ENHANCING SUSTAINABILITY ASSESSMENT OF BRIDGES IN AGGRESSIVE ENVIRONMENTS THROUGH MULTI-CRITERIA GROUP DECISION-MAKING

MEJORA DE LA EVALUACIÓN DE LA SOSTENIBILIDAD DE PUENTES EN ENTORNOS AGRESIVOS MEDIANTE LA DECISIÓN GRUPAL MULTICRITERIO

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ABSTRACT:

The construction industry is increasingly recognized as critical in achieving Sustainable Development Goals. Construction activities and infrastructure have both beneficial and non-beneficial impacts, making infrastructure design a focal point of current research investigating how best to contribute to sustainability as society demands. Although methods exist to assess infrastructures' economic, environmental, and social life cycle, the challenge remains in combining these dimensions into a single holistic indicator to facilitate decision-making. This study applies four decision-making techniques (ANP, TOPSIS, COPRAS, and VIKOR) to evaluate five different design alternatives for a concrete bridge exposed to a coastal environment. The results indicate that concretes containing even small amounts of silica fume perform better over their life cycle than other solutions usually considered to increase durability, such as water/cement ratio reduction or concrete cover increase.

Keywords: sustainable design, bridges, life cycle assessment, Analytic Network Process, TOPSIS, VIKOR, COPRAS, Multi-criteria decision-making

1.- INTRODUCTION

Sustainability has become a focal point for both the public and private sectors. Since establishing the Sustainable Development Goals in 2015, society has taken concrete actions to implement them. One example is the challenging European Green Deal, which aims to make Europe climate neutral by 2050, focusing on promoting circular economy initiatives. The construction sector is crucial in achieving this goal, as it is responsible for a significant negative environmental impact. Cement production alone is estimated to contribute to approximately 10% of global greenhouse gas emissions [1]. Consequently, the design optimization of infrastructures to reduce economic or environmental impacts is in the spotlight of many researchers, whose works focus on a wide variety of infrastructures such as bridges [2], buildings [3], earth retaining walls [4] or pavements [5], among many others. Also different maintenance strategies are evaluated to reduce life cycle response of infrastructures [6]. Public institutions increasingly emphasize the need to design sustainable infrastructure and buildings, advocating responsible consumption of raw materials and using building materials with low embodied energy and low carbon footprints. This emphasis is also being reflected in regional and state aid for projects with a straightforward sustainable approach, in demand for compliance with specific environmental and social requirements in tenders for public projects of all kinds, the requirement for increasingly demanding levels of certification (ENVISION, LEEDs, BREEAM, ...), and others [7].

Sustainability issues are often dealt with by society following ecological reductionism, while sustainability issues have a multidimensional nature, and their assessment requires an "orchestration of sciences" [8]. To achieve this multidisciplinary approach to sustainability assessment, multi-criteria decision-making (MCDM) techniques are a very effective tool [9]. In this context, research has been conducted in recent years to develop tools and methods to assess the sustainability of infrastructures and draw relevant conclusions to guide future design actions in various structures, applying a wide variety of MCDM techniques to that end. However, there has yet to be a consensus on the MCDM method to focus on sustainable infrastructure assessment. On the contrary, some authors claim that sustainability assessment conclusions should result from applying several MCDM techniques [10].

The present work aims to assess the life cycle sustainability of five design alternatives to a concrete bridge in a coastal region. The robustness of the results against different MCDM methods has been checked by applying four MCDM techniques, namely the Analytic Network Process (ANP), TOPSIS, VIKOR, and COPRAS. For the application of these decision-making techniques, three experts are involved in the decision-making process. The sustainability assessment considers a set of 9 quantitative criteria covering all three dimensions of sustainability, namely economy, environment, and society. The paper is structured as follows. In Section 2, the four different MCDM techniques are described. Section 3 presents the case study to be analyzed, the design alternatives to investigate, and the main assumptions considered for their life cycle assessment. Section 4 shows the main results of the study. Finally, the conclusions derived from this assessment are summarized in Section 5.

2.- MATERIALS AND METHODS

2.1.- TOPSIS

The TOPSIS method (which stands for Technique for Order of Preference by Similarity to the Ideal Solution) was first defined by Yoon and Hwang [11] back in 1981 and has become one of the most popular multi-criteria decision-making methods used in civil engineering decision problems [12]. To cite some examples, the TOPSIS technique has been recently applied to evaluate sustainability-related impacts associated with particular bridges [13] or building [3] construction methods. Marzouk and Sabbah [14] used this technique to integrate sustainable social criteria in selecting suppliers along the construction supply chain.

Applying the TOPSIS technique starts with constructing the decision matrix $R = [r_{ij}]$ and determining the relevance w_i of each criterion i involved in the problem. Usually, the Analytical Hierarchy Process (AHP) [15] is used to that end. It shall be noted that, while the relevances w_i are relative values ranging from 0 to 1 and must sum 1, the elements of the decision matrix R are measured in terms of each criterion (for example, € equivalent CO_2 emissions to air, …). Consequently, the values included in the decision matrix R need to be normalized as:

$$r'_{ij} = \frac{r_{ij}}{\sqrt{\sum_{j=1}^{n} r_{ij}^2}} \quad (1)$$

where n is the number of criteria involved in the problem, then the normalized decision matrix is weighted in the following way:

$$v_{ij} = w_i \cdot r'_{ij} \quad (2)$$

where w_i is the weight of the i^{th} criterion; now, the so-called positive and negative ideal solutions (*PIS* and *NIS*, respectively) are obtained for each criterion. For the case of *PIS*, these are two hypothetical alternatives built by combining the best scores for each criterion considering all the alternatives involved in the decision-making process and the other way around for the *NIS*. After that, the Euclidean distance of each alternative is calculated to the *PIS* and *NIS* as follows:

$$d_j^+ = \sqrt{\sum_{i=1}^{n} \left(v_{ij} - v_i^+\right)^2} \quad (3)$$

$$d_j^- = \sqrt{\sum_{i=1}^{n} \left(v_{ij} - v_i^-\right)^2} \quad (4)$$

where v_i^+ and v_i^- are the components of the *PIS* and *NIS*, respectively, d_j^+ and d_j^- are the Euclidean distances of alternative j to the *PIS* and *NIS*, respectively. Finally, a closeness index Q_j is calculated to evaluate the relative distance of each alternative j to the *PIS* as:

$$Q_j = \frac{d_j^-}{d_j^- + d_j^+} \quad (5)$$

According to the TOPSIS technique, the best solution will be the one with the greatest closeness index Q_j.

2.2.- VIKOR

VIseKriterijuska Optimizacija I Komoromisno Resenje (VIKOR) technique is a widely used MCDM technique introduced by Opricovic [16] to aid decision-making problems involving conflicting criteria. Regarding sustainability-related engineering problems, VIKOR has recently been used to assess short-span bridges [17] or two bridges under a fuzzy logic approach [18]. García-Segura et al. [19] applied a combined AHP-VIKOR approach to evaluate and optimize the sustainability of bridge designs.

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The first step to applying VIKOR involves constructing the decision matrix $R = [r_{ij}]$ and determining the criteria weights w_i. Then, the best and worst values of all criterion functions must be determined, namely r_i^+ and r_i^-. Then, the decision matrix R is normalized as follows:

$$r'_{ij} = \frac{r_i^+ - r_{ij}}{r_i^+ - r_i^-} \quad (6)$$

After that, the weighted and normalized Manhattan distance S_j and the weighted and normalized Chebyshev distance R_j of every alternative j are computed as:

$$S_j = \sum_{i=1}^{n} w_i \cdot r'_{ij} \quad (7)$$

$$R_j = max\{w_i \cdot r'_{ij}\} \quad (8)$$

The last step consists in evaluating a VIKOR measure index Q_j for each alternative j, which is calculated as:

$$Q_j = v \cdot \frac{S_j - min\{S_j\}}{max\{S_j\} - min\{S_j\}} + (1 - v) \cdot \frac{R_j - min\{R_j\}}{max\{R_j\} - min\{R_j\}} \quad (9)$$

Where v is a strategic factor determining the relevance of the two distance metrics, usually, both metrics are compromised by setting $v = 0.5$, which is the approach adopted in this research. According to this technique, the best alternative gets the greatest score in Q_j, provided that the difference with the Q-score of the second best alternative is greater than $1/(j-1)$.

2.3.- COPRAS

COPRAS (Complex Proportional Assessment) method was first introduced by Zavadskas [20] as a way to overcome one of the main disadvantages of the Simple Additive Weighting (SAW) MCDM method, namely the fact that it can only work with maximizing attributes. Given its simplicity and ease of application [21], [22], the COPRAS method has been used in various sustainability-related decision-making problems. Invidiata et al. [23] successfully applied COPRAS to evaluate the sustainability of building design strategies. COPRAS technique has also been used to assess the sustainability of several construction projects [24], [25].

As usual in other MCDM techniques, the COPRAS method requires initiation construction of the problem decision matrix $R = [r_{ij}]$ and determining the criteria weights w_i. Then, the decision matrix is normalized as:

$$r'_{ij} = \frac{r_{ij}}{\sum_{i=1}^{n} r_{ij}} \quad (10)$$

After that, the normalized decision matrix R' is weighted as follows:

$$v_{ij} = w_i \cdot r'_{ij} \quad (11)$$

Then, the sum of the weighted normalized scores for both beneficial and cost criteria associated to each alternative j are calculated separately as:

$$S_{+j} = \sum_{i=1}^{n} w_i \cdot r'_{ij,+} \quad (12)$$

$$S_{-j} = \sum_{i=1}^{n} w_i \cdot r'_{ij,-} \quad (13)$$

where $r'_{ij,+}$ and $r'_{ij,-}$ are normalized scores for the benefit-type and cost-type criteria, respectively. Then, the relative priority Q_j of each alternative j is computed as:

$$Q_j = S_{+j} + \frac{\sum_{k=1}^{m} S_{-k}}{S_{-j} \cdot \sum_{k=1}^{m} S_{-k}} \quad (14)$$

where m is the total number of alternatives involved in the decision-making problem. The best alternative, according to COPRAS, is the one that results in the greatest value of the index Q_j.

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2.4.- ANALYTIC NETWORK PROCESS (ANP)

The Analytic Network Process was first introduced by Saaty [26] as a more general form of the widely used AHP decision-making technique. The ANP method allows for considering complex relations between criteria and alternatives, thus resulting in more accurate modeling of complex real-life problems. ANP has also been widely used in the context of the sustainable design of infrastructures of various types. Ignatius et al. [27] applied ANP to assess green buildings following a fuzzy-logic approach. Dehdasht et al. [28] proposed a hybrid DEMATEL-ANP methodology for risk assessment in oil and gas construction projects. ANP was also recently used to select materials for building projects considering sustainable decision criteria [29]. Navarro et al. [30] also applied ANP for the life cycle assessment of different design alternatives for concrete bridges near shore.

The first step of the ANP method consists in constructing the network model of the decision-making problem to be assessed. Alternatives and criteria are first grouped into clusters containing elements with common properties. Then, the relations between elements are defined by identifying and reflecting them in an influential supermatrix A. Note that relations can be established between elements within a cluster (inner dependences), but also between elements included in different clusters (outer dependences) The relations that can exist between the elements of the network (criteria and alternatives) can be one- or bi-directional, meaning that two connected elements can influence each other, or only one can influence the other, but not the other way round. So, if an element *i* is influenced by an element *j*, then a_{ij} = 1, if not, a_{ij} = 0. Note that the supermatrix A is not necessarily symmetrical.

Once the network has been modeled as the influential supermatrix A, the influences identified with a 1 need to be quantified. This is usually done by applying the AHP technique to determine how relevant such relations are. It shall be noted that the AHP is applied cluster by cluster, only considering non-zero elements. After that, the resulting supermatrix shall be weighted to make it stochastic, i.e., to let the columns sum 1.

This weighted supermatrix shall be powered as many times as needed to make every column identical. The resulting matrix is called the limiting supermatrix. Each of the columns contains the resulting relative weights of the criteria involved and the score of each of the alternatives under analysis.

2.5.- GROUP AGGREGATION TECHNIQUE

Each DM needs to be assigned a so-called voting power to account for the preferences of different decision-makers (DM) in a particular decision-making problem. This aggregation strategy seeks to assign each of them a relevance or voting weight according to their capacities or experience in the field to be assessed [31]. Calculating the voting power of the DMs involved in the decision-making problem is not straightforward, and different approaches can be followed. Here, the voting relevance of each DM is derived based on a neutrosophic approach [32]. Such a technique allows accounting for aspects not only related to the DM's expertise in different fields but also to his/her inconsistencies or uncertainties when emitting judgments during the decision-making process. The DM's expertise is considered to be directly related to his/her credibility δ_i, and can be obtained as:

$$\delta_i = \left(\frac{N_i}{\max_{k=1\dots p}\{N_k\}} + \sum_n K_{c,i}\right)/(n+1) \tag{15}$$

where *p* stands for the number of DMs involved in the process, N_k represents the years of experience of the DM *k*, and $K_{c,i}$ is a set of *n* coefficients ranging from 0 to 1 that represent the knowledge level of the DM *i* in different fields of expertise related to the decision to be made. In this sustainability-related research, four expertise fields are considered relevant, namely economical analysis, environmental and social issues, and structural design.
The uncertainties of each DM are accounted for by means of a so-called expert's indeterminacy θ_i:

$$\theta_i = \sum\nolimits_{q,r=1\dots n} \left(1 - SC_{q,r}^i\right)/J^2 \tag{16}$$

where *J* is the number of judgments emitted along the decision-making process or sub-process, and $SC_{q,r}^i$ is the self-confidence expressed by the DM *i* when comparing elements *q* and *r* in each comparison matrix filled along the decision-making process.
The last neutrosophic term that allows determining the voting power of each expert represents his/her inconsistencies along the process. This is measured as:

$$\varepsilon_i = \sum \left(CR_m^i / CR_{lim,m}\right)/M_i \tag{17}$$

where CR_m^i is the AHP consistency ratio of the expert *i* when filling the comparison matrix *m*, and $CR_{lim,m}$ is the limiting consistency ratio for the number of criteria compared in matrix *m*. Finally, the voting power of expert i is determined as [33]:

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$$\varphi_i = \frac{1-\sqrt{\{(1-\delta_i)^2+{\theta_i}^2+{\varepsilon_i}^2\}/3}}{\sum_{k=1}^{p}\left(1-\sqrt{\{(1-\delta_k)^2+{\theta_k}^2+{\varepsilon_k}^2\}/3}\right)} \quad (18)$$

3.- CASE STUDY

The decision-making methodologies are applied to assess the life cycle sustainability performance of different design alternatives for a concrete bridge exposed to a coastal environment. The functional unit of the analysis consists of a 1 m long and 12 m wide box-girder concrete deck, which is required to last a service life of 100 years. The five design alternatives considered here are meant to increase the durability of a conventional design. To do so, the first alternative under study consists of a conventional concrete design with an increased concrete geometrical cover of 50 mm (this alternative is called CC50 hereafter). The second alternative is a conventional design with a reduced water-to-cement ratio (alternative W/C35 hereafter) to prevent chloride ingress. The third alternative consists of a design containing polymer-modified concrete (PMC10 hereafter. The last two design options are based on concrete with silica fume and fly ash additions (alternatives SF5 and FA20 hereafter). These two subproducts reduce the cement content required to obtain a similar characteristic compressive strength to the reference concrete mix. The composition and characterization of each design option to be assessed are presented in Table 1.

Alternative	CC50	W/C35	PMC10	FA20	SF5
Cement (kg/m³)	350	350	350	329	315
Water (l/m³)	140	122	140	140	140
Gravel (kg/m³)	1017	1037	1017	1017	1017
Sand (kg/m³)	1068	1095	1068	1086	1098
Silica fume (kg/m³)	-	-	-	-	17.5
Fly ash (kg/m³)	-	-	-	70	-
Plasticiser (kg/m³)	5.25	7	-	4.94	-
Latex (kg/m³)	-	-	35	-	-
Cover (mm)	50	40	40	40	40

Table 1: Definition of each design alternative

To adequately evaluate the impacts along the life cycle, the maintenance needs of each alternative need to be addressed. Different methods exist to evaluate the deterioration of structures along the maintenance stage of their life cycle [34]. Here, to make alternatives comparable, it is assumed that maintenance operations are held for each one at the year when the reliability index β reaches 60% of the target reliability β_{lim}. The target reliability is taken as β_{lim} = 1.3, which corresponds to a 10% failure probability [35]. The probabilistic characterization of the parameters used for the reliability-based calculation of the durability of each design, as well as the resulting maintenance interval, are summarized in Table 2. Table 2 provides the mean value for each parameter, as well as the standard deviation in brackets.

Alternative	CC50	W/C35	PMC10	FA20	SF5
D_0 (x10^{-12} m²/s)	8.90 (0.90)	5.80 (0.47)	6.51 (0.55)	4.65 (0.35)	2.94 (0.23)
C_{cr} (%)	0.60 (0.10)	0.60 (0.10)	0.60 (0.10)	0.60 (0.10)	0.60 (0.06)
Cover (mm)	50 (2.5)	40 (2)	40 (2)	40 (2)	40 (2)
Mainten. interval ($\beta_{lim}/\beta(t)$ = 0.6)	9 yrs.	12 yrs.	10 yrs.	17 yrs.	25 yrs.

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

To assess the economic, environmental, and social life cycle impacts resulting from each alternative during the construction, use, maintenance, and end-of-life stages, a set of 9 criteria has been defined. The first two criteria are related to the economic dimension of sustainability and basic account for the economic costs resulting from each design's installation and periodical maintenance, respectively. Costs resulting from periodical maintenance and demolition are discounted to 2022 values, assuming a discount rate *d* = 2%.
Three criteria are defined to evaluate the environmental impacts. These are the three endpoint environmental indicators proposed by ReCiPe [36] life cycle environmental assessment technique. The first corresponds to the damage done to human health, the second is related to the damage caused to ecosystems, and the last impact evaluates the increase in resource scarcity due to the consumption

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of natural resources during the extraction, production, and installation activities. The inventory data from which the relevant information was obtained to quantify the three endpoint indicators were gathered from the environmental database Ecoinvent.
The last four criteria are meant to evaluate the impacts generated on the social dimension of sustainability. These are derived from Navarro et al. [37]. The first criteria account for the employment generated along the different production, construction, maintenance, and demolition activities. The second social indicator considers the contribution of each alternative to regional economic development. The third impact includes the affection to users resulting from excessive maintenance activities, which may affect the accessibility of the users, as well as may decrease traffic safety during these operations. The last social indicator accounts for how the different alternatives affect the public opinion of the local communities, as the maintenance activities can generate dust, vibrations or even affect the aesthetics of the installation site. The data required to characterize the social background of every life cycle activity, has been gathered from national statistical databases, such as the Spanish Tax Office or the Spanish National Statistics Institute databases.

4.- RESULTS AND DISCUSSION

4.1.- LIFE CYCLE ASSESSMENT RESULTS

The impacts of each design option in the cycle life are shown in Figures 1 to 3. It shall be noted that the impacts presented here are unweighted and need to be weighted. From the results obtained in the two economic metrics, it can be observed that the solution that incurs the lesser life cycle costs is the one based on the addition of silica fume to the concrete mix (SF5), closely followed by alternative FA20. The least economical solution, in this case, would be the one using polymer-modified concrete (PMC10), which doubles the life cycle costs of the most economical solutions. It is important to note that in every case but for SF5, the maintenance costs are higher than the construction costs. Maintenance operations can be more than three times the construction costs, as in the case of CC50.

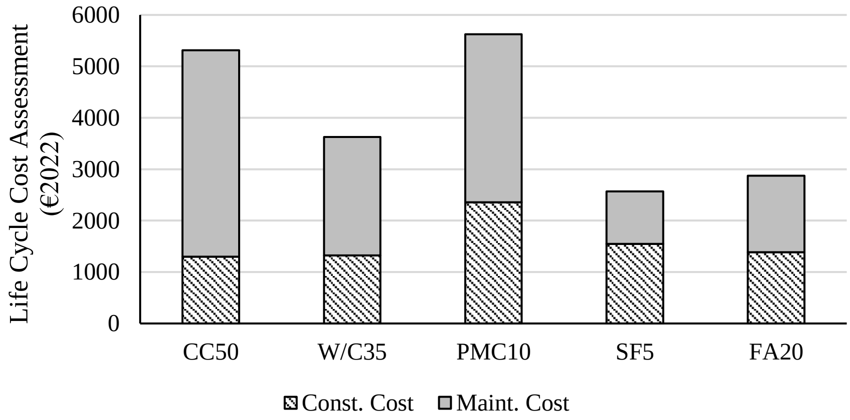

Figure 1 Economic life cycle impacts. Unweighted results

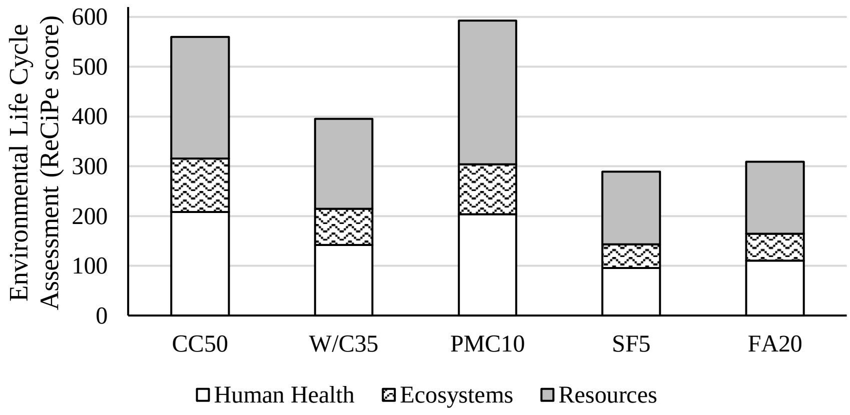

Figure 2 Environmental life cycle impacts. Unweighted results

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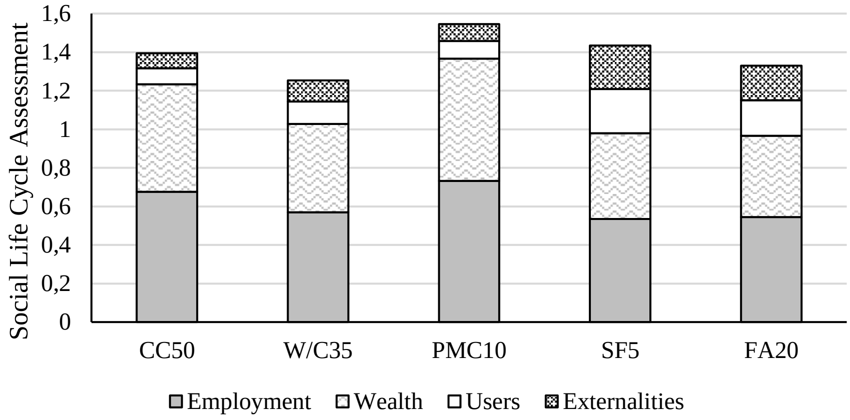

Figure 3 Social life cycle impacts. Unweighted results

Regarding the environmental results, a similar trend is observed, being SF5 the solution which has a better environmental performance, and PMC10 resulting again in the worst solution. Particularly relevant for every alternative are the impacts of the scarcity of natural resources. It shall be noted that while the economic and the environmental criteria are cost-type, the social criteria are defined as benefit-type, i.e., the greatest the social impact, the better. It can be observed that, for the present case study, the impacts on users and public opinion are almost negligible compared to the effects on workers and regional development in the case of the more maintenance-demanding alternatives. For the case of SF5 and FA20, although the impacts on workers and regional development are more significant, the impacts on users and public opinion take up to a third of their total social scoring.

4.2.- SUSTAINABILITY PERFORMANCE EVALUATION

To evaluate the sustainability performance, the results presented above need to be converted into one indicator to allow for comparing the different alternatives and making a decision. Other MCDM techniques are applied to that end. However, for ANP, the rest of the MCDM techniques analyzed here require weighting the criteria as input for the analysis. As ANP results in both alternative scoring and criteria weighting, the weights from this technique are used as input when applying the remaining methods. It shall be noted that the results of MCDM techniques are always influenced by the subjectivity of the decision-makers involved to a greater or lesser extent. In the present research, this source of subjectivity appears when the decision makers are requested to compare the relevance of criteria as an appropriate step for applying both AHP and ANP techniques. Several approaches exist to reduce the subjectivity of the results, such as reducing the number of judgments required by each decision-maker or following a fuzzy-based approach to model the uncertainties as a source of relevant information [31]. However, the subjective assessment of the results remains out of the scope of the present study.

4.2.1.- Criteria weighting

Three experts have been involved in the ANP process to derive aggregated criteria weights. The neutrosophic characterization of each of them and their respective voting power resulting from applying the methodology described above is presented in Table 3.

Decision maker	DM_1	DM_2	DM_3
Years of experience	5	19	15
Expertise in economic assessment	0.8	0.8	0.4
Expertise in environmental assessment	1	0.4	0.8
Expertise in social assessment	0.6	1	0.6
Knowledge in structural design	0.6	1	1
DM's credibility δ_i	0.653	0.840	0.718
DM's mean indeterminacy θ_i	0.512	0.455	0.424
DM's inconsistency ε_i	0.265	0.270	0.229
Expert's voting power ϕ_i	0.310	0.346	0.344

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Table 3: Parameters defining the voting power of each expert

Table 4 shows the normalized criteria weighting of each expert after applying the ANP technique and the aggregated weights resulting after assigning each DM his/her respective voting relevance.

Decision maker	DM_1	DM_2	DM_3	ΣDM_i
Construction costs	0.037	0.120	0.020	0.060
Maintenance costs	0.033	0.094	0.025	0.051
Damage to human health	0.169	0.149	0.206	0.175
Damage to ecosystems	0.321	0.290	0.299	0.303
Resource scarcity	0.243	0.233	0.199	0.225
Employment generation	0.086	0.044	0.074	0.067
Economic regional development	0.052	0.033	0.057	0.047
Affection to users	0.030	0.019	0.052	0.034
Public opinion – Externalities	0.029	0.019	0.068	0.039

Table 4: Normalized criteria weighting for each expert and after aggregation

4.2.2. MCDM results

TOPSIS, COPRAS, VIKOR, and ANP methods are now applied to obtain a relative score for each design alternative that reflects their sustainability performance along their life cycle. The aggregated and normalized criteria weights obtained after applying the ANP process serve as an input for using COPRAS, VIKOR, and TOPSIS techniques. The results obtained assuming these weights are presented in Table 5.

Alternative	TOPSIS	VIKOR	COPRAS	ANP
CC50	0.183	0.976	0.525	0.156
W/C35	0.609	0.352	0.686	0.194
PMC10	0.129	0.923	0.524	0.150
SF5	0.915	0.006	0.939	0.260
FA20	0.866	0.055	0.863	0.240

Table 5: Alternative scoring applying different MCDM techniques

It is observed that irrespective of the MCDM technique applied, SF5 has resulted in the best alternative, followed in every case by alternative FA20. The excellent life cycle performance of concrete designs with silica fume or fly ash as additions to the concrete mix is based on the reduced maintenance operations expected to guarantee the required service life. However, with the high durability of these solutions, the environmental performance of these designs has resulted in being essential in achieving such good scoring. This is explained by the fact that adding silica fume and fly ash to the concrete mixes reduces the cement required to get the desired compressive strength. Being that the production of cement is a main environmental stressor along the life cycle of every concrete structure, the reduction of the cement content in concrete mixes turns out to be essential to increase the environmental performance of these designs. In addition, fly ash and silica fume are by-products of the industry, thus meaning that their reuse has a positive environmental impact contributing to the circular economy concept. The benefits of silica fume and fly ash-based additions from a life cycle perspective have already been reported in previous research [38], although not applied in aggressive, chloride-laden environments.

It is observed that the worst-performing solutions regarding their sustainability performance are CC50 and PMC10, depending on the MCDM technique applied. Regarding CC50, it shall be concluded that increasing the concrete cover to a conventional design in chloride-laden environments is inefficient, as the maintenance demands are excessive, and so are the impacts along the use and maintenance life cycle stage (Figures 1 to 3). On the other hand, the durability increase when adding latex-based additives to a conventional design is counter balanced by the high environmental impacts associated with the production and transport of this material. Such results are in good accordance with previous recent research [39].

To evaluate the performance of each MCDM method, the distinguishing power is analyzed. This distinguishing capability of an MCDM technique *i* is determined here through an index C_i obtained as:

$$C_i = \frac{|Q_{best,i} - Q_{2nd,i}|}{|Q_{best,i} - Q_{worst,i}|} \tag{19}$$

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where $Q_{best,i}$ is the score resulting for the best solution according to MCDM technique i, $Q_{2nd,i}$ the score of the second best solution, and $Q_{worst,i}$ is the score of the least scoring alternative. The distinguishing indices of each solution are shown in Table 6:

	TOPSIS	VIKOR	COPRAS	ANP
$\lvert Q_{best,i} - Q_{2nd,i}\rvert$	0.049	0.049	0.075	0.020
$\lvert Q_{best,i} - Q_{worst,i}\rvert$	0.732	0.970	0.413	0.104
C_i	0.067	0.050	0.182	0.191

Table 6: Durability parameters for the calculation of each alternative's reliability

In particular, this case study shows that both ANP and COPRAS have the highest distinctive capabilities. This contradicts the usual thinking that TOPSIS could lead to more significant differentiation between alternatives because it is based on a vector normalization of the alternatives and not on a linear normalization, as with other MCDM techniques such as COPRAS.

5.- CONCLUSIONS

The present study aims to assess the life cycle sustainability performance of five different design options for a concrete bridge in a coastal region. Four alternative and well-recognized MCDM techniques are accounted for to address the sustainability performance of each design, namely ANP, TOPSIS, VIKOR, and COPRAS. Three experts have been involved in the derivation of the criteria weights. The results obtained show that the use of concretes, including even a small amount of silica fume in the mix, leads to outstanding performance in comparison to other designs oriented to enhance the durability of concrete structures, such as concrete cover increase, w/c ratio reduction or the inclusion of polymers in concrete. Such results rely on the better durability of silica fume-based solutions in chloride-laden environments, as the reduced concrete porosity prevents chlorides from accessing the reinforcing bars. Consequently, the maintenance demands of such a solution are almost negligible compared to the rest of the alternatives. Adding high proportions of fly ash also results in very good life cycle performances for similar reasons. For the case study analyzed, these conclusions are consistent irrespective of the decision-making method applied.

REFERENCES

[1] Lehne, J. & Preston, F., Making concrete change – Innovation in low-carbon cement and concrete. The Royal Institute of International Affairs, 2018. ISBN 978 1 78413 272 9.

[2] Peng, J., Yang, Y., Bian, H., Zhang, J. & Wang, L., Optimisation of maintenance strategy of deteriorating bridges considering sustainability criteria. *Structure and Infrastructure Engineering*, **18**(3), pp. 395-411, 2022.

[3] Sánchez-Garrido, A.J., Navarro, I.J., & Yepes, V., Multi-criteria decision-making applied to the sustainability of building structures based on Modern Methods of Construction. *Journal of Cleaner Production*, **330**, p. 129724, 2022.

[4] Molina-Moreno, F., García-Segura, Martí, J.V. & Yepes, V., Optimization of Buttressed Earth-Retaining Walls using Hybrid Harmony Search Algorithms. *Engineering Structures*, **134**, pp. 205-216, 2017.

[5] Torres-Machí, C., Chamorro, A., Videla, C., Pellicer, E. & Yepes, V., An iterative approach for the optimization of pavement maintenance management at the network level. *The Scientific World Journal*, **2014**, p. 524329, 2014.

[6] Hadizadeh-Bazaz, M., Navarro, I.J. & Yepes, V., Performance comparison of structural damage detection methods based on frequency response function and power spectral density. *DYNA*, **97**, pp. 493-500, 2022.

[7] Ascione, F., De Masi, R. F., Mastellone, M. & Vanoli, G. P., Building rating systems: A novel review about capabilities, current limits and open issues. *Sustainable Cities and Society*, **76**, 103498, 2022.

[8] Munda, G., Multiple Criteria Decision Analysis and Sustainable Development. *Operations Research & Management Science*, **233**, pp. 1235-1267, 2016.

[9] Sousa, M., Almeida, M.F. & Calili, R., Multiple Criteria Decision Making for the Achievement of the UN Sustainable Development Goals: A Systematic Literature Review and a Research Agenda. *Sustainability*, **13**(8), p. 4129, 2021.

[10] Tučník, P. & Bureš, V., Experimental Evaluation of Suitability of Selected Multi-Criteria Decision-Making Methods for Large-Scale Agent-Based Simulations. *PLOS ONE,* **11**(11), *p.* e0165171, 2016.

[11] C.L. Hwang & K. Yoon, Multiple Attribute Decision Making, Springer-Verlag, Berlin, 1981.

[12] Navarro, I.J., Penadés-Plà, V., Martínez-Muñoz, D., Rempling, R. & Yepes, V., Life cycle sustainability assessment for multi-criteria decision making in bridge design: a review. *Journal of Civil Engineering & Management*, **26**(7), pp. 690-704, 2020.

[13] Jia, J., Ibrahim, M., Hadi, M., Orabi, W & Xiao, Y., Multi-Criteria Evaluation Framework in Selection of Accelerated Bridge Construction (ABC) Method. *Sustainability*, **10**(11), p. 4059, 2018.

ISSN: 0012-7361 eISSN: 1989-1490 / DYNA Vol.98, n.5 DOI: https://doi.org//10.6036//10816

[14] Marzouk, M. & Sabbah, M., AHP-TOPSIS social sustainability approach for selecting supplier in construction supply chain. *Cleaner Environmental Systems*¸**2**, p. 100034, 2021.
[15] Saaty, T.L., The Analytic Hierarchy Process, McGraw-Hill, 1981.
[16] Opricovic, S. Multicriteria optimization of civil engineering systems. Fac. Civ. Eng. Belgrade, 2, 5–21, 1998.
[17] Kripka, M., Yepes, V. & Milani, C.J., Selection of sustainable short-span bridge design in Brazil. *Sustainability*, **11**(5), p. 1307, 2019.
[18] Bansal, S., Singh, A. & Singh, S.K., Sustainability evaluation of two iconic bridge corridors under construction using Fuzzy Vikor technique: A case study. *Revista ALCONPAT*, **7**(1), 2017.
[19] García-Segura, T., Penadés-Plà, V. & Yepes, V., Sustainable bridge design by metamodel-assisted multi-objective optimization and decision-making under uncertainty. *Journal of Cleaner Production*, **202**, pp. 904-915, 2018.
[20] Zavadskas, E. K., Kaklauskas, A. & Sarka, V., The new method of multicriteria complex proportional assessment of projects. *Technological and Economic Development of Economy*, **1**(3), pp. 131–139, 1994.
[21] Mulliner, E., Malys, N. & Maliene, V., Comparative analysis of MCDM methods for the assessment of sustainable housing affordability. *Omega*, **59**, pp. 146-156, 2016.
[22] Nuuter, T., Lill, I. & Tupenaite, L., Comparison of housing market sustainability in European countries based on multiple criteria assessment. *Land Use Policy*, **42**, pp. 642-651, 2015.
[23] Invidiata, A., Lavagna, M. & Ghisi, E., Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings. *Building and Environment*, **139**, pp. 58-68, 2018.
[24] Zolfani, S.H., Pourhossein, M., Yazdani, M. & Zavadskas, E.K., Evaluating construction projects of hotels based on environmental sustainability with MCDM framework. *Alexandria Engineering Journal*, **57**(1), pp. 357-365, 2018.
[25] Krishankumar, R., Mishra, A.R., Cavallaro, F., Zavadskas, E.K., Antuchevičienė, J. & Ravichandran, K.S., A New Approach to the Viable Ranking of Zero-Carbon Construction Materials with Generalized Fuzzy Information. *Sustainability*, ***14***(13), p. 7691, 2022.
[26] Saaty, T.L., Fundamentals of the analytic network process — Dependence and feedback in decision-making with a single network. *Journal of Systems Science and Systems Engineering*, **13**, pp. 129-157, 2004.
[27] Ignatius, J., Rahman, A., Yazdani, M., Šaparauskas, J. & Haron., S.H., An integrated fuzzy anp–qfd approach for green building assessment. *Journal of Civil Engineering & Management*, **22**(4), pp. 551-563, 2016.
[28] Dehdasht, G., Zin, R.M., Ferwati, M.S., Abdullahi, M.M., Keyvanfar, A. & McCaffer, R., DEMATEL-ANP Risk Assessment in Oil and Gas Construction Projects. *Sustainability*, **9**(8), p.1420, 2017.
[29] Mahmoudkelaye, S., Azari, K.T., Pourvaziri, M. & Asadian, E., Sustainable material selection for building enclosure through ANP method. *Case Studies in Construction Materials*, **9**, p. e00200, 2018.
[30] Navarro, I.J., Martí, J.V. & Yepes, V., Group analytic network process for the sustainability assessment of bridges near shore. *WIT Transactions on Ecology and the Environment*, **157**, WIT Press, 2022, ISSN 174-3541
[31] Sierra, L.A., Pellicer, E. & Yepes, V., Method for estimating the social sustainability of infrastructure projects. *Environmental Impact Assessment Review*, **65**, pp. 41-53, 2017.
[32] Sodenkamp, M.A., Tavana, M., & Di Caprio, D. An aggregation method for solving group multi-criteria decision-making problems with single-valued neutrosophic sets. *Applied Soft Computing*, **71**, pp. 715–727, 2018.
[33] Navarro, I.J., Yepes, V. & Martí, J.V., Sustainability assessment of concrete bridge deck designs in coastal environments using neutrosophic criteria weights. *Structure and Infrastructure Engineering*, **16** (7), pp. 949-967, 2020.
[34] Hadizadeh-Bazaz, M., Navarro, I.J. & Yepes, V., Performance comparison of structural damage detection methods based on Frequency Response Function and Power Spectral Density. *DYNA*, **97**(5), pp. 493-500, 2022.
[35] ISO 2394:2015. General principles on reliability for structures. Geneva, ISO, 2015.
[36] Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. & Van Zelm, R. ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. The Hague: Ministerie van Volkshuisvesting, 2009.
[37] Navarro, I.J., Yepes, V. & Martí, J.V., Social life cycle assessment of concrete bridge decks exposed to aggressive environments. *Environmental Impact Assessment Review*, **72**, pp. 50-63, 2018.
[38] Tait, M., Cheung, W., A comparative cradle-to-gate life cycle assessment of three concrete mix designs. *International Journal of Life Cycle Assessment*, **21**(6), p. 847e860, 2016.
[39] Navarro, I.J., Yepes, V., Martí, J.V. & González-Vidosa, F., Life cycle impact assessment of corrosion preventive designs applied to prestressed concrete bridge decks. *Journal of Cleaner Production*, **196**, pp. 698-713, 2018

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