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Dematel-Based Completion Technique Applied for the Sustainability Assessment of Bridges Near Shore

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ABSTRACT

In recent times, the construction industry has been recognized as a critical sector in achieving the Sustainable Development Goals. However, construction activities and infrastructure have both beneficial and non-beneficial impacts, making infrastructure design the focus of current research in finding the best way to meet society's demands for sustainability. Although methods for economic, environmental, and social life cycle assessments of infrastructures are well-known, the challenge lies in combining these dimensions into a comprehensive indicator that aids decision-making. This study uses three decision-making techniques, namely TOPSIS, COPRAS, and VIKOR, to evaluate five different design alternatives for a concrete bridge exposed to a coastal environment. To enhance the consistency of the multi-criteria decision-making process, a DEMATEL-based approach is applied. The study's results demonstrate unanimously that concrete containing even small amounts of silica fume performs better over its life cycle than other solutions typically considered to increase durability, such as reducing the water/cement ratio or increasing concrete cover.

1. INTRODUCTION

The pursuit of sustainable development has become a top priority for both the public and private sectors. Since the inception of the Sustainable Development Goals in 2015, our society has taken significant strides towards their implementation. An excellent example is the ambitious European Green Deal, which aims to achieve climate neutrality in Europe while promoting a circular economy. The construction industry is crucial in achieving this objective, as it is one of the sectors with the most substantial negative impact on the environment. As a result, numerous researchers are focusing on infrastructure design optimization to minimize economic and environmental impacts. Their work encompasses a wide range of infrastructures [1-5], making it a highly significant area of interest.

When it comes to addressing sustainability concerns, society often resorts to ecological reductionism, oversimplifying the complex and multidimensional nature of these issues. In reality, assessing sustainability requires a holistic approach that acknowledges the need to consider multiple perspectives and disciplines. Multi-criteria decision-making (MCDM) techniques are highly effective tools for achieving a multidisciplinary approach to sustainability assessment [6]. Consequently, researchers have been working in recent years to develop various tools and methods for evaluating the sustainability of different infrastructures. A wide range of MCDM techniques has been employed to draw relevant conclusions, which can inform future design actions. However, there is no consensus on which MCDM method is best suited for sustainable infrastructure assessment. Some authors argue that using multiple MCDM techniques is necessary to achieve a comprehensive and reliable sustainability assessment [7].

The use of MCDM techniques typically depends on determining the relevance of each criterion in the final decision. This is often done through the Analytic Hierarchy Process (AHP), a widely used MCDM technique. However, there has been criticism of AHP's accuracy for complex problems since human judgment consistency is inversely proportional to problem complexity. Several approaches aim to reduce uncertainty in the results. One popular method is reducing the number of judgments requested from experts to increase the consistency of their judgments by simplifying the problem's complexity.

This study proposes using the DEMATEL technique to reduce the number of comparisons required of experts to determine criteria weights using the AHP technique. After determining the weights, the study assesses the life cycle sustainability of five design alternatives for a concrete bridge in a coastal area, using three MCDM techniques: TOPSIS, VIKOR, and COPRAS. The sustainability assessment considered a set of nine quantitative criteria that encompassed all three sustainability dimensions: economy, environment, and society.

2. MATERIALS AND METHODS

2.1 AHP

The Analytic Hierarchy Process (AHP) is a MCDM technique first defined by Saaty back in 1980 [8]. This method is nowadays widely used to determine the weights to be assigned to each criterion involved in decision-making problems of any kind. This technique requires an expert to compare pairwise the relevance that each criterion shall have with respect to each other when taking the decision. By doing so, a square so-called comparison matrix A_{nxn} is constructed, where n is the number of criteria involved in the decision-making process. The comparison between two criteria is based on the Saaty's fundamental scale, which is used to transform linguistic judgements into numerical values (Table 1).

Table 1. Saaty's fundamental scale [8]

Semantic Comparison Term	Numerical Equivalence
Criteria A and B are equally relevant	1
Criterion A is slightly more relevant than B	3
Criterion A is more relevant than B	5
Criterion A is much more relevant than B	7
Criterion A is extremely more relevant than B	9
Intermediate values can be used if required	2, 4, 6, 8

The elements of the resulting comparison matrix A_{nxn} correspond to values of the Saaty's fundamental scale. It shall be noted that if criterion A is considered, for example, extremely more relevant than criterion B, then criterion B is considered extremely less relevant than criterion A. This results in the comparison matrix A_{nxn} to be reciprocal by definition, i.e., $a_{ij} = 1/a_{ji}$. The AHP allows to extract the relevance of each criterion from a so-built comparison matrix as the values of the eigenvector associated to the greatest eigenvalue of the matrix (λ_{max}).

The resulting criteria weights are considered valid only of the comparison matrix A_{nxn} is consistent, i.e., the judgements of the decision maker should have been coherent. If a perfect consistency of a comparison matrix was achieved, that would result in $a_{ij} \times a_{jk} = a_{ik}\ \forall\ i, j, k$.

The consistency shall be evaluated by means of the so-called Consistency Index CI, of the comparison matrix A_{nxn}, as:

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

where, n is the total number of criteria involved in the decision-making process. The resulting weights are then valid only if the Consistency Ratio $CR = CI/RI$ falls below a limiting value CR_{lim} which depends on the number of criteria n (Table 2). In the above presented equation RI stands for the so-called Random Index, which indicates the consistency of a fully randomized nxn comparison matrix.

Table 2. Values for RI and CR_{lim} depending on the number of criteria involved

Number of Criteria n	3	5	7	9
Random Index RI	0.58	1.12	1.32	1.45
Allowable CR_{lim}	0.05	0.10	0.10	0.10

2.2 DEMATEL-based completion technique

The weights obtained through the application of the above presented AHP technique are widely used as a basis for many other decision-making techniques, such as TOPSIS, COPRAS or VIKOR. However, one of the most criticised aspects of the AHP technique is that the resulting criteria weights are highly subjective. In fact, the ability of the decision makers to adequately reflect their view on a problem diminishes as the complexity of the problem increases. There exist several approaches to attempt reducing the subjectivity of the decisions based on the application of MCDM techniques. Research has been conducted on the application of the fuzzy theory to mathematically model the diffusivity of human thinking and include it as a source of relevant information for the decision-making process [9, 10].

Another approach which is also in the spotlight of many researchers is to reduce the complexity of the problem by reducing the number of judgements to be made by the decision maker when filling the AHP comparison matrix [11, 12]. To do so, the DEMATEL method can be used.

2.2.1 DEMATEL method

The goal of the MCDM DEMATEL technique is to transform intricate cause-and-effect connections among diverse elements into a well-structured and easy-to-understand visual model. This involves grouping factors into cause-and-effect categories, as explained in reference [13]. The conventional approach involves four distinct stages:

Stage 1: To generate a Direct Influence Matrix (DIM), experts are requested to complete a comparison matrix using a process similar to the Analytic Hierarchy Process (AHP). In this process, each expert estimates the degree of influence that factor i has on factor j using a four-level scale of integers ranging from 0 to 3. The scores represent "no influence," "low influence," "medium influence," and "high influence," respectively. The non-negative influence matrix $DIM_k = \{z_{ij}\}$ is created for each expert k, where z_{ij} denotes the assigned influence score based on the aforementioned scale. The diagonal elements in the matrix are set to zero. Finally, the Direct Influence Matrix DIM is derived by averaging the matrices DIM_k obtained from all the experts.

Stage 2: The direct influence matrix shall now be normalized to the so-called NIM by dividing each element z_{ij} by p, where:

$$\mathrm{p} = \max\left(\max_{1 \le i \le n} \sum_{j=1}^{n} z_{ij}\,,\ \max_{1 \le j \le n} \sum_{i=1}^{n} z_{ij}\right) \tag{2}$$

Stage 3: A total relation matrix TRM is now constructed by aggregating both direct and indirect influential effects as:

$$\begin{aligned} TRM = NIM + NIM^2 + NIM^3 + \cdots + NIM^\infty = \\ NIM(I - NIM)^{-1} \end{aligned} \tag{3}$$

In the equation above, I stands for an identity $n \times n$ matrix.

Stage 4: To determine the influential factors R_i and C_i, the sum of each row and column of the TRM must be calculated. If R_i - C_i is positive, a particular factor i is classified as a cause, whereas if it is negative, it is considered an effect.

2.2.2 DEMATEL-based AHP restoration

Zhou et al. [14] proposed a technique inspired by DEMATEL to restore incomplete AHP comparison matrices and ensure their initial state and consistency. This is relevant because DEMATEL is designed to uncover non-evident relationships among a group of factors, and both DEMATEL and AHP rely on the analysis of comparison matrices. This restoration technique can be used to reduce the number of pairwise comparisons to be made by the decision-maker, this reducing the complexity of the assessment and increasing the accuracy of the resulting weights. The DEMATEL-based completion technique consists in the following stages:

Stage 1: From an incomplete AHP comparison matrix A_{nxn}^* = $\{a_{ij}\}$, a DIM matrix can be derived. The elements of the DIM matrix $\{z_{ij}\}$ are set equal to a_{ij}, but are set to zero, when the comparison element a_{ij} is unknown.

Stage 2: To generate the normalized influence matrix (*NIM*), each element z_{ij} of the matrix shall be divided by p as in the classical DEMATEL method.

Stage 3: The total relation matrix $TRM = \{g_{ij}\}$ shall now be computed as in classical DEMATEL.

Stage 4: Based on the relationships between factors identified in the total relation matrix (TRM), a fully reciprocal pairwise comparison matrix $A_{nxn}' = \{a'_{ij}\}$ as:

$$g_{ij}/a'_{ij} = g_{ji}/a'_{ji} \tag{4}$$

It is important to ensure that the synthetic comparison matrix A'_{nxn} includes reciprocal central elements. To achieve this and considering the equation above that describes the relationship between factors, any missing entry a_{ij} in the original incomplete comparison matrix A_{nxn}^* can be calculated.

2.3 Scoring MCDM techniques

2.3.1 TOPSIS

The TOPSIS method was introduced by Hwang and Yoon [15] and is recognised as the most popular MCDM method used in civil engineering [16]. TOPSIS has been used to analyse the sustainability performance of wide variety of infrastructures, from bridges [17, 18] to buildings [2]. TOPSIS technique is applied following several steps. The first step consists in constructing a decision matrix $R = [r_{ij}]$ and obtaining the weight w_i of each criterion i considered in the problem. Weights are usually derived using the Analytical Hierarchy Process (AHP) [19]. The decision matrix R is then normalized as:

$$r'_{ij} = \frac{r_{ij}}{\sqrt{\sum_{j=1}^{n} r_{ij}^2}} \tag{5}$$

In the equation above, n is the total number of criteria. Now, the normalized decision matrix is weighted as:

$$v_{ij} = w_i \cdot r'_{ij} \tag{6}$$

The ideal positive and negative solutions (PIS or NIS) are derived for each criterion. These solutions are constructed by maximising the utility criteria and minimising the cost criteria in the PIS case and vice versa in the NIS case. After that, the distance of each alternative to the *PIS* and *NIS* is obtained as:

$$d_j^+ = \sqrt{\sum_{i=1}^{n} \left(v_{ij} - v_i^+\right)^2} \tag{7}$$

$$d_j^- = \sqrt{\sum_{i=1}^{n} \left(v_{ij} - v_i^-\right)^2} \tag{8}$$

In the equations above, v_i^+ and v_i^- are the elements of the *PIS* and *NIS* respectively, d_j^+ and d_j^- are the distances of alternative j to the *PIS* and *NIS*, respectively. Finally, a score Q_j is obtained that evaluates the relative distance of each alternative j to the *PIS* as:

$$Q_j = \frac{d_j^-}{d_j^- + d_j^+} \tag{9}$$

2.3.2 VIKOR

VIKOR is a MCDM method introduced by Opricovic [20] overcome the limitations of existing MCDM techniques where decision problems involve conflicting criteria. VIKOR is also a popular assessment tool, that has been used as well to solve the evaluation performance of a variety of infrastructures, such as bridges [21-23], airport infrastructures [24] or logistic centers [25].

VIKOR shares the same first step as TOPSIS: a decision matrix must be constructed $R = [r_{ij}]$ the criteria weights w_i must be determined. The second step consists in finding the best and worst criteria values, namely r_i^+ and r_i^-, so that the decision matrix R can be normalized as:

$$r'_{ij} = \frac{r_i^+ - r_{ij}}{r_i^+ - r_i^-} \tag{10}$$

The third step requires to determine two distance measures S_j and R_j for each alternative j as follows:

$$S_j = \sum_{i=1}^{n} w_i \cdot r'_{ij} \tag{11}$$

$$R_j = max\{w_i \cdot r'_{ij}\} \tag{12}$$

At last, the VIKOR measure index Q_j for each alternative j is calculated as:

$$Q_j = v \cdot \frac{S_j - min\{S_j\}}{max\{S_j\} - min\{S_j\}} + (1 - v) \cdot \frac{R_j - min\{R_j\}}{max\{R_j\} - min\{R_j\}} \tag{13}$$

It is usual to compromise both distance metrics S_j and R_j by setting $v = 0.5$. The alternative that results in the greatest score Q_j will be the best performing one according to this decision-making technique.

2.3.3 COPRAS

COPRAS technique was defined by Zavadskas et al. [26] and has been also applied in a wide range related decision-making situations related with sustainability issues, such as the design of buildings [27, 28], the choice of construction materials [29] and others [30] due to its simplicity. As usual in other decision-making methods, COPRAS requires a decision matrix $R = [r_{ij}]$ and the obtention of the criteria relevancies w_i as a starting point Then, the decision matrix must be normalized:

$$r'_{ij} = \frac{r_{ij}}{\sum_{i=1}^{n} r_{ij}} \tag{14}$$

The second step consists in normalizing the decision matrix elements as:

$$v_{ij} = w_i \cdot r'_{ij} \tag{15}$$

Then, the sum of the weighted normalized scores for both cost and benefit criteria for each alternative j are obtained as:

$$S_{+j} = \sum_{i=1}^{n} w_i \cdot r'_{ij,+} \tag{16}$$

$$S_{-j} = \sum_{i=1}^{n} w_i \cdot r'_{ij,-} \quad (17)$$

In the equations above, $r'_{ij,+}$ and $r'_{ij,-}$ represent respectivelyfor the normalized scoring for the benefit and cost criteria. After doing so, the final score Q_j of each alternative j is calculated:

$$Q_j = S_{+j} + \frac{\sum_{k=1}^{m} S_{-k}}{S_{-j} \cdot \sum_{k=1}^{m} S_{-k}} \quad (18)$$

The alternative that reaches the greatest value of the index Q_j results in the best performance according to COPRAS method.

3. CASE STUDY

The MCDM methods presented above are applied for the evaluation of the sustainability life cycle performance of different design alternatives to a particular concrete bridge near shore. In those environments, the aggressive chloride-laden atmosphere induces the corrosion of the reinforcing steel, thus leading to intensive maintenance demanding designs. Being the maintenance stage usually a great source of negative impacts in every dimension of sustainability (economy, environment and society), working on enhancing the durability of coastal structures results in an effective way to reduce the impacts that harm the sustainability of these structures. To prevent concrete to degrade and increase the durability of concrete structures exposed to marine environments, conventional concrete designs are usually modified. The present analysis considers five different alternatives intended to provide high durability and thus reducing maintenance. The first one consists in using a conventional concrete mix but considering a concrete cover of 50 mm, which is significantly greater than usual cover values. This design alternative will be called CC50 hereafter. The second alternative consists in using reduced water to cement ratios to reduce the porosity of the concrete cover and consequently reducing the capacity of chlorides to ingress and reach the rebars (alternative W/C35 hereafter). The third alternative consists in reducing the porosity of concrete through the addition of latex-based additives to the concrete mix (alternative PMC10). The fourth alternative is based on the addition of silica fume to the concrete mix, which also results in reduced concrete porosity. A similar effect is achieved by using fly-ash additions. These two design alternatives will be called SF5 and FA20 hereafter respectively. The characterization of each of the above-described design alternatives is shown in Table 3.

The sustainability performance of these five design alternatives is evaluated on a functional unit consisting of a 1 m long portion of a concrete bridge deck built near shore. The considered bridge shows a conventional 2.3 m deep and 12 m wide box-girder section. The analysis considers a 100 year long maintenance stage. To investigate the different maintenance needs of each design option, a reliability analysis is conducted. The required maintenance interval for each design alternative is set to the interval for which its reliability reaches 60% of a target reliability β_{lim} = 1.3, which corresponds to a probability of failure of 9.68% [31]. In the analysis, failure is assumed to occur when the chloride concentration at the rebar depth reaches the critical chloride threshold associated to each alternative. The advance of the chloride front is modelled following Fick's second Law of diffusion, as recommended in Fib Bulletin 34 [32]. The reliability analysis has been performed for each alternative running 20,000 Monte-Carlo simulations to ensure that results converge, resulting in a relative estimation error below 1%. The parameters used to characterize probabilistically each design option are presented in Table 4. Table 4 contains the mean value for each parameter and the standard deviation in parentheses. In Table 4, D_0 stands for the chloride diffusivity of concrete, and C_{cr} for the critical chloride threshold, both parameters that affect the chloride ingress into concrete.

Table 3. Definition of each design 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	-	-
Concrete Cover (mm)	50	40	40	40	40

Table 4. Parameters for the reliability evaluation of each design option

Parameter	CC50	W/C35	PMC10	FA20	SF5
D_0 ($\times 10^{-12}$ 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.

The sustainability performance of each design option is evaluated through a set of 9 criteria. The first two criteria deal with the economic impacts of the designs. The first criterion (C1) considers the costs associated to the construction of the functional unit defined for each of the alternatives under study. The second criterion (C2) includes the costs resulting from the maintenance along the life cycle of each of the designs. It shall be noted that a discount rate d = 2% has been considered to discount future expenses to the date of construction. The costs of materials, machinery and construction activities are taken from national databases for the construction industry.

Three criteria have been defined to capture the environmental performance of each design. In particular, these three criteria stand for the three endpoint indicators associated with the environmental life cycle assessment technique ReCiPe [33]. These indicators are the damage to human health (C3), the damage to ecosystems (C4) and the affection to the availability of natural resources (C5) resulting from the production of the construction materials and energy consumptions along the life cycle of each design option. The inventory data from which the relevant information for quantifying the three selected endpoint indicators was obtained came from the environmental database Ecoinvent [34].

At last, a set of four criteria are defined to assess the social impacts derived from the different design alternatives. These criteria are suggested in studys [35, 36] to evaluate the social impacts of bridges. The first of these criteria (C6) deals with the ability of each design to generate employment. The second social criteria (C7) considers the contribution of each alternative to the economic wealth of the regions affected by the different construction and maintenance activities associated to it. The third social criterion (C8) takes into account how the recurrent maintenance activities might affect the traffic safety and accessibility of the users of the bridge. The last social criterion (C9) accounts for the negative effect that maintenance activities can have on the public opinion of the local communities, which are affected by the noise, vibrations or dust generated by these. The inventory data to determine the values of the social impacts has been gathered from the Spanish National Statistics Institute [37] and the Spanish Tax Office [38].

4. RESULTS AND DISCUSSION

4.1 Life cycle assessment of the design alternatives

Table 5 shows the life cycle performance of each of the design alternatives against the different economic, environmental and social impacts involved in the present decision-making problem. It shall be noted that impacts are referred to the functional unit described above and exclude the effect of every activity that might be equal between alternatives.

Table 5. Life cycle impact results for each alternative under study

Criterion ID	Definition	CC50	W/C35	PMC10	SF5	FA20
C1	Construction Costs	1296.4 €	1322.5 €	2355.7 €	1546.2 €	1386.3 €
C2	Maintenance Costs	4014.8 €	2301.3 €	3269.8 €	1025.3 €	1489.4 €
C3	Human Health	207.8	141.7	203.5	95.6	110.3
C4	Ecosystems	107.8	73.1	100.5	47.6	53.9
C5	Resources	244	180.1	288.8	145.6	145
C6	Employment Generation	67.5%	57%	73.2%	53.5%	54.4%
C7	Economic Wealth	55.8%	45.8%	63.4%	44.5%	42.2%
C8	Users	8.3%	11.5%	9.1%	22.9%	18.4%
C9	Externalities	7.9%	11.1%	8.8%	22.5%	18%

It can be observed the solution associated with the greatest life cycle costs is the solution based on the addition of latex to the baseline concrete mix, closely follower by the CC50 solution. Although close in total terms, it shall be highlighted that PMC incurs in lesser maintenance costs than CC50 solution. The reduced competitiveness of this alternative in comparison to the rest relies on its associated high construction costs (C1). The concrete mix solution with the lowest life cycle costs is the one that involves adding silica fume (SF5) to the mix. The alternative FA20 solution closely follows in terms of cost-effectiveness. It is interesting to note that in almost every case, costs resulting from maintenance along the life cycle of the different alternatives under analysis are greater than the installation costs. An exception to that conclusion is the SF5 alternative.

When it comes to environmental aspects, it can be observed that, in general terms, the impact on the availability of natural resources is the most impacting effect of every alternative, followed by the impact on human health. Environmental results (criteria C3 to C5) are expressed in accordance with the ReCiPe scoring system. Regarding the life cycle performance of each alternative, similar results are obtained as for the economical assessment: PMC10 solution is again the worst environmentally performing alternative, closely followed by CC50.

However, in terms of social impacts, PMC10 is the most favourable solution, while W/C35 has the least impact. It's important to note that while economic and environmental criteria are cost-based (i.e., the best solution is the one that scores less), social criteria are benefit-based, meaning that the greater the social impact, the better the solution. In this study, it is observed that for the maintenance-demanding alternatives, the impacts on users and public opinion are relatively insignificant if compared to the impacts on workers and on the regional development. For SF5 and FA20, even though the impacts on workers and regional development are more significant, the impacts on users and public opinion account for up to a third of their total social score.

4.2 Sustainability performance evaluation

In order to compare the various alternatives and make a decision based on sustainability performance, the results shown above must be converted into a single indicator. To achieve this, a variety of MCDM techniques are utilized, namely TOPSIS, VIKOR and COPRAS. Each of these methods uses as an input the criteria weighting resulting from the application of the AHP technique. However, in order to maximize the accuracy of the weighting calculation, the number of comparisons is reduced in order to reduce the complexity of the assessment problem and increase the reliability of the results. The above presented DEMATEL-based completion technique is used to restore complete comparison matrices out of the incomplete ones.

4.2.1 Criteria weighting

To derive the relevance of the above-described criteria, a conventional AHP technique is applied. The weights resulting after evaluating the maximum eigenvector are presented in Table 6. It can be observed that, according to the decision maker’s perception of the problem, environmental aspects should weight much more than economic and social impacts. In fact, the environmental criteria weights (C3 to C5) sum up to 61.7%, while the economic criteria (C1 and C2) sum up to 23.7% and the social ones (C6 to C9) sum 14.7%. The consistency of the comparison matrix is evaluated by means of the Consistency Ratio, which takes a value of CR = 9.6% for the present analysis. As This value is below the limiting CR_{lim} = 10% required for 9×9 comparison matrices, the obtained weights are consistent.

Table 6. Criteria weights resulting from the application of the AHP technique

Decision Criterion	Weight of the Criterion
C1 - Construction Costs	0.158
C2 - Maintenance Costs	0.079
C3 - Human Health	0.149
C4 - Ecosystem	0.181
C5 - Resources	0.287
C6 - Employment	0.027
C7 - Wealth	0.031
C8 - Users	0.049
C9 - Externalities	0.040

4.2.2 Completion results

Three distinct incompleteness levels of the baseline matrix are considered to assess the effectiveness of the presented completion technique. For each scenario, a varying number of entries are randomly chosen and considered as missing. In particular, for scenario 1, 5 entries are removed, 8 for scenario 2 and 12 for scenario 3, which implies the elimination of 33% of the judgements required to the decision maker when completing a conventional 9×9 comparison matrix. 1000 simulations are run to generate in each of them a unique random incomplete comparison matrix based on the baseline one presented above.

Figure 1 shows the dispersion of the weights resulting for each criterion depending on the number of entries missing in the baseline comparison matrix. Although 3 scenarios have been evaluated, results are shown for scenarios 1 and 3, being scenario 2 enveloped by these. It can be observed that the maximum deviation from the baseline is obtained, as expected, in scenario 4, where 33% of the judgements are omitted. The average relative deviation between these weights and the baseline weight set is 4.9%. It can be noticed that as the number of missing entries increases, there is an increase in the dispersion of the results, even though the mean fits well. However, the maximum deviation with respect to the baseline is 7.6%.

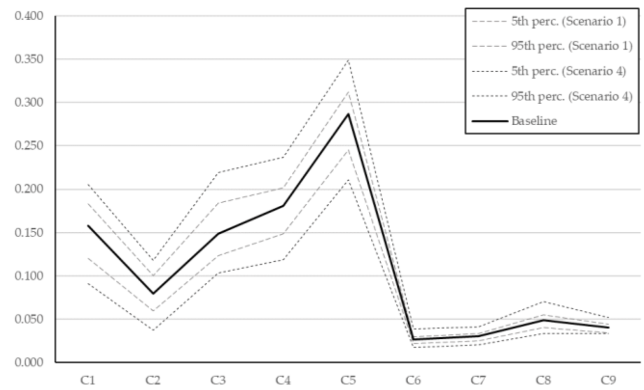

Figure 1. Weights of the different criteria considering incompleteness scenarios 3 and 4

Considering the outcomes, the root mean square error (RMSE) is utilized to assess the overall effectiveness of the completion model. The RMSE measures the disparities between the forecasted estimations and the baseline weights. Figure 2 shows the normalized RMSE obtained for each criterion and incompleteness scenario. It can be observed that the greatest estimation errors are associated, as expected, for the incompleteness scenario with the greatest number of entries to be restored, namely scenario 3, for which the mean normalized RMSE reaches 24.2%.

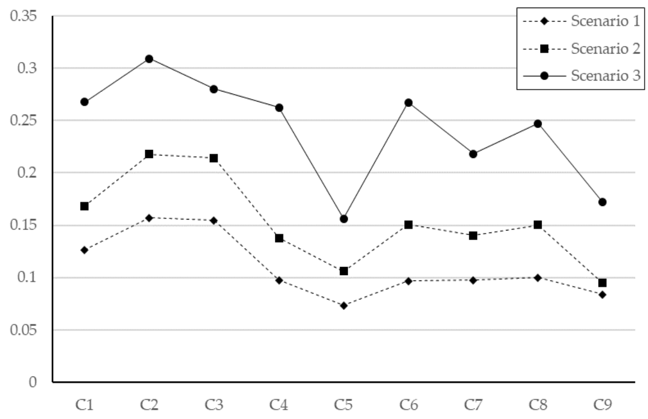

Figure 2. Normalized root mean square error for each criterion

It can be concluded from the results presented that the weight estimation is robust even if 8 entries are missing (incompleteness scenario 2). Removing more than 8 would lead to greater error values and results dispersion, and a so-called rank reversal phenomenon could occur.

4.2.3 MCDM results

The TOPSIS, COPRAS and VIKOR methods have been adopted to calculate a relative score for each design alternative, providing insight into its sustainability performance during its life cycle. The results obtained assuming these weights are presented in Table 7. These have been obtained considering the baseline weighting set.

Table 7. Alternative scores for the different MCDM techniques considering the baseline weights set

Alternative	TOPSIS	VIKOR	COPRAS
CC50	0.329	0.521	0.715
W/C35	0.665	0.689	0.260
PMC10	0.101	0.485	1.000
SF5	0.913	0.906	0.013
FA20	0.888	0.854	0.035

It can be observed that the best solution in terms of its sustainability life cycle performance is the alternative based on the use of silica fume as an addition to a conventional concrete mix (SF5), closely followed by alternative SF20. The outstanding performance of these solutions when used in chloride-laden environments is explained by the fact that the use of such additions result in a drastic reduction of the chloride diffusivity of the concrete cover, thus hindering the advance of the chloride front into the reinforcing bars. The reduced maintenance of these solutions, together with the fact that it allows a reduction in the cement content, results in the best sustainability scores among the rest of the alternatives.

The sensitivity of the results is now checked against the different defined incompleteness scenarios. Results are presented in Tables 8, 9 and 10. Mean weights for each of these scenarios are considered as an input to get the alternative scoring.

Table 8. TOPSIS scores considering different incompleteness scenarios

Alternative	CC50	W/C35	PMC10	SF5	FA20
Baseline	0.329	0.665	0.101	0.913	0.888
Scenario 1	0.321	0.661	0.101	0.915	0.887
Scenario 2	0.317	0.659	0.100	0.916	0.887
Scenario 3	0.314	0.656	0.100	0.916	0.884

Table 9. VIKOR scores considering different incompleteness scenarios

Alternative	CC50	W/C35	PMC10	SF5	FA20
Baseline	0.521	0.689	0.485	0.906	0.854
Scenario 1	0.519	0.689	0.485	0.909	0.855
Scenario 2	0.519	0.689	0.485	0.911	0.856
Scenario 3	0.519	0.688	0.487	0.911	0.855

Table 10. VIKOR scores considering different incompleteness scenarios

Alternative	CC50	W/C35	PMC10	SF5	FA20
Baseline	0.715	0.260	1.000	0.013	0.035
Scenario 1	0.720	0.264	1.000	0.013	0.036
Scenario 2	0.723	0.265	1.000	0.012	0.036
Scenario 3	0.724	0.268	1.000	0.009	0.038

It can be concluded that, although slight differences can be observed depending on the incompleteness scenario considered, the results are on average robust and consistent.

5. CONCLUSIONS

This research aims to evaluate the life cycle sustainability of five design alternatives to a concrete bridge exposed to a chloride-laden, marine environment. The alternatives are based on usual approaches to overcome such aggressive environments. The analysis of their life cycle performance is conducted by means of a set of 9 criteria, including a variety of economic, environmental and social criteria. The evaluation is based on a multi-criteria decision-making approach in order to derive a sustainability score for each solution that allows us to compare alternatives. As there is no consensus on the best MCDM technique, three scoring MCDM methods are used here, namely TOPSIS, VIKOR and COPRAS. All of them consider as an input the weights derived from the AHP technique. To reduce the subjectivity of the input weights, a DEMATEL-based approach is applied to reduce the number of judgements required by the decision maker, thus reducing the complexity of the assessment and increasing the reliability of the obtained results.

From the results, it can be concluded that using silica fume and fly ash additions to conventional concrete mixes increases significantly the sustainability performance of concrete designs exposed to chlorides. The use of silica fume and fly ash increases the durability of concrete against chlorides, reducing enormously the maintenance requirements along their life cycle. On the other hand, such additions allow to reduce the cement content, reducing the environmental impacts associated to the production of cement. Moreover, these products result as by-products of the industry. Its recycling also contributes significantly to the environment.

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