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Sustainable retrofits on reinforced concrete infrastructures

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ABSTRACT The infrastructure sector is paying increasing attention to sustainability. In particular, certain events have proven how preventive local interventions can save both user lives and the same infrastructures, thus highlighting the importance of maintenance. The ineffectiveness of concrete repairs is one of the main issues in civil engineering. Merely 50% of restoration operations on concrete buildings is considered to be effective in Europe, although rehabilitation costs cover nearly half of the annual construction investments. This study investigates a potential strategy to improve the sustainability of infrastructure restoration solutions. A simplified examination of CO_2 emissions, intervention costs, social factors, structural performances, and other factors considered relevant for this research, is followed by a comparison and ranking of the potential rehabilitation solutions. Four approaches have been selected to design retrofit interventions on a real column of the Sardinian Brabau bridge in Italy: i) complete column replacement; ii) substitution of the damaged longitudinal rebars with machined bars and the casting of a new concrete cover in ultra-high performance fibre-reinforced concrete; iii) longitudinal and transverse fibre-reinforced polymer wrapping; iv) concrete jacketing at the base. Through the application of selected criteria, a methodological and procedural approach is developed. It provides a tool for assessing the sustainability of infrastructure maintenance works throughout the entire life cycle in the subsequent phases of this research.

Key words: reinforced concrete, sustainability, bridge column retrofit, multi-criteria, AHP, MIVES.

1. Introduction

Historically, concrete has been regarded as a highly reliable and resilient material. However, just like any kind of structure or material, concrete also requires maintenance and monitoring. It is evident that when it comes to complex and significant infrastructures, the choice of one intervention technique over another should be carefully evaluated. Although the infrastructure research sector is currently lagging in terms of sustainability, interest in the subject is beginning to gain increasing attention. It is undeniable that retrofit sustainability of reinforced concrete (RC) infrastructures depends on a wide range of factors that can be grouped into three major categories: environmental, economic, and social.

In addition, it is crucial to consider these three categories in combination with structural factors, so as to achieve the prospective resilience for each specific intervention framework (Suhendro, 2014).

The selection of the parameters to be taken into account is influenced by the intended goal, which can vary depending on the object considered, the human factors (decision-maker, group of decision-makers, client, legislative authority, etc.), and the boundary conditions, which influence decision-making (Baglivo *et al*., 2014).

This research aims at evaluating intervention alternatives applied to a single bridge column in order to restore the original pier capacity in the plastic hinge area. To achieve this result, four hypotheses are made and, after the project design phase, a Multi-Criteria Decision Analysis (MCDA) is carried out to evaluate the intervention that can be defined as the most sustainable (Kiani *et al*., 2018).

Several Multiple Attribute Decision Making (MADM) methodologies have been used in the state of the art to support engineers and contractors at various stages of the bridge life cycle. Each repair technique may have unique advantages when applied to already existing structures, but may also present significant drawbacks that must be taken into account. Consequently, the multitude of options available in the state of the art may result in an inefficient, or even poor, design choice. Penadés-Plà *et al*. (2016) provide a basic overview of the MADM analysis, used to assess bridge sustainability, organised into four main groups: planning and design, construction, operation and maintenance, and demolition and recycling.

The reasons for choosing and promoting this methodology are also evident in a number of publications [among which fib Bulletin No.71 (Fib, 2013)], where life cycle analysis is described as a multi-parametric assessment, and in part of the Italian regulatory paradigm (Gazzetta Ufficiale, 2016), where this methodology is already considered a multi-criterial approach.

Furthermore, attention should be drawn to the fact that the number of publications on this topic, retrieved in Scopus in the field of engineering/architecture (AEC sector), is 28,904, with a significant increase over the last 15 years (Fig. 1).

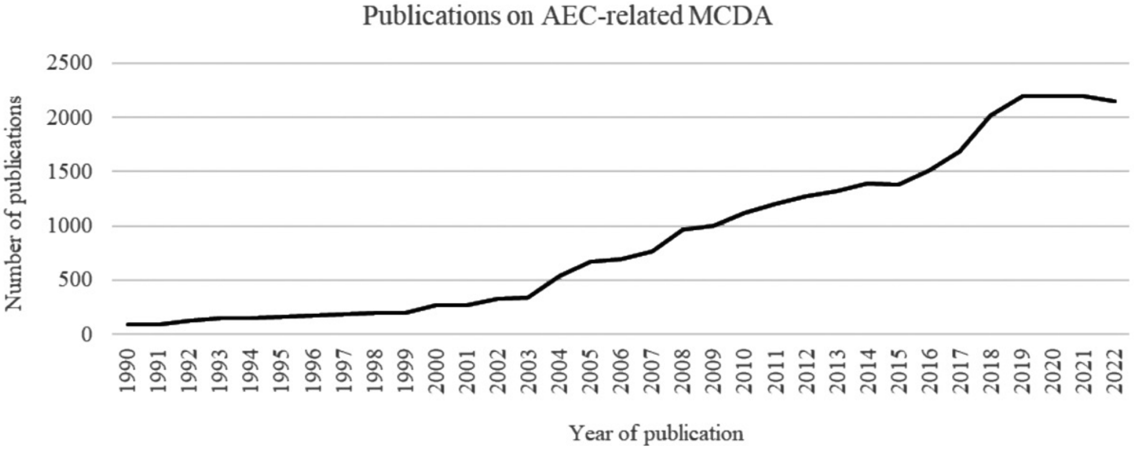


Fig. 1 - Increase in publications concerning MCDA related to the construction sector in recent years.

2. Case study: column bridge rehabilitation

The Brabau bridge is a one-kilometre beam bridge located near the city of Oristano, in the Sardinian region in Italy (Fig. 2).

The subject of this research, as a case study, is one of the two columns belonging to the frame pier (Fig. 3). As a consequence, the pier can be analysed as a cantilevered element, without considering the effect due to the frame. The column is 3,850 mm high and has a circular cross-

Fig. 2 - The Brabau bridge location in orange with the close by cities.

section with a diameter of 1,200 mm. The normal strength concrete (NSC) used has a nominal compressive strength and associated strain of 30 MPa and 0.2%, respectively, while the softening branch experiences zero stress at 0.4% strain. The concrete cover has a depth of 40 mm, and the estimated axial force on a single column is 4,500 kN.

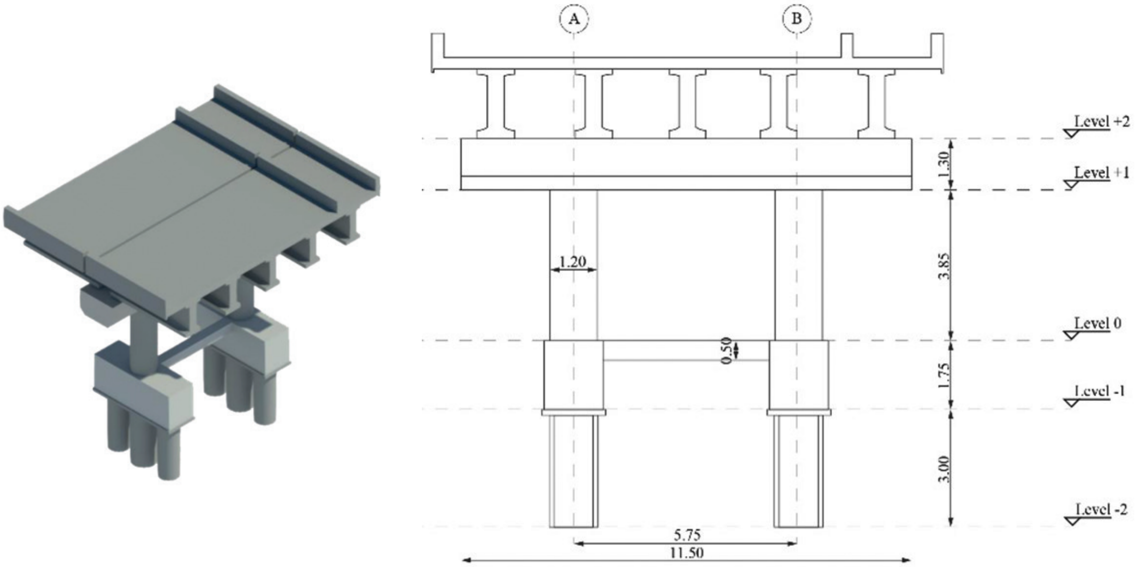


Fig. 3 - Model of the Brabau bridge pier analysed in this study.

Twenty 24-milimiter diameter rebars are set in a concentric circular layer, and a spiral 12-milimiter diameter and 250-milimiter pitch rebar serves as transverse reinforcement. The yielding stress is 536 MPa, the ultimate stress is 649 MPa, and the corresponding strain for the uncorroded reinforcing steel bars is 11.6%.

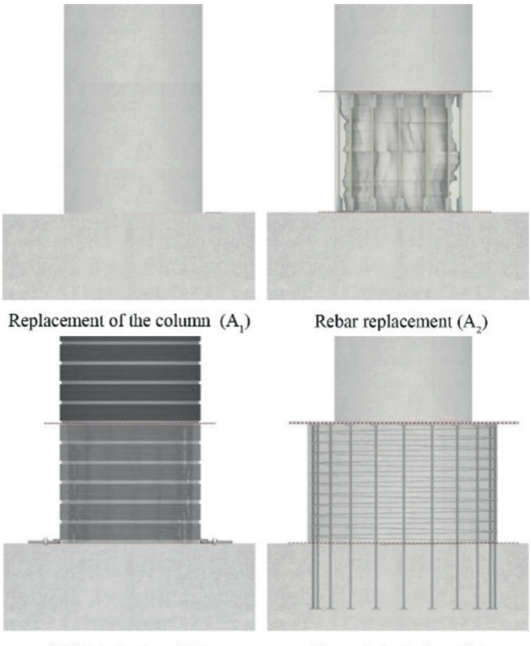
2.1. Intervention alternatives

The research aims at assessing the sustainability of four post-damage rehabilitation interventions through a multi-parameter approach. The structural performance target is the restoration of the initial capacity, without any improvements or adaptations to the code.

To estimate the quantity of material needed for the application of each intervention and the structural performance to be achieved, alternatives are designed, analysed, and modelled using Building Information Modelling (BIM) and Finite Element Modelling (FEM) models (Fig. 4).

Retrofit interventions on the Brabau bridge columns offer an effective approach to the enhancement of the structural performance and durability of the existing concrete columns. The retrofit strategies aim at addressing various issues such as inadequate capacity, deterioration, or changes in design requirements. Common retrofit techniques for bridge columns include jacketing, external post-tensioning, fibre-reinforced polymer (FRP) wrapping, and steel bracing.

Component replacement is usually among the most used alternative owing to ease of implementation. Local retrofit interventions are often overlooked due to realisation difficulties, although they can allow low traffic and, consequently, the usability of the bridge or infrastructure. Local interventions enable the limiting of costs and ensure connections yet when the retrofit application requires a higher specialisation level, qualified workers can be more difficult to hire.


Replacement of the column (A_1) Rebar replacement (A_2)

CFRP jacketing (A_3) Concrete jacketing (A_4)

Fig. 4 - Models of the four alternatives to be assessed.

The following four interventions are chosen for comparison.

Replacement of the column (A_1): this consists in the removal of the severely damaged column, and its replacement with a new pier, without adapting the code provisions. During the quantity evaluation stage, reinforcing bars were meticulously modelled in a BIM environment to correctly estimate the emissions and material consumption (Fig. 5). Complete column replacement is currently among the most common practices for infrastructure rehabilitation in Italy.

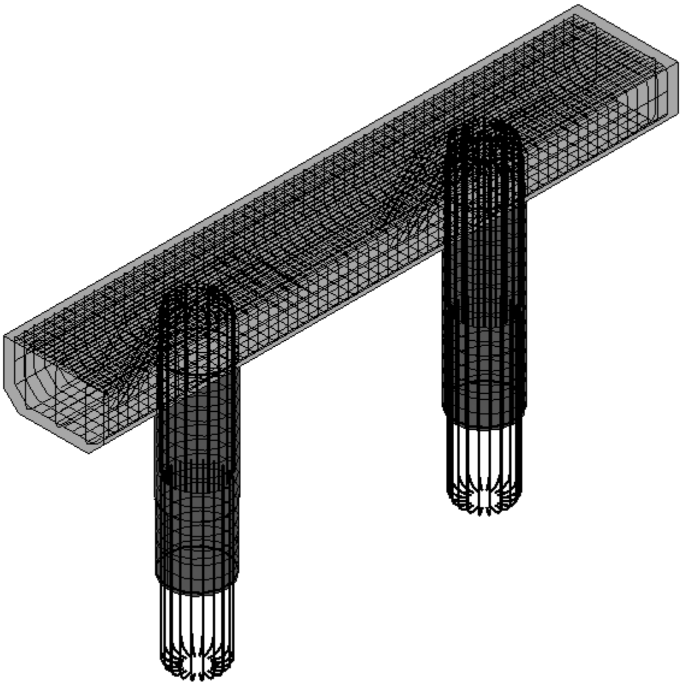


Fig. 5 - BIM column reinforcement modelling.

Rebar replacement (A_2): this technique has been suggested in recent years to repair corrosion and earthquake damaged columns (Pelle *et al.*, 2022). The external concrete layer (110 mm deep) is removed to allow for the replacement of damaged longitudinal rebars for the entire height of the plastic hinge, and to prevent the corrosion of new steel rebars. The intervention height is assumed to be equal to double the length of the plastic hinge ($2L_p$). The repaired zone must also be extended into the foundation so as to evenly distribute the tensions at the pier footing. The surface of the concrete core is treated to strengthen the bond between the old and new concrete.

The damaged longitudinal rebars are replaced with new machined steel rebars (Fig. 6). The A_m/A_s ratio denotes the turning factor, which, in this case, is considered equal to 0.6, where A_m and A_s are the machined and original cross-sectional rebar areas, respectively.

The installation is performed with couplers that are attached to the rear of the old rebars and welded to the new machined steel rebar segments aligned with the old rebars. Ultra-High Performance Concrete (UHPC), extremely compact, and with a limited chloride penetration depth, is selected for the concrete replacement so as to increase the durability of the structure and provide the required shear strength (Xue *et al.*, 2022, 2023).

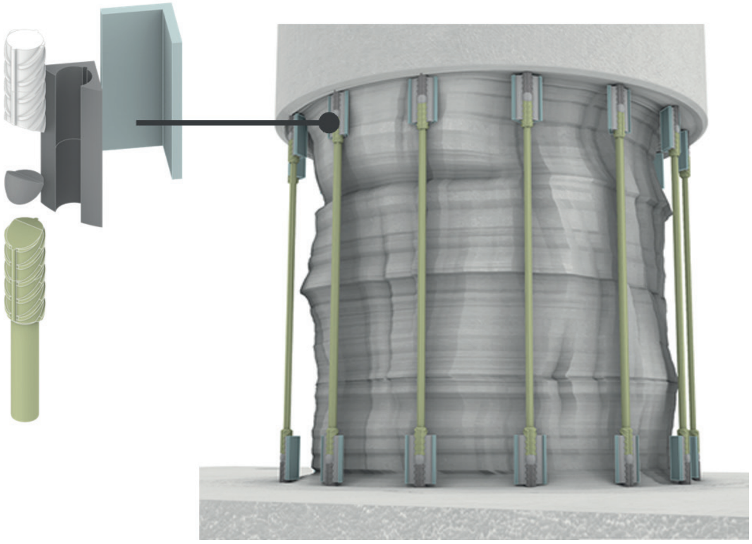


Fig. 6 - Rebar replacement model in a BIM environment.

Carbon Fibre-Reinforced Polymer (CFRP) jacketing (A_3): FRPs, such as carbon or glass fibre-reinforced sheets, are wrapped around the column surface to provide additional strength and confinement. This technique is lightweight, corrosion-resistant, and offers a high-strength-to-weight ratio, making it an attractive option for retrofitting (Kovalchuk *et al.*, 2018).

This intervention aims at restoring the original resistance moment M_{Rd}, by removing the existing reinforcement bars and installing two types of CFRPs (Fig. 7): vertical (to restore M_{Rd}); horizontal (to restore shear resistance V_{Rd}, and ensure confinement). In the sectional model, the column is considered wrapped by a layer of CFRP, such as a fragile elastic material, with the assumption of perfect adhesion to the concrete. The CFRP is anchored to the base by means of bolted stainless steel couplers. Shear resistance $V_{Rd,f}$, can be calculated for the continuous shear reinforcement U-type jacket, as shown in Eq. 1, based on the Mörsch model as required by the reference standards, which are the Italian guidelines of the Consiglio Superiore dei Lavori Pubblici (the High Council of Public Works):

$$V_{Rd,f} = \frac{1}{\gamma_{Rd}} \cdot 0.9d \cdot f_{fed} \cdot 2t_f \cdot (cot\theta + cot\beta) \cdot \frac{w_f}{p_f} \tag{1}$$

with γ_{Rd} being the partial coefficient for the strength model equal to 1.20 (CNR, 2013); *d* the height of the section; f_{fed} the effective strength of the reinforcement system; t_f the thickness of the FRP reinforcement; *b* the inclination angle of the fibres with respect to the element axis; *q* the inclination angle of the shear cracks with respect to the element axis (if unknown, considered as 45°); w_f the stripe width; p_f the stripe pitch.

Concrete with a compressive strength of 37 MPa serves as the repair material. The resistance moment was imposed during the design phase, even if the results obtained with the engineering of the solution were different. The ductility value was expected to be low, making this particular solution an important evaluation criterion.

Concrete jacketing (A_4): jacketing consists in wrapping a new layer of concrete or steel around an existing column, thus, effectively, increasing its strength and confinement. This technique can

Fig. 7 - Experimental samples of CFRP application onto a concrete column, in the following order: 1) removal of damaged concrete and epoxy resin injections; 2) replacement of the bars; 3) restoration of the concrete surface; 4) application of transverse and longitudinal CFRP jacketing.

improve the column load-bearing capacity and, therefore, provide additional resistance against seismic forces (Santos *et al.*, 2016). This solution is well known and widely applied (Lehman *et al.*, 2001).

Jacketing ensures a resistance moment, M_{Rd}, equal to that of the original column, at the base of the repaired column.

Both longitudinal and transverse reinforcement rebars are considered severely damaged and the contribution to the strength in the repaired column is provided by the concrete jacketing and new reinforcement. Approximately 15 to 20 of the new longitudinal bars are designed with a smaller diameter compared to the previous ones, in order to avoid an excessive increase in the resistance moment. The shear contribution of the transverse reinforcement is provided by a spiral having a diameter and pitch equal to 12 and 100 mm, respectively. A jacket height of 1,800 mm is chosen to avoid the column from yielding above the jacket.

2.2. BIM

To compare and rank interventions on large-scale structures and infrastructures, it is essential to keep all the necessary data in an orderly and comprehensible way. To this end, a storage tool is necessary to collect the information. BIM, for architecture and engineering, sometimes referred to as Civil Information Modelling in a more specific way, provides an extremely useful multi-dimensional modelling and data collection environment (Cepa *et al.*, 2023).

For the environmental and economic aspects, the project quantities, reference costs, and emission data are necessary at least during the production and implementation phase. Through the creation of categories and local parameters, it was possible to add this information within the model with formulae that would make standard parametric information (such as volume) interact with specifically created information (such as emissions).

All the data were collected in an abacus and exported so as to have the necessary data available to carry out the sustainability assessment (Table 1).

Table 1 - Abacus (or schedule) exported from the BIM with the required data.

Category	**Volume**	**Pile diameter**	**Pile height**	**Reinforcement volume**	**Volume**	**Cost**	**Emission CO_2**
Pile	4.31 [m^3]	1,200 [m]	3,850 [m]	111,029.29 [cm^3]	4.19 [m^3]	716.50 [€]	1,084 [kg_{eq}]
Pile	4.31 [m^3]	1,200 [m]	3,850 [m]	111,029.29 [cm^3]	4.19 [m^3]	716.50 [€]	1,084 [kg_{eq}]
Total	8.62 [m^3]			222,058.58 [cm^3]	8.38 [m^3]	1,433.00 [€]	2,168 [kg_{eq}]

2.3. Numerical simulations and FEM

For all alternatives, by properly modifying the model described in Pelle *et al*. (2022), a COMSOL Multiphysics simulation is performed to simulate the chloride ingress taking into account the influences of humidity, temperature, aging, and corrosion-induced cracking of the column cover. The time-dependent reduction of the steel reinforcement cross-section is calculated once the corrosion current intensity has been determined on the basis of the chloride concentration.

To perform unidirectional moment-curvature analysis for each intervention, four different RC circular cross-section fibre models of the pier base have been developed in the OpenSees platform.

A circular RC section with one layer of steel evenly distributed around the perimeter and a confined core is modelled in OpenSees by using a circular patch to define the concrete core and a circular patch to define the exterior layer, while the circular layer command is used to define a circular layer of fibres representing the reinforcement bars The core concrete ends at the inner radius, marking the centre of the reinforcing bars. A basic model is defined as parametric in order to achieve the four different models by varying the inner and exterior radii, number and cross area of the bars, and material properties.

In alternative 1, the unconfined concrete core is simulated using the Concrete01 uniaxial material model available in OpenSees. Under uncorroded conditions, the falling branch reaches zero stress for the spalling strain value equal to 0.4%. Concrete04 uniaxial material is employed to simulate the behaviour of the confined concrete core, and the effect of confinement due to the presence of transverse reinforcement is accounted for by using the Mander model (Pelle *et al*., 2023). Steel rebars have been modelled by using the Steel02 uniaxial material available in OpenSees.

In alternative 2, as previously stated, basic FEM is employed, however a number of parameters are conveniently modified. In particular, the cross-sectional reinforcement area is reduced as the old rebars are replaced by new machined rebars. The new external concrete layer made of ultra-high performance fibre-reinforced concrete (UHPFRC) is modelled by adapting the Concrete02 model to fit the simple stress-strain relationship proposed by Naeimi and Moustafa (2021).

In alternative 3, similarly to alternative 2, the external patch is used to simulate the presence of the new FRP layers used in the retrofit procedure. The stress-strain behaviour of this material is provided by that of a uniaxial elastic material. However, due to the design material of the mixture, the elastic material is assumed to have failed when the strain value is greater than the ultimate rupture strain of 0.0167. The width of the external circular patch had been reduced according to the design of the wrapping. As stated, in this case, the contribution of steel rebars is not taken into account, and, so, the circular fibre layers are not modelled.

In both alternative 2 and 3 models, debonding is assumed to not occur at the interface between the UHPFRC and core concrete, and between the FRP and core concrete, respectively. Ultimately, the model used to model alternative 4 is identical to that described for alternative 1, with the exception that the inner and outer radii have been increased according to the design of this retrofitting solution.

3. Sustainability evaluation

In the field of RC, evaluating sustainable infrastructure criteria plays a crucial role in decision-making processes. Multi-Criteria Decision-Making (MCDM) methods provide a systematic framework for assessing and ranking different solutions based on their sustainability impact. By considering various environmental, social, and economic factors, MCDM enables engineers and decision-makers to make informed choices, aligned with sustainable development goals.

One commonly used MCDM technique is the Analytic Hierarchy Process (AHP), which enables decision-makers to prioritise criteria by pairwise comparisons, and to assign the relative importance weights to each criterion (Saaty, 1980). By quantifying the importance of different sustainability factors, such as energy efficiency, carbon footprint, material sourcing, social impact, and Life Cycle Assessment (LCA), AHP helps to evaluate the overall sustainability performance of RC structures.

LCA is another valuable tool for evaluating the environmental impact of RC infrastructures (Deng *et al*., 2020). LCA considers the entire life cycle of a structure, from raw material extraction and manufacturing to construction, use, and end-of-life phases. It quantifies energy consumption, greenhouse gas emissions, waste generation, and other environmental indicators, providing a comprehensive sustainability performance assessment of the structure.

Social aspects of sustainability, such as community and stakeholder well-being, can also be incorporated into the decision-making process. Social Life Cycle Assessment (SLCA) is a methodology that evaluates the social and socio-economic impacts of infrastructure projects (Hunkeler *et al*., 2008). SLCA takes into account aspects like human rights, labour conditions, community engagement, and local economic benefits, which enable decision-makers to consider social equity and well-being in the evaluation of RC projects.

Economic factors are also crucial in the decision-making process for sustainable infrastructures. Cost-benefit analyses, return on investments, and life cycle cost analyses are commonly used techniques to evaluate the economic viability of RC structures (Nguyen *et al*., 2019). These methods support the assessment of financial implications of different design choices, construction techniques, and maintenance strategies, and ensure that sustainable infrastructures are economically feasible in the long run.

In this study, the decision was taken to evaluate environmental, social, and economic aspects through multi-criteria analyses, and to separately include the structural aspects, instead of integrating them in the social part, as generally done.

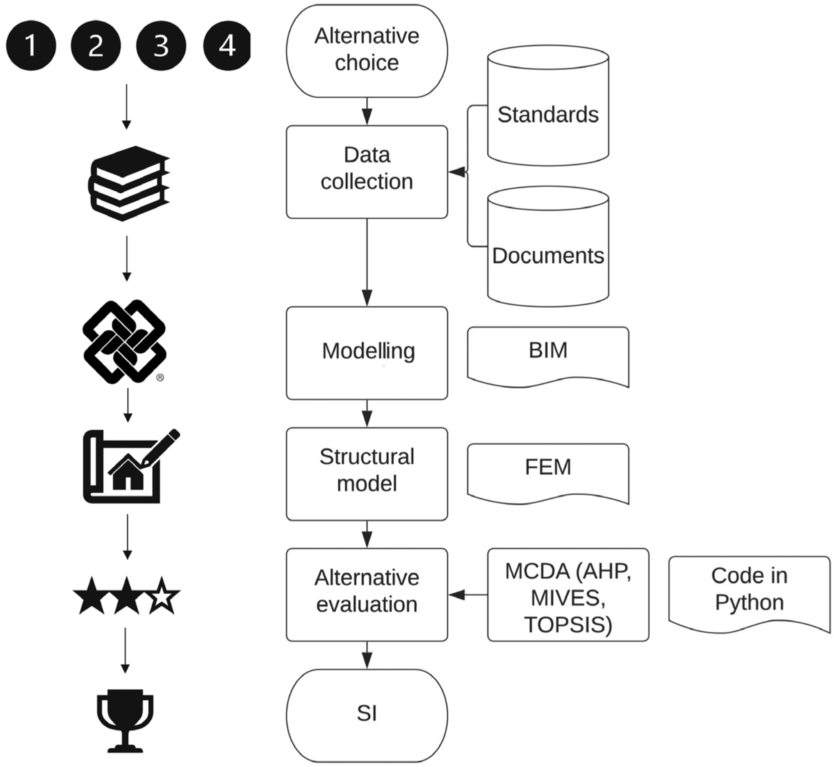


Fig. 8 - Flowchart of the proposed methodology.

A multi-criteria analysis has been conducted based on the AHP, *Modelo Integrado de cuantificacion de Valor para Edificacion Sostenibles* (MIVES)*,* and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approaches. These methods were used together.

A combined method has been developed to overcome a number of gaps that multi-criteria methodologies present when used individually.

This analysis assessed environmental, economic, social, and structural aspects according to the proposed approach of this research, as outlined in Fig. 8.

3.1. The AHP

The AHP methodology, proposed by Saaty (1977), can be used alone or in combination with other MCDA methodologies. This method is used to simplify linear hierarchical systems dealing with difficult problems. It involves the construction of a multi-level decision tree of criteria (Fig. 9) for ranking the alternatives.

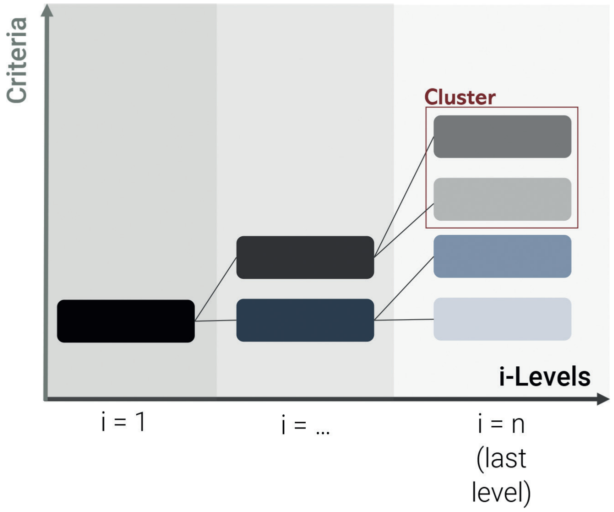


Fig. 9 - Clustering of criteria according to the AHP hierarchy grouping levels.

A decision tree is constructed along the branches, and the criteria (weighted by importance) are grouped along the branches by subject, according to which the intervention alternatives are compared. The criteria of the last level are quantifiable, and alternatives are compared for each criterion of each group. A weight, given by the comparison between criteria belonging to the same cluster (or group), is assigned to each criterion.

Comparisons and weights can be made and attributed, respectively, in many ways. In this research, the method of self-value and grouping through clustering by absolute and relative measurement is adopted.

In each cluster, with an ordered pair of objects (C_i, C_j) of a level, the decision-maker expresses a judgment from one to nine (Saaty scale) of comparison (C_{ij}) grouped in a comparison-matrix, as:

$$C_{ij} = \frac{1}{C_{ji}} \text{ with } C_{ii} = 1, \forall i. \tag{2}$$

At the end of the process a weight (w_i) is assigned to each level so that the sum of the weights is equal to one, with an *i* value ranging from one to *n* (total number of criteria involved in each level of comparison):

$$w_i = [w_1, \ldots, w_n], \quad \sum_{i=1}^{n} w_i = 1. \tag{3}$$

The weights, expressed as a percentage, must be checked. Using the Saaty (1977, 1980) evaluation method, it is necessary to validate the so-called Consistency Ratio (*CR*), which is considered consistent if less than 0.10. The *CR* is equal to the ratio between the Consistency Index (*CI*) and the Ratio Index (*RI*). In general, *RI* is a fixed number linked to the number of criteria (Saaty, 2008) and *CI* is obtained as:

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{4}$$

where λ_{max} represents the maximum eigenvalue.

Each last-level criterion is assigned a value for each alternative that quantifies the approval of this alternative. This step is carried out as in the MIVES methodology.

3.2. MIVES

To assign analytical validity and precise preference, decision-makers must select the value function for each indicator once the decision tree and weight are processed. Therefore, the value multiplied by the incidence, determined using the AHP methodology, is obtained. With the MIVES methodology, the $V_{k_{ji}}(x_{k_{ji},A})$ satisfaction value is determined, and expressed as a percentage, by examining a value function calculated in the calculated x, for the i indicator for each alternative (A), while in the AHP method weights are determined using matrix calculations (Pons *et al.*, 2016).

Therefore, the value function must be calculated for each indicator that is taken into consideration. It can be of various shapes, including S-shape, linear, concave, or convex, with different increasing or decreasing monotonies. The reference x-value indicator, namely x_{min} and x_{max}, are fixed on the abscissa axis. Conversely, the minimum and maximum approval values, which are always pairs of one and zero, are placed in the y-axis. Knowing the function limit values (x_{min} and x_{max}), shape and monotony are, therefore, optional factors to be chosen at the discretion of the decision-maker. Thus, the following value function is given:

$$V_{k_{j_i}} = A + B \cdot \left(1 - e^{-k\cdot\left(\frac{\left|x_{i,A}-x_{min}\right|}{C}\right)^{P}}\right); B = \frac{1}{1-e^{-k\cdot\left(\frac{\left|x_{max}-x_{min}\right|}{C}\right)}} \tag{5}$$

where x_{min} and x_{max} are the minimum and maximum values, respectively; $x_{i,A}$ is the value of the alternative; A and B are parameters that allow the function to be between zero and one on the y-axis and x-axis; P is a form factor that defines whether the curve is concave, convex, linear, or S-shaped; C approximates the x-axis of the inflection point; K approximates the ordinate of the inflection point (Table 2). A is usually equal to zero.

Examples of shapes and monotonies built with value functions are shown in Fig. 10.

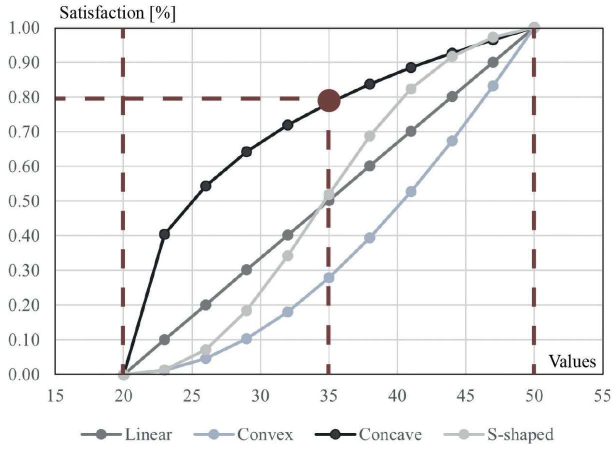


Fig. 10 - Example of the increasing value function used at the discretion of the experts, and the corresponding satisfaction value obtained.

Table 2 - *C*, *K*, and *P* values depending on the chosen function.

Increasing function			
Function	**C**	**K**	**P**
Linear	$C \approx X_{min}$	≈0	≈1
Convex	$X_{min}+((X_{max}-X_{min})/2)<C<X_{min}$	<0.5	>1
Concave	$X_{min}<C<(X_{min}+(X_{max}-X_{min})/2)$	>0.5	<1
S-shaped	$X_{min}+((X_{max}-X_{min})/5)<C<(X_{min}+4(X_{max}-X_{min})/5)$	0.2/0.8	>1
Decreasing function			
Function	**C**	**K**	**P**
Linear	$C \approx X_{min}$	≈0	≈1
Convex	$X_{max}<C<(X_{max}+(X_{min}-X_{max})/2)$	<0.5	>1
Concave	$X_{min}-((X_{min}-X_{max})/2)<C<X_{min}$	>0.5	<1
S-shaped	$(X_{max}-4(X_{max}-X_{min})/5)<C<X_{max}-((X_{max}-X_{min})/5)$	0.2/0.8	>1

Therefore, a sum that goes up the decision tree, and combines the values of the MIVES functions with the weights produced by the AHP methodology, is employed to reach the final result, known as the Sustainability Index (*SI*):

$$SI = \sum_{k=1}^{r}\sum_{j=1}^{c_k}\sum_{i=1}^{n_{k_j}} \alpha_k \cdot \left\{\beta_{k_j} \cdot \left[\gamma_{k_{j_i}} \cdot V_{k_{j_i}}(x_{k_{j_i},A})\right]\right\} \tag{6}$$

where: k = first level criteria index; r = number of first level criteria; j = second level criteria index; c_k = number of second level criteria considered of third level; i = third level criteria index; = number of third level criteria considered of second level; α_k = first level weight; β_{k_j} = second level weight; $\gamma_{k_{ji}}$ = third level weight; $V_{k_{ji}}$ $(x_{k_{ji},A})$ = satisfaction value.

It is feasible to determine which alternative best reflects the preferences of the decision maker by comparing the *SI*s.

3.3. TOPSIS

The TOPSIS method, proposed by Hwang and Yoon (1981), is based on the geometric theory that the ideal solution should be the furthest away from a negative ideal solution (*A-*), and the closest to a positive ideal solution (*A+*). This distance is called relative closeness (C_i), and it is obtained as:

$$S^{+} = \sqrt[2]{\sum_{j=1}^{c}(v_{ij} - v_{j+})^2} \; ; \; S^{-} = \sqrt[2]{\sum_{j=1}^{c}(v_{ij} - v_{j-})^2} \; ; \; C_i = \frac{S^{-}}{S^{+} + S^{-}} \tag{7}$$

where S^- is the distance from the negative ideal solution and S^+ from the positive one, respectively.

To overcome the drawbacks of current methods, the proposed methodology combines the three techniques: AHP, MIVES, and TOPSIS.

4. Application

4.1. Choice of criteria

In the context of MCDM analyses, used to evaluate sustainable RC infrastructures, the choice of criteria is a critical step. Selecting appropriate criteria ensures that key aspects of sustainability are accounted for, and enables a comprehensive performance assessment of the RC structures. Several criteria, commonly employed in MCDM for sustainable infrastructure evaluation, include environmental impact, social considerations, economic viability, and technical feasibility.

The environmental impact criteria usually encompass indicators such as energy efficiency, greenhouse gas emissions, resource depletion, and waste generation (de Brito *et al*., 2012). These criteria help evaluate the ecological footprint of RC structures and promote environmentally responsible decision-making. Social considerations include aspects like community well-being, health and safety, cultural heritage preservation, and social equity (Othman *et al*., 2018). Incorporating these criteria ensures that the infrastructure projects benefit the local community and address social needs.

Economic viability, or traffic, criteria are essential for assessing the financial implications of RC structures. These criteria involve life cycle cost analyses, cost-benefit analyses, and return on investments, which enable decision-makers to evaluate the economic feasibility, and long-term financial performance of infrastructure projects (Alshawi *et al*., 2013). Technical feasibility criteria consider factors such as constructability, durability, structural integrity, and maintenance requirements (Banihashemi and Ghanbari, 2017). Evaluating these criteria ensures that the selected infrastructure solutions are technically practical.

By incorporating these diverse criteria into the MCDM framework, decision-makers are able to make well-informed choices that balance environmental, social, economic, and technical sustainability aspects in RC infrastructure projects. The importance of these criteria may vary depending on the project and stakeholders involved. Thus, it is crucial to consult stakeholders and consider local contextual factors when defining the criteria for evaluating sustainable infrastructures.

The following criteria, clustered in a decision tree, have been used for the sustainability evaluation of the four alternatives (Fig. 11).

The discussion that follows looks at a few criteria that were taken as examples, although in more detail (Briseghella *et al*., 2022). With regards to CO_2 emissions (C_{111}), the first three stages of cement manufacturing listed in the Environmental Product Declaration (EPD) of the product (corresponding to production phases A1-A3 of the company Buzzi Unicem), and reported in Report Cementi 2021, are among those producing emissions. The emissions are estimated to be 862 kg CO_2 eq (average value of the Siniscola factory), which is slightly higher than the industry standard. To construct the model according to the seven dimensions of the BIM environment, the emission parameter has also been added to the material descriptions. The total is, then, increased by the predicted emissions for transportation to the construction site (A4). By comparing the number of trucks (heavy vehicles) used for each alternative, the emissions related to the transportation from the manufacturer to the factory, and from the factory to the construction site, are estimated. The calculation is in accordance with Commission Regulation (EU) 2017/2400 (EUR-Lex, 2023).

Waste production (C_{124}) is based on the calculation of the disposal volumes of demolished portions, and on data declared in the EPDs.

The durability analysis (C_{211}) illustrates the time-dependent evolution of chloride-induced corrosion, predicted by multi-physics FEM-based simulations for each intervention methodology,

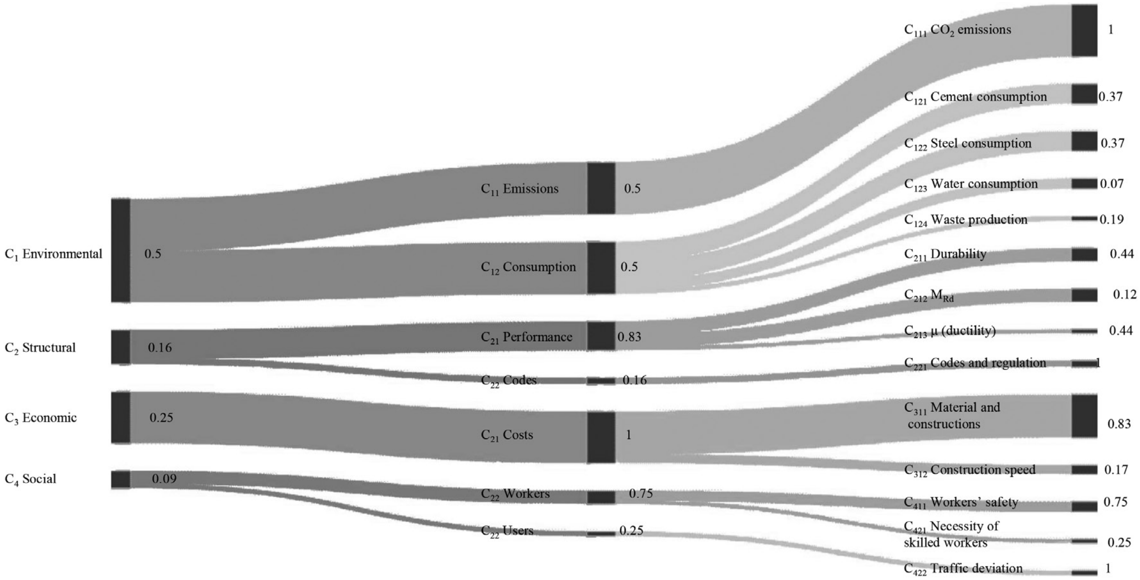


Fig. 11 - Decision tree criteria with hierarchy.

and is expressed as the loss of reinforcement area sections or the ratio between the corroded section, A_{pt}, and the original bar section, A'_s (Fig. 12). The analysis of the option involving the replacement of the pier with a new one, results in a loss in the reinforcing area of roughly 11%, after 50 years. On the contrary, UHPC, utilised as repair material in alternative 2, increases the durability of RC components exposed to corrosive environments due to its excellent compactness. Since the diffusion coefficient, in this case, is two to three orders of magnitude lower than that of normal-strength concrete, chloride penetration into the concrete is prevented. Thus, it seems reasonable that the result of the analysis indicates that the reinforcement section will not substantially decrease over a 50-year span. Worth mentioning is that the FRP jacketing used in alternative 3 can help to increase pier longevity in addition to restoring its mechanical performance. This is possible as the external wrapping can greatly lower the corrosion rate due to its low permeability to chloride. Ultimately, yet importantly, the fourth solution seems to behave in the worst manner in corrosive environments.

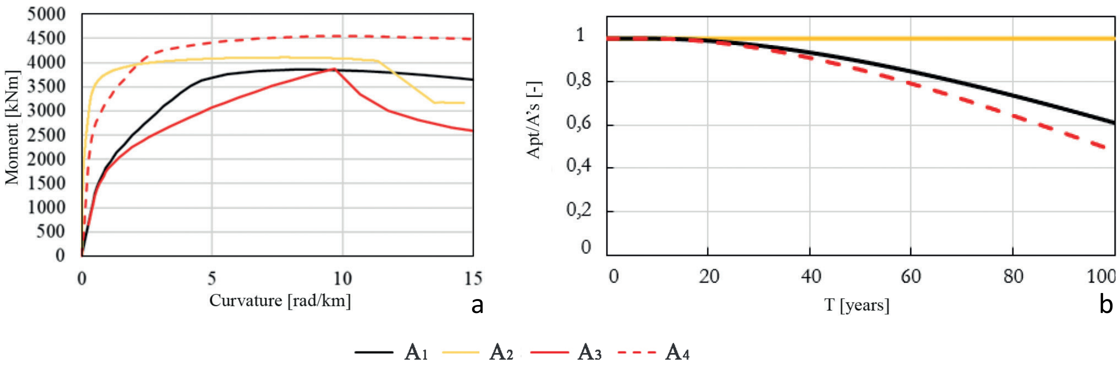


Fig. 12 - Rebar section reduction over time (a) and moment curvature (b).

The aim of the column repairs is to recreate the original, uncorroded pier resistance moment (C_{212}). However, the engineering of the solutions resulted in final results, which were slightly different from the desired values. The four solutions have slightly different resistance moments, with values ranging from 3,868 to 4,546 kNm.

Regarding ductility (C_{213}), worthy of attention is the fact that the ductility was adjusted to zero as a precautionary measure in the case of FRP intervention, due to the brittle behaviour of such material.

The existence of codes and regulations (C_{221}) is considered a key factor, although it is frequently disregarded. Its inclusion is crucial as planning retrofitting measures is challenging.

In the BIM environment, material and construction costs (C_{311}) are calculated by adding the cost parameter to each modelled element. The costs are taken from the construction cost list of the Sardinian region.

Some parameters, such as the need for skilled workers (C_{421}), are counted as values that can be 0.0, 0.5, or 1.0, according to the discretion of the decision-makers.

4.2. Values

Quantified values for each alternative, and each criterion of the last level of the tree, are shown in Table 3.

Table 3 - Alternative results for the MIVES comparison.

Indicator	**Unit**	**A1**	**A2**	**A3**	**A4**
C_{111} CO_2 emissions	[kgCO_2eq]	12,110.81	589.36	521.70	1,029.91
C_{121} Cement consumption	[kg]	10,584.00	683.71	605.22	1,194.79
C_{122} Steel consumption	[kg]	4,066.30	244.83	296.94	238.13
C_{123} Water consumption	[kg]	5,292.00	108.70	89.10	468.00
C_{124} Waste production	[m^3]	26.57	0.66	0.66	0.39
C_{211} Durability (corrosion)	[%]	0.89	1.00	1.00	0.85
C_{212} M_{Rd}	[kNm]	3,947.00	4,087.00	3,868.90	4,546.00
C_{213} μ (ductility)	[%]	5.50	8.39	4.04	6.35
C_{221} Codes and regulation	-	1.00	0.00	0.50	0.00
C_{311} Material and construction	[Euro]	40,764.41	18,711.3	89,439.4	18,429.56
C_{312} Construction speed	[days]	10.00	4.00	4.00	4.00
C_{411} Workers' safety	-	0.32	0.28	0.27	0.26
C_{421} Necessity of skilled workers	-	0.00	1.00	0.50	0.00
C_{422} Traffic deviation	[km·n_{days}]	54.00	18.00	12.60	18.00

For example, for the resistance moment criterion (Fig. 13), the following value function was used, and alternatives were compared.

The steps necessary for the development of this methodology are, therefore, the following:

- a tree is built and weights are assigned by using the AHP methodology;
- a D = [x_{ij}] alternative *x* criterion matrix is created where the satisfaction values obtained with the MIVES approach are considered;
- no normalisation will be used, as MIVES is a type of normalisation where the data set is reduced within the 0-1 range;

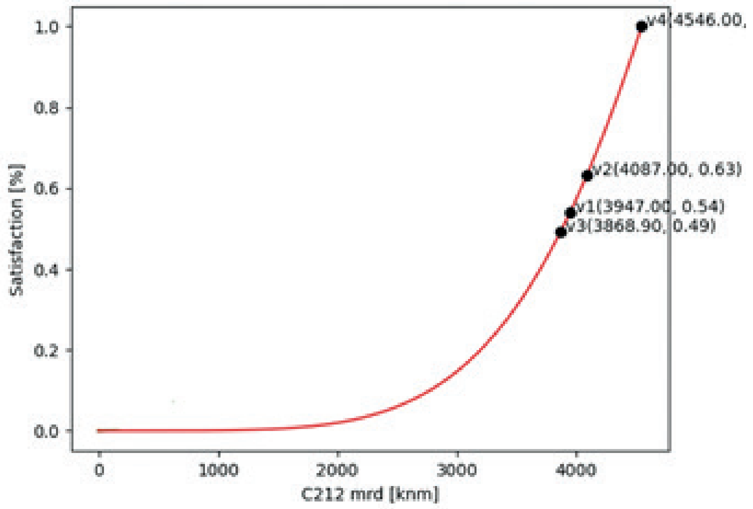


Fig. 13 - Comparison of resistance moment values according to the value function chosen.

- the values are finally weighed locally;
- in the V = [$w_j V_{k_{ji}}$ ($x_{k_{ji},A}$) = v_{ij}] matrix for each criterion, the value of the best and worst alternative is taken, forming a new dot matrix of an ideal positive A^+ and negative A^- solution;
- each of the alternatives, real (A_1, ..., A_n) and fictional (A^+ and A^-), can be conceived as a point in the c-dimensional space;
- S^+ and S^- distances between the fictitious and real alternatives are calculated, and relative proximity C_i is established;
- this procedure is repeated at each level of the decision tree;
- the rank of alternatives is established.

5. Results

5.1. Local results

This methodology starts with the local analysis (Fig. 14) for each cluster, and, then, continues up the decision tree. This allows to control the process and to maintain the hierarchical nature proposed by Saaty (1977, 1980).

By using the proposed combined method, during evaluation, the alternative matrix per criteria is developed (refer to Table 4), and, then, weighed (refer to Table 5) with the weights assigned to each criterion being analysed.

Table 4 - Alternative matrix per criteria.

Indicator	**A_1**	**A_2**	**A_3**	**A_4**
C_{211}	0.6	1	1	0.48
C_{212}	0.54	0.63	0.49	1
C_{213}	0.67	1	0.39	0.8

Table 5 - Weighted alternative matrix per criteria.

Indicator	**A_1**	**A_2**	**A_3**	**A_4**
C_{211}	0.26	0.44	0.44	0.21
C_{212}	0.06	0.07	0.06	0.12
C_{213}	0.29	0.44	0.17	0.35

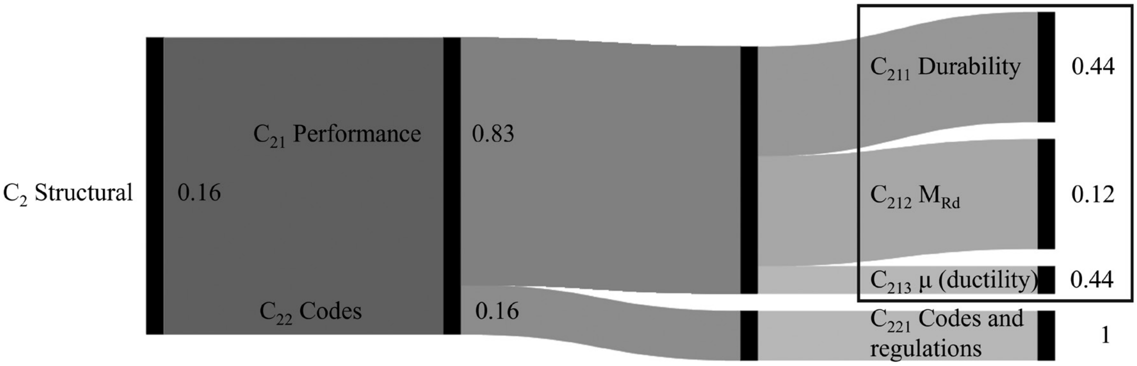


Fig. 14 - Focus on a cluster of the structural criteria in the last level.

At this point, the ideal alternatives for calculating the distance in three-dimensional space (Fig. 15) are established (since there are three criteria in this case) in Table 6.

Table 6 - Matrix of the ideal solutions.

Indicator	**A^+**	**A^-**
C_{211}	0.44	0.21
C_{212}	0.12	0.06
C_{213}	0.44	0.17

The following results are, therefore, obtained (Table 7). With these, it is hence possible to compare the alternatives at local level and, also, understand how to improve the local results of the globally successful alternative at a later stage.

Table 7 - Priority was established with the TOPSIS approach with relative closeness.

	A_1	**A_2**	**A_3**	**A_4**
S^+	0.235	0.044	0.275	0.245
S^-	0.248	0.353	0.229	0.19
C_i	0.513	0.889	0.24	0.437

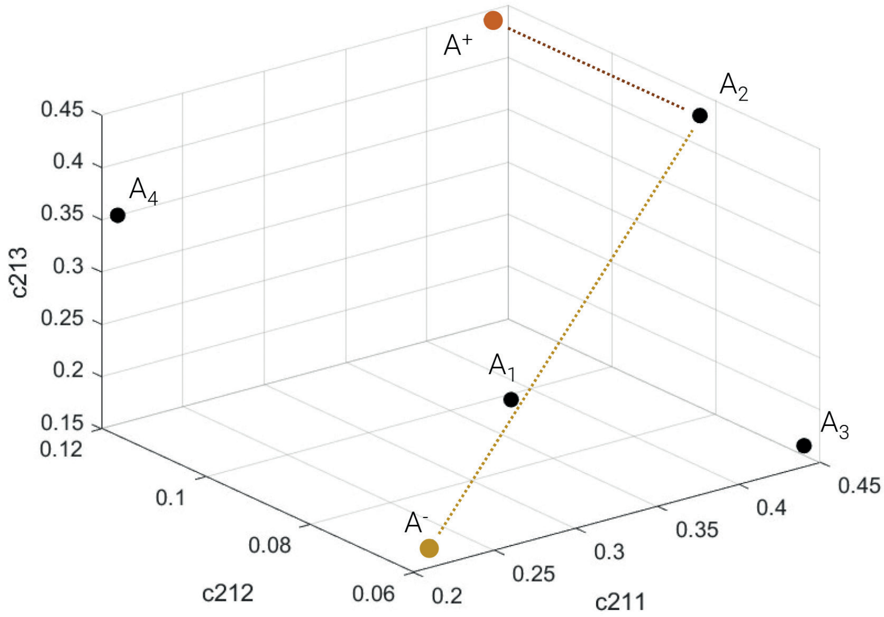


Fig. 15 - Distance-based method to establish the priority of the alternatives in a multi-dimensional space.

Thus, a local priority, based on the distance method, where the starting values are obtained with the MIVES methodology, and the weights with the AHP methodology, respectively, exists.

At this point, using the hierarchical tree structure, priorities at the global level can be established.

5.2. Global results

After conducting the analysis, A2 (rebar replacement) can be established to be the most sustainable alternative for this study case, according to the proposed approach.

The relative closeness results of each alternative, for each criterion, are given in Table 8. The results of the last level weighted alternatives are shown in Table 9.

Table 8 - Relative closeness for first-level criterion.

	A_1	A_2	A_3	A_4
C_1	0	0.99	0.96	0.97
C_2	0	0.99	0.98	0.96
C_3	0	0.99	1	0.96
C_4	0	0.99	0.98	0.97

Table 9 - Final results with ranking.

	A_1	A_2	A_3	A_4
Results	0	0.98	0.97	0.96

A_1 and A_4 should be disregarded even if they are the most prevalent in practice. This shows how more complex interventions might be the most economical and environmentally friendly if properly examined.

Hence, despite being the most challenging to implement, the second alternative has proven to be the most feasible overall, and appropriate from all aspects considered in this study. The best alternative is an example of how innovative retrofit solutions may be advantageous and sustainable, and how they might eventually take the place of more traditional and inefficient rehabilitation alternatives from both an economic and environmental perspective.

The replacement of the bars (A_2) is a suitable choice since it tends to consider sustainability in the long run and raises awareness of maintenance issues.

6. Conclusions

This work aims to propose a methodology for assessing the sustainability of retrofit interventions on bridges and infrastructures with the purpose of limiting environmental impacts by indicating the advantages of choosing local interventions.

A workflow is developed to evaluate the infrastructure in order to choose the most environmentally, economically, socially, and structurally sustainable retrofit alternatives. The interventions are selected in a discrete workspace, modelled in BIM and FEM environments, and data are collected for comparison.

A combined multi-criteria method is developed to help designers and guide them towards a knowledgeable choice.

The advantages of using the proposed methodology can be listed as follows:

1. the linear hierarchical structure will be maintained without being reduced to a single criterion level;
2. the relative proximity of a hypothetical optimal alternative will be used to establish the classification of alternatives, thus also allowing for an understanding of how the proposed alternative can be improved;
3. the MIVES approach for the TOPSIS methodology offers another advantage: the best alternative is always the one with the highest value, as the level of satisfaction is considered (with the classic TOPSIS approach, the values are only normalised and weighed, therefore, a normalised and weighed low value will remain low, even if sometimes it is the better alternative; for example, as it occurs for costs);
4. the best alternative for a given policy cluster can be determined and found locally.

The application was presented in a case study, the results of which highlighted the advantages, and positive factors in knowledgeably choosing local retrofit interventions instead of replacements, which are not always necessary.

By implementing retrofit interventions on the Brabau bridge columns, the structural integrity and seismic performance of the bridge can be significantly improved, to ensure its long-term durability and safety. However, it is also necessary to check other criteria, such as the environmental, economic and social impact. This work provides a methodology to carry out this multi-dimensional evaluation.

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