GROUP ANALYTIC NETWORK PROCESS FOR THE SUSTAINABILITY ASSESSMENT OF BRIDGES NEAR SHORE

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ABSTRACT

Since the Paris Agreement was established, great interest has arisen in evaluating the sustainability performance of our structures along with their life cycles. The remarkable economic expenses, the important environmental impacts associated with the construction sector, and the great social benefits that might be derived from a well-designed infrastructure system have put the design of essential infrastructures in the spotlight of many researchers. One of today's main challenges is the derivation of adequate sustainability indicators that aid designers when deciding on the most sustainable design alternative. The sustainability performance of infrastructures is based on various indicators that are often conflicting given their different nature. Consequently, the obtention of such indicators usually needs to be addressed using multi-criteria decision-making methods. The present communication shows the analytic hierarchy process (ANP) for the sustainability assessment of a concrete bridge exposed to a coastal environment, involving several decision-makers. A set of nine quantitative criteria, covering the economic, environmental, and social dimensions of sustainability, has been considered here.

Keywords: life cycle assessment, sustainability, sustainable design, bridges, analytic network process, multi-criteria decision-making, group.

1 INTRODUCTION

There has been a great deal of concern about assessing infrastructure sustainability since the well-known Sustainable Development Goals (SDGs) were recently established in 2015. Such interest is justified since the construction sector is recognized as a major environmental stressor, also responsible for a vast proportion of the yearly budgetary expenses of almost every nation. However, the development of infrastructures is, at the same time, an essential resource for the social and economic wellbeing of the regions. Therefore, the design of infrastructures that effectively contribute to the development of the sustainable society to which we all aspire is becoming a great challenge for engineers and architects, as they need to seek a careful balance between the economic, environmental, and social consequences that result from the infrastructures they design. Recent research has been conducted on structural optimization considering a sustainable approach for several infrastructures, such as bridges [1], [2], earth-retaining walls [3], wind turbine foundations [4], buildings [5], dams [6], or tunnels [7], among others.

Such balance is, however, not evident, as it involves conflicting criteria of different nature, and it needs to maximize the positive impacts of their designs and minimize at the same time the negative ones. Consequently, to address the problem of sustainable design, a multi-criteria decision-making (MCDM) approach is usually adopted. MCDM methods are generally based on a first determination of the relevance of each criterion based on the decision maker's (DM) knowledge and their overview of the problem to be assessed. Once such weights are determined, different MCDM procedures exist to determine an adequate solution according to the DM's understanding of the problem, such as TOPSIS, VIKOR, ELECTRE, and others.

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The popular method for deriving criteria weights based on DM knowledge is the analytic hierarchy process (AHP) [8]. To determine the criteria weights according to AHP, the DM needs to make pairwise comparisons judging the relative relevance of each criterion concerning each of the rest. One of the main drawbacks of such a methodology is that its weights are highly subjective while decisive for the final decision. This implies that the resulting decision might be affected by the so-called non-probabilistic uncertainties associated with the ability of the DM to consistently reflect their vision of the problem while making the pairwise comparisons. In addition, the more complex is the decision problem to be assessed, and the greater the number of criteria involved, the lower the DM's ability to make accurate or even meaningful judgements [9], [10]. This is particularly the case in sustainability-related decision-making problems, where different and conflicting criteria are usually involved [11].

Consequently, research has been conducted during the last decades to effectively capture the DM's vision of the problem and reflect it in a meaningful criteria weighting. Mainly two trends stand out when dealing with such problems. On the one hand, studies have been conducted that integrate fuzzy [10], [13], intuitionistic [14], or even neutrosophic logic [15] in the AHP procedure to transform the abovementioned uncertainties into a source of useful information for the decision-making problem. On the other hand, other studies emphasize reducing the complexity of the problem to increase the DM's consistency. A popular trend to streamline the decision-making problem is reducing the number of pairwise comparisons to be conducted, thus making it easier for the DM to make consistent judgements. It shall be noted that both trends are not exclusive, and studies have been conducted combining both approaches [16].

The analytic network process (ANP) is an extension of the AHP that allows considering the relations between criteria. ANP has arisen as an adequate decision-making procedure to address sustainability-related problems [17], [18], as it adequately captures the complexity of sustainability issues. In addition, ANP can serve as an effective tool to simplify the decision problem. It may lead to less and more understandable comparisons that might be easier to address by the DM if the problem is properly formulated.

The present communication shows how the ANP can lead to such results when used to determine the weights of quantitative criteria sets. Here, nine sustainability-related criteria are used to determine the design alternative of a particular infrastructure that mainly contributes to sustainability. The infrastructure chosen for this study is a concrete bridge near the shore, thus exposed to an aggressive environment that will lead to significant maintenance. The sustainability life-cycle performance of five different alternative designs is analyzed, and the decision on the excellent design is conducted based on ANP integrating three DMs.

2 MATERIALS AND METHODS

2.1 The analytic network process

As exposed above, in an AHP-based decision model, the criteria, subcriteria, and alternatives are hierarchical, i.e., there is a linear, one-directional relation between these levels. The ANP, on the contrary, allows for a much wider definition of the relations between components, which are now structured in the form of a network. The different elements of the model, be they criteria, subcriteria, or alternatives, are grouped into so-called clusters. The ANP allows a bidirectional relation between clusters, meaning that some or all the elements in one cluster can depend on the elements in another cluster and vice versa. In addition, the ANP allows considering cluster elements that depend on elements contained in that cluster. Both types of dependences are called outer and inner dependences, respectively, and both can be one- or bidirectional.

The construction of the model network that properly represents the decision-making problem to be addressed is an essential step in an ANP. The DM needs first to determine the alternatives and criteria involved in the problem and adequately define the clusters and establish the relations that they consider that might exist between the model elements. Those network relations are then presented in the form of the so-called influential supermatrix that includes every element of the network (criteria, subcriteria, and alternatives). Each element m_{ij} of this matrix is filled with 1 or 0 values, 1 meaning that the element *i* is influenced by element *j*. It must be highlighted that this matrix is not reciprocal, i.e., element *i* might be influenced by element *j* but not necessarily the other way round.

Once the influential supermatrix has been constructed, the DM must determine the influence of every element belonging to each cluster on any other element. For each cluster, attention will only be paid to those matrix components that are not zero. Such influence is obtained using the usual AHP method. For example, consider that elements A and B, both belonging to cluster C1, influence element C (Fig. 1). A simple AHP model will be constructed to determine which of the two has a more significant influence on element C.

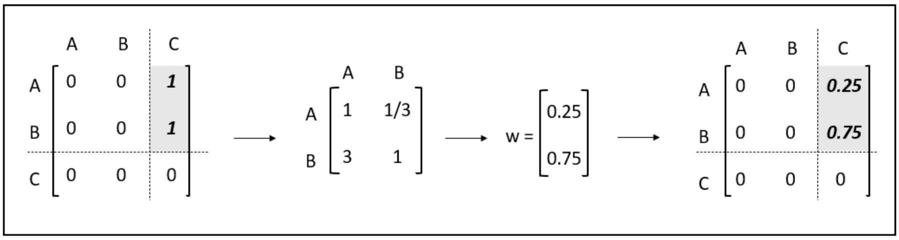


Figure 1: Example of influence determination between elements of a supermatrix.

The DM must fill such a comparison matrix, as usual, using Saaty's fundamental scale to fill a consistent comparison matrix. With every element of the influential supermatrix, a so-called unweighted supermatrix will be constructed. The elements of the influential supermatrix filled with 1 will now be filled with the corresponding weights as shown above (Fig. 1).

It shall be noted that the unweighted supermatrix is not stochastic, i.e., its columns do not sum 1. To make the unweighted supermatrix be stochastic, the elements of each cluster shall be multiplied by the weight of each cluster (considering both criteria and alternatives clusters). These weights are obtained again using a conventional AHP procedure. The resulting stochastic supermatrix is then called the weighted supermatrix.

The last step to determine the criteria weights and the preferred alternatives consists in raising the weighted supermatrix as many times as needed for the elements of each column to converge and remain stable. Such matrix is then called the limiting supermatrix and contains the desired criteria weights and the final rating of the alternatives in each column.

2.2 Group aggregation technique

When several experts are intervening in the decision-making problem, the question arises on including each expert's priorities in the process. Although in recent times complex techniques have been developed to that end, it is common practice to assign each of them a particular voting power and directly aggregate the results obtained by each of them. That voting power is usually determined based on the expert's experience or knowledge in the field [19]. However, as already mentioned above, the more complex a decision problem is, the less accurate and meaningful the expert's judgements, irrespective of their knowledge. The derivation of the experts' voting power proposed here is based on the neutrosophic expert's relevance suggested by [20], [21], where aspects such as the expert's inconsistencies and their manifested self-confidence when emitting judgements are also accounted for.

First, each expert's credibility/knowledge is determined as:

$$\delta_i = \left(\frac{N_i}{\max_{k=1\ldots p}\{N_k\}} + \sum_n K_{c,i}\right)/(n+1), \tag{1}$$

where N_i represents the years of experience of the expert i, and $K_{c,i}$ is a set of n coefficients representing the ith expert's knowledge on the relevant fields to be assessed, and p is the number of experts participating in the decision process. For the sustainability assessment of infrastructures, four coefficients consider their expertise in the social, economic, environmental, and technical assessment of structural designs.

Secondly, the experts' indeterminacy when emitting their judgements is evaluated as:

$$\theta_i = \sum_{q,r=1\ldots n}\left(1 - SC_{qr}^i\right)/M^2, \tag{2}$$

where $SC_{qr}{}^i$ is the average self-confidence expressed by expert i when emitting each pairwise comparison along with the decision-making problem, and M is the total number of judgements emitted.

Lastly, the mean inconsistency of each expert is evaluated based on the inconsistencies derived from each of his/her pairwise comparisons, as:

$$\varepsilon_i = \sum\left(CR_j^i/CR_{lim,j}\right)/J_i, \tag{3}$$

where $CR_i{}^i$ is the consistency ratio of the i^{th} expert regarding the jth comparison matrix filled along the ANP decision process, $CR_{lim,j}$ is the respective limiting consistency ratio which depends on the number of elements to be compared, and J_i is the total number of matrices filled by expert i.

Once these three factors are determined for each expert, the voting power φ_i for an expert i is determined as [22]:

$$\varphi_i = \frac{1-\sqrt{\{(1-\delta_i)^2+{\theta_i}^2+{\varepsilon_i}^2\}/3}}{\sum_{k=1}^{p}\left(1-\sqrt{\{(1-\delta_k)^2+{\theta_k}^2+{\varepsilon_k}^2\}/3}\right)}. \tag{4}$$

Note that if the mean inconsistency of an expert and his/her mean indeterminacy falls to zero, the voting power will be directly proportional to his/her credibility, as usually done in recent research.

3 CASE STUDY

3.1 Description of the functional unit and design alternatives

The methodology described above is used here for the sustainability assessment of five different design alternatives of a concrete bridge deck located in Galicia (Spain) in a coastal environment. The case study presented here is based on Navarro et al. [22]. Besides a conventional baseline design (REF hereafter), three design alternatives are evaluated to prevent chloride-induced corrosion. These reduce the water/cement ratio (alternative W/C35 hereafter), including silica fume or fly ash to the concrete mix, partially substituting the original cement content (alternatives FA20 and HS10, respectively). At last, an alternative with the baseline concrete mix but with galvanized steel reinforcement will also be analysed against its sustainability response along its life cycle (alternative GALV hereafter). Table 1 shows the analysed concrete mixes for each alternative.

Table 1: Concrete mixes for each design alternative.

Concrete mix	REF/GALV	W/C35	SF10	FA20
Cement (kg/m^3)	350	350	280	329
Water (l/m^3)	140	122	140	140
Gravel (kg/m^3)	1,017	1,037	1,017	1,017
Sand (kg/m^3)	1,068	1,095	1,129	1,086
Silica fume (kg/m^3)	–	–	35	–
Fly ash (kg/m^3)	–	–	–	70
Plasticiser (kg/m^3)	5.25	7	4.20	4.94

The functional unit considered here for evaluating the life cycle economic, environmental, and social impacts of each of the abovementioned design alternatives is a 1 m long and 12 m wide bridge deck, including the maintenance operations required to guarantee a service life of 100 years.

In the present life cycle analysis of the abovementioned design alternatives, the maintenance needs for each are different depending on their durability against chlorides. Periodical maintenance is chosen for each of them so that the probability of failure at the year when preventive maintenance takes place is less than 10%. For the present analysis, failure is considered when the chloride content at the rebar depth exceeds the critical chloride threshold. Table 2 presents the parameters assumed for the reliability analysis and the maintenance period chosen for each alternative.

Table 2: Durability parameters for the calculation of each alternative's reliability.

Parameter	REF	GALV	W/C35	SF10	FA20
D_0 ($\times 10^{-12}$ m^2/s)	8.90 (0.90)	8.90 (0.90)	5.80 (0.47)	1.23 (0.17)	4.65 (0.35)
C_{cr} (%)	0.60 (0.10)	1.20 (0.21)	0.60 (0.10)	0.60 (0.03)	0.60 (0.10)
Cover (mm)	40 (2)	40 (2)	40 (2)	40 (2)	40 (2)
Maintenance interval (years)	8	20	15	50	25

Table 2 provides the mean value for each parameter, as well as the standard deviation in brackets.

3.2 Impacts assessment

A set of nine criteria is considered here to quantify the sustainability performance of each alternative, each of them corresponding to one particular type of impact. Table 3 describes the criteria.

Table 3: Decision criteria considered for the sustainability assessment of bridge infrastructures.

Sustainability criterion	Description of the impact	Impact assessment
Construction costs	Economic costs associated to the materials and the construction activities required for the construction of the functional unit	Measured in €. No normalization required
Maintenance costs	Economic costs associated to the materials consumed in maintenance operations	Measured in €. No normalization required. Future costs discounted assuming d = 2%
Damage to human health	Damage to human health derived from the manufacture of the construction materials consumed along the life cycle of the bridge	ReCiPe methodology. Includes increase in respiratory disease, in various cancer types and malnutrition, among others
Damage to ecosystems	Damage to ecosystems and species derived from the manufacture of the construction materials consumed along the life cycle of the bridge	ReCiPe methodology. Includes damage to freshwater species, to terrestrial species and to marine species
Scarcity of natural resources	Consumption of natural resources such as gas or oil derived from the manufacture of the construction materials consumed along the life cycle of the bridge	ReCiPe methodology. Measures the increased extraction costs of oil, gas or coal
Employment generation	Employment generated through the manufacture, construction, and maintenance activities	Indicator based on (Cita social). Takes into account gender issues, fair salary, workers safety and unemployment
Economic wealth generation	Economic inflow to regions where production centres are located	Indicator based on (Cita social). Takes into account the Gross Domestic Product of the regions affected by the product system
Impacts on infrastructure users	Construction and maintenance activities affect the accessibility and the safety of users	Indicator based on (Cita social). Considers the maintenance times and driving speed reduction
Externalities	Noise, dust generation, vibrations and affection to public opinion derived from construction and maintenance activities	Indicator based on (Cita social). Considers maintenance times

The economic, environmental, and social life cycle impacts have been calculated for each alternative considering the same evaluation methodology [22], resulting in the values provided in Table 4. It shall also be noted that the present case study shares the same product system like the one provided in Navarro et al. [22].

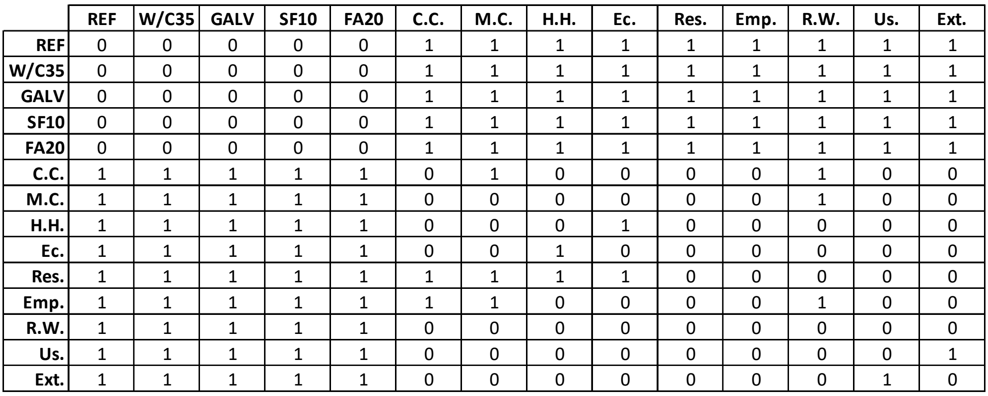
4 RESULTS AND DISCUSSION

Following the ANP procedure described in Section 2.1, the decision problem must be converted into a cluster network. Here, four clusters are considered. The first includes the five design alternatives: REF, W/C35, GALV, SC10, and FA20. The second cluster contains the two economic design criteria: construction and maintenance costs. The third cluster includes three environmental criteria: damage to human health, ecosystems, and resource availability. The last cluster contains the four social criteria in Table 3: employment generation, regional wealth increase, affection to users, and negative impacts on public opinion due to externalities derived from maintenance operations.

Table 4: Sustainability assessment results considering all three dimensions of sustainability.

Impact/criterion	REF	GALV	W/C35	SF10	FA20	Units
Construction cost	1296.38	1322.5	2707.73	1566.64	1386.27	€
Maintenance cost	5850.46	2353.45	2121.26	262.67	1624.01	€
Human health	283.92	142.89	151.85	67.17	130.94	Score
Ecosystems	146.93	73.65	75.81	32.14	64.56	Score
Resources	315.2	181.2	190.6	113.3	164.1	Score
Employment	0.681	0.5704	0.5743	0.5096	0.5585	–
Wealth	0.6557	0.4600	0.8007	0.4006	0.4503	–
Users	0.0655	0.1400	0.1568	0.5017	0.1962	–
Externalities	0.0618	0.1363	0.1532	0.4980	0.1959	–

Each DM is then free to establish the outer and inner dependence relations that he/she considers are relevant to the problem. It shall be noted that the DMs start from a pre-established model, where the sustainability of every alternative depends on every criterion, and the value of every criterion depends on every alternative. Fig. 2 shows the network that results from DM 1's view of the problem presented as an influential supermatrix.

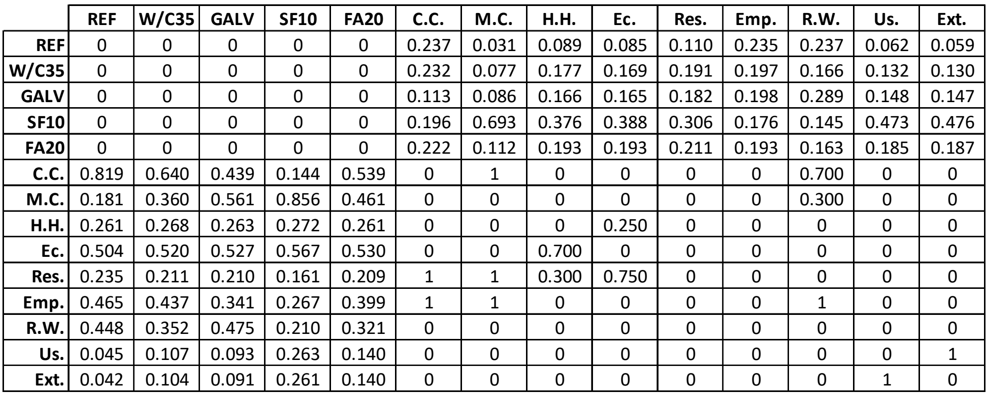


	REF	W/C35	GALV	SF10	FA20	C.C.	M.C.	H.H.	Ec.	Res.	Emp.	R.W.	Us.	Ext.
REF	0	0	0	0	0	1	1	1	1	1	1	1	1	1
W/C35	0	0	0	0	0	1	1	1	1	1	1	1	1	1
GALV	0	0	0	0	0	1	1	1	1	1	1	1	1	1
SF10	0	0	0	0	0	1	1	1	1	1	1	1	1	1
FA20	0	0	0	0	0	1	1	1	1	1	1	1	1	1
C.C.	1	1	1	1	1	0	1	0	0	0	0	1	0	0
M.C.	1	1	1	1	1	0	0	0	0	0	0	1	0	0
H.H.	1	1	1	1	1	0	0	0	1	0	0	0	0	0
Ec.	1	1	1	1	1	0	0	1	0	0	0	0	0	0
Res.	1	1	1	1	1	1	1	1	1	0	0	0	0	0
Emp.	1	1	1	1	1	1	1	0	0	0	0	1	0	0
R.W.	1	1	1	1	1	0	0	0	0	0	0	0	0	0
Us.	1	1	1	1	1	0	0	0	0	0	0	0	0	1
Ext.	1	1	1	1	1	0	0	0	0	0	0	0	1	0

Figure 2: Influential supermatrix from DM 1. (C.C. = construction costs; M.C. = maintenance costs; H.H. = human health; Ec. = ecosystems; Res. = resources depletion; Emp. = employment; R.W. = regional wealth; Us. = Users; Ext = externalities.)

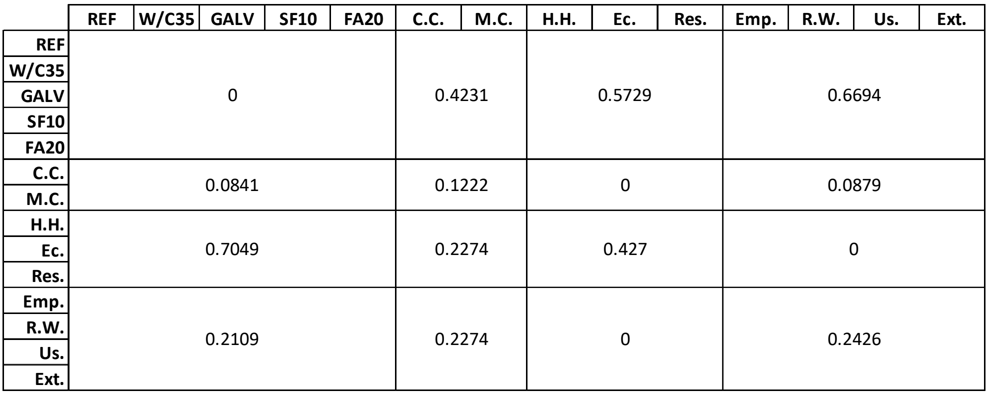
Henceforth, and for simplicity, ANP results will be shown only for DM 1. The unweighted supermatrix will be obtained once the influential matrix has been constructed (Fig. 3). It shall be noted that, given that the present problem includes only quantitative criteria, the values of the first five rows and columns of the supermatrix can be obtained straightforwardly from the values presented in Table 4.

In order to obtain a stochastic, weighted supermatrix, the DM is required to determine the weight of the clusters using a conventional AHP procedure. It shall be noted that, in those pairwise comparisons, only those clusters involved are considered, thus simplifying the number of comparisons to be done and therefore increasing consistency (Fig. 4).



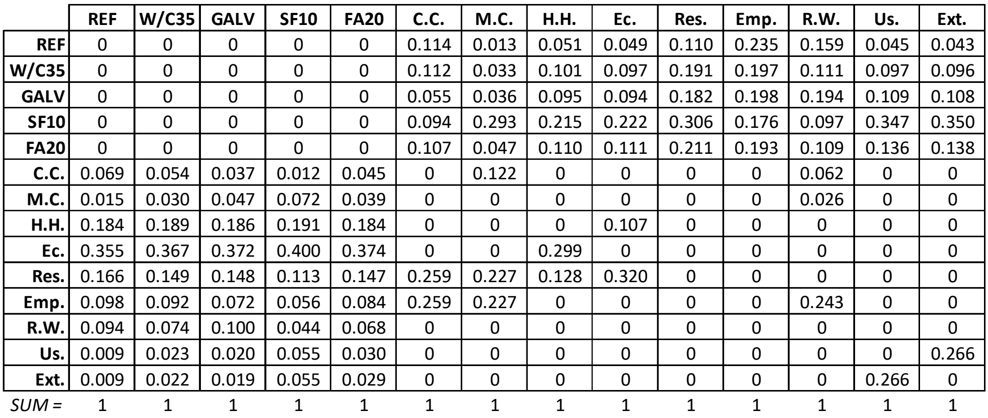
	REF	W/C35	GALV	SF10	FA20	C.C.	M.C.	H.H.	Ec.	Res.	Emp.	R.W.	Us.	Ext.
REF	0	0	0	0	0	0.237	0.031	0.089	0.085	0.110	0.235	0.237	0.062	0.059
W/C35	0	0	0	0	0	0.232	0.077	0.177	0.169	0.191	0.197	0.166	0.132	0.130
GALV	0	0	0	0	0	0.113	0.086	0.166	0.165	0.182	0.198	0.289	0.148	0.147
SF10	0	0	0	0	0	0.196	0.693	0.376	0.388	0.306	0.176	0.145	0.473	0.476
FA20	0	0	0	0	0	0.222	0.112	0.193	0.193	0.211	0.193	0.163	0.185	0.187
C.C.	0.819	0.640	0.439	0.144	0.539	0	1	0	0	0	0	0.700	0	0
M.C.	0.181	0.360	0.561	0.856	0.461	0	0	0	0	0	0	0.300	0	0
H.H.	0.261	0.268	0.263	0.272	0.261	0	0	0	0.250	0	0	0	0	0
Ec.	0.504	0.520	0.527	0.567	0.530	0	0	0.700	0	0	0	0	0	0
Res.	0.235	0.211	0.210	0.161	0.209	1	1	0.300	0.750	0	0	0	0	0
Emp.	0.465	0.437	0.341	0.267	0.399	1	1	0	0	0	0	1	0	0
R.W.	0.448	0.352	0.475	0.210	0.321	0	0	0	0	0	0	0	0	0
Us.	0.045	0.107	0.093	0.263	0.140	0	0	0	0	0	0	0	0	1
Ext.	0.042	0.104	0.091	0.261	0.140	0	0	0	0	0	0	0	1	0

Figure 3: Unweighted supermatrix from DM 1.



	REF	W/C35	GALV	SF10	FA20	C.C.	M.C.	H.H.	Ec.	Res.	Emp.	R.W.	Us.	Ext.
REF	0					0.4231		0.5729			0.6694			
W/C35														
GALV														
SF10														
FA20														
C.C.	0.0841					0.1222		0			0.0879			
M.C.														
H.H.	0.7049					0.2274		0.427			0			
Ec.														
Res.														
Emp.	0.2109					0.2274		0			0.2426			
R.W.														
Us.														
Ext.														

Figure 4: Weight of each cluster from DM 1.



	REF	W/C35	GALV	SF10	FA20	C.C.	M.C.	H.H.	Ec.	Res.	Emp.	R.W.	Us.	Ext.
REF	0	0	0	0	0	0.114	0.013	0.051	0.049	0.110	0.235	0.159	0.045	0.043
W/C35	0	0	0	0	0	0.112	0.033	0.101	0.097	0.191	0.197	0.111	0.097	0.096
GALV	0	0	0	0	0	0.055	0.036	0.095	0.094	0.182	0.198	0.194	0.109	0.108
SF10	0	0	0	0	0	0.094	0.293	0.215	0.222	0.306	0.176	0.097	0.347	0.350
FA20	0	0	0	0	0	0.107	0.047	0.110	0.111	0.211	0.193	0.109	0.136	0.138
C.C.	0.069	0.054	0.037	0.012	0.045	0	0.122	0	0	0	0	0.062	0	0
M.C.	0.015	0.030	0.047	0.072	0.039	0	0	0	0	0	0	0.026	0	0
H.H.	0.184	0.189	0.186	0.191	0.184	0	0	0	0.107	0	0	0	0	0
Ec.	0.355	0.367	0.372	0.400	0.374	0	0	0.299	0	0	0	0	0	0
Res.	0.166	0.149	0.148	0.113	0.147	0.259	0.227	0.128	0.320	0	0	0	0	0
Emp.	0.098	0.092	0.072	0.056	0.084	0.259	0.227	0	0	0	0	0.243	0	0
R.W.	0.094	0.074	0.100	0.044	0.068	0	0	0	0	0	0	0	0	0
Us.	0.009	0.023	0.020	0.055	0.030	0	0	0	0	0	0	0	0	0.266
Ext.	0.009	0.022	0.019	0.055	0.029	0	0	0	0	0	0	0	0.266	0
SUM =	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Figure 5: Weighted supermatrix from DM 1.

Considering the clusters weights presented above, the final weighted supermatrix that results from the dependence network developed by DM 1 is shown in Fig. 5.

The final limiting supermatrix is obtained by powering the weighted supermatrix presented above many times as needed, as every column converges to the same values. Fig. 6 shows the limiting supermatrix obtained for DM 1. From this matrix, the weights of each criterion according to DM 1's view of the problem can be derived from rows 6 to 14 once they get normalized.

	REF	**W/C35**	**GALV**	**SF10**	**FA20**	**C.C.**	**M.C.**	**H.H.**	**Ec.**	**Res.**	**Emp.**	**R.W.**	**Us.**	**Ext.**
REF	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
W/C35	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074
GALV	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074	0.074
SF10	0.138	0.138	0.138	0.138	0.138	0.138	0.138	0.138	0.138	0.138	0.138	0.138	0.138	0.138
FA20	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082
C.C.	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
M.C.	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020	0.020
H.H.	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098
Ec.	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188	0.188
Res.	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140	0.140
Emp.	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049	0.049
R.W.	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029	0.029
Us.	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
Ext.	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018	0.018

Figure 6: Limiting supermatrix from DM 1, showing the weights of each criterion as well as the ranking of the alternatives.

On the other hand, the values of the first five rows provide the ranking of the alternatives according to DM 1's judgements. It is observed that the preferred alternative is SF10, namely the one that consists in partially substituting a portion of the cement included in the baseline concrete mix with silica fume.

Lastly, results from each DM shall be aggregated into a final ranking of alternatives. Table 5 provides the characterization of each DM, depending on their knowledge, the self-confidence reported by them while emitting judgements, and the mean consistency when making the pairwise comparisons required by their respective influential supermatrices. The resulting voting power for each of them is also presented.

Table 5: Characterisation of each DM.

	DM 1	DM 2	DM 3
Years of experience	5	19	15
Knowledge in structural design	0.6	1	1
Knowledge in environmental issues	1	0.4	0.8
Knowledge in economic issues	0.8	0.8	0.4
Knowledge in social issues	0.6	1	0.6
Expert's credibility	0.653	0.840	0.718
Expert's indeterminacy	0.512	0.455	0.424
Expert's inconsistency	0.265	0.270	0.229
Expert's voting power	0.310	0.346	0.344

Considering the above, the scores for each alternative are normalized and aggregated, seeing the relevance of each DM. Table 6 shows the final, aggregated ranking of alternatives.

Table 6: Final scoring of the alternatives.

	REF	W/C35	GALV	SF10	FA20
Aggregated ANP score	0.122	0.176	0.174	0.334	0.195

It is observed that the preferred solution in terms of life cycle sustainability performance is SF10, with a clear advantage if compared to the other design alternative, followed by FA20. Similar results were previously reported by Navarro et al. [22], where design solutions consisting of concrete with silica fume provided the best performances in coastal environments. It is interesting to note the reduced inconsistencies of the DM if compared to the ones reported by Navarro et al. [22]. This is due to the reduced number of comparisons (16 in the case of DM 1, 17 for DM 2, and 18 for DM 3) if compared to the 36 required by a traditional AHP when dealing with a decision problem that includes nine criteria, as the present one.

It shall also be highlighted that ANP allows the DMs to capture their vision of the problem by providing pairwise comparisons and determining the relations they consider relevant to the problem, which can be quite different from one DM to the other.

5 CONCLUSIONS

The construction sector has arisen as an essential tool to reach the sustainable future we all aspire to. It can be responsible for many positive and negative effects on the economy, the environment, and society. However, although crucial to achieving the SDGs recently established, the sustainability assessment of infrastructures still needs further development. The present communication evaluates the sustainability performance of five different bridge deck design alternatives along their life cycle based on the MCDM procedure called ANP. The final ranking of alternatives results from aggregating the judgements of a panel of experts, whose voting power has been determined following a neutrosophic approach.

The preferred design option in terms of its sustainability performance is based on the partial substitution of cement by silica fume. Thus, its durability is increased concerning the conventional baseline design while avoiding part of the negative impacts derived from cement production. Results show the advantages of using ANP when the problem can be formulated based on a quantitative definition of the criteria involved in the decision-making process. In such cases, the ANP methodology reduces the number of judgements to be expressed by the experts and increases their consistency, thus leading to more reliable results.

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