to address decision-making problems involving quantitative criteria has proven useful in reducing the inconsistencies associated with conventional methods (AHP), thus increasing the reliability of the final decision. As shown in the discussion of the results obtained, using a quantitative ANP made it possible, when

faced with the same decision problem, to make judgments with an average consistency more than three times higher than that obtained by the conventional AHP technique.

Given the above, it should be noted that the validity of the present conclusions is limited by the fact that corrosion processes have been considered to affect only the longitudinal rebars. Future lines of research will include the affection of corrosion on shear reinforcement.

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