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ORIGINAL ARTICLE

The greenway for bridge column rehabilitation: a comparison between different techniques based on multi-criteria decision analysis

O caminho verde para pilares de pontes: uma comparação entre as operações de retrofitting e substituição com análise de decisão multicritério

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Abstract: One of the biggest issues in civil engineering is the poor performance of concrete repairs. In fact, in Europe only 50% of concrete structures restorations are estimated to be successful, even though rehabilitation costs account for about half of the yearly construction budgets. This research aims at investigating a potential green approach to the sustainability of rehabilitation solutions for infrastructures. Following a simplified analysis of $C0_2$ emissions, intervention costs, social aspects, structural performances and other variables considered relevant to the scope, possible rehabilitation techniques are compared and ranked. The following four different options have therefore been designed to be applied to an actual column of the Brabau Bridge in Sardinia (Italy): i. complete removal and replacement of the column, ii. replacement of the damaged longitudinal rebars by machined bars and ultra-high performance fibre-reinforced concrete (UHPFRC) strengthening, iii. longitudinal and transverse fiber reinforced polymers (FRP) wrapping, iv. concrete jacketing. A methodological and procedural strategy is established through multi-criteria analysis that will allow future developments to assess the whole Life Cycle Assessment of the maintenance work.

Keywords: reinforced concrete, sustainability, bridge column rehabilitation, multi-criteria, AHP.

Resumo: Um dos maiores problemas da engenharia civil é o mau desempenho dos reparos em concreto. Estima-se que apenas 50% das restaurações de estruturas de concreto na Europa sejam bem-sucedidas, apesar de os custos de reabilitação e reparo serem estimados em cerca de metade dos orçamentos anuais de construção. Esta pesquisa visa investigar uma potencial abordagem verde para a sustentabilidade de soluções de reabilitação de infraestruturas. Após uma análise simplificada das emissões de C02, custos de intervenção, aspectos sociais, desempenhos estruturais e outros aspectos considerados relevantes para o escopo, as possíveis ações de manutenção são comparadas e classificadas. As seguintes quatro opções diferentes foram, portanto, projetadas para serem aplicadas a uma coluna da Ponte Brabau na Sardenha (Itália): i. remoção e substituição completas da coluna, ii. substituição das barras longitudinais danificadas por barras usinadas e reforço UHPFRC, iii. envolvimento longitudinal e transversal de CFRP, iv. revestimento de concreto. Uma estratégia metodológica e processual é estabelecida através de uma análise multicritério que permitirá em futuros desenvolvimentos avaliar todo o Ciclo de Vida da obra de manutenção

Palavras-chave: concreto reforçado, sustentabilidade, reabilitação de pilares de pontes, multicritério, AHP.

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1 INTRODUCTION

1.1 Sustainability issue and life cycle assessment of concrete

Sustainability is a growing concern in the infrastructure sector, playing a central role in the assessment of construction works. Nevertheless, to the authors' knowledge, there is a lack in the current state-of-the-art of methodologies for the green design or repairing of existing infrastructures [1].

It is important to note that the term "Green Concrete" originated around the end of the 90's, when the concept of sustainability was first connected to infrastructure. It was coined (also on materials in general) in 1998 in Denmark at the Danish Technological Institute Concrete Centre (TELESCOP project 1997-2000) suggesting a renewed need for sustainability in the construction sector. At that time, the name did not have any special connotations, as the technologies that make innovative research possible today were not available yet [2].

In recent years, this definition has been implemented, identifying as *green concrete* a specific conglomerate that uses waste materials as aggregates, whose production does not involve high carbon dioxide emissions and whose structural performance is high throughout the life cycle [3].

The new terminology and research developments raised awareness in the academic community of the importance of energy containment, responsible raw material usage, and optimal construction technology practices. In terms of the sustainability of structures, the term "green" should be used to refer to the full life cycle assessment (LCA) rather than just the manufacture of a single element. Therefore, improved construction methodologies are studied to strongly decrease greenhouse gasses emissions even for infrastructures.

In Europe, the cost of interventions on the damaged or deteriorated portions of viaducts and bridges is estimated to be high, representing about half of the annual budget for constructions. Even so, no more than 50% of rehabilitation actions on reinforced concrete structures are considered to be effective. Often, the inefficacy is caused by wrong materials choices, sometimes by technological choices or inconsistency between the intervention and the original substrate. Renovation and rehabilitation projects must be carried out to restore or even improve initial performance. Only by taking a proactive approach that cost savings can be obtained [4].

A new discipline is emerging that includes the study of bridges through the entire life cycle, from the production of the material to the disposal of the work. The term life cycle means an integrated analysis that represents a multi-parametric investigation. This takes into account various aspects of sustainability commonly identified for the three macro categories: environmental, social and economic [5]. The triple dimension of sustainability (LCSA) is thus integrated through the cost of life (LCC), its environmental assessment (LCA) and social analysis (SLCA), namely (Equation 1):

$$LCSA = LCC + LCA + SLCA \tag{1}$$

This scenario may include circular economy approach identified as follow: from cradle to gate (the least detailed, from cradle to the construction site); from cradle to grave (the most frequent, understood in Italian from cradle to grave); from cradle to cradle (recognising the importance of recycling and reuse, from cradle to cradle) [6], [7].

Life-cycle sustainable assessment (life-cycle analysis) is regulated nationally and internationally by ISO 14040-14044. For this reason, there is a wide range of possible life cycle diagnostic alternatives, depending on the analysed structure and the chosen material [8], [9].

1.2 Ranking and classification method for sustainable retrofit of bridges

The infrastructure sector is still lagging in terms of the concept of sustainability of structures or materials and the theme of green concrete is only beginning to gain interest. For this reason, a general review of the current state-of-the-art has been conducted with the bibliographic research software VOS Viewer [10]. The software allows to carry out bibliometric and scientometric research through the analysis and identification of the main authors, the keywords, the number of publications, citations and their dispersion over time. This aims at identifying the most discussed themes, their correlation and their development over time.

An analysis through mapping and hierarchical clustering is used to produce useful graphical information that permits a first overview of the subject, recognizing in a short time which approaches may be most suitable for the study of the sustainability of concrete for bridges and infrastructures.

Two different types of searches are here presented: firstly the general state of the sustainability of interventions for concrete bridges is reviewed through the Scopus and Web Science databases; secondly, the same search is applied more in detail to multi-criteria decision analysis.

The first search revealed five clusters, and the dispersed results of a total of 67 articles highlighted the need for further study (Figure 1a). The second, filtered for multi-criteria analysis, included only 19 documents, showing three more defined clusters, in which themes are mainly the same: interventions for seismic actions and safety (Figure 1b).

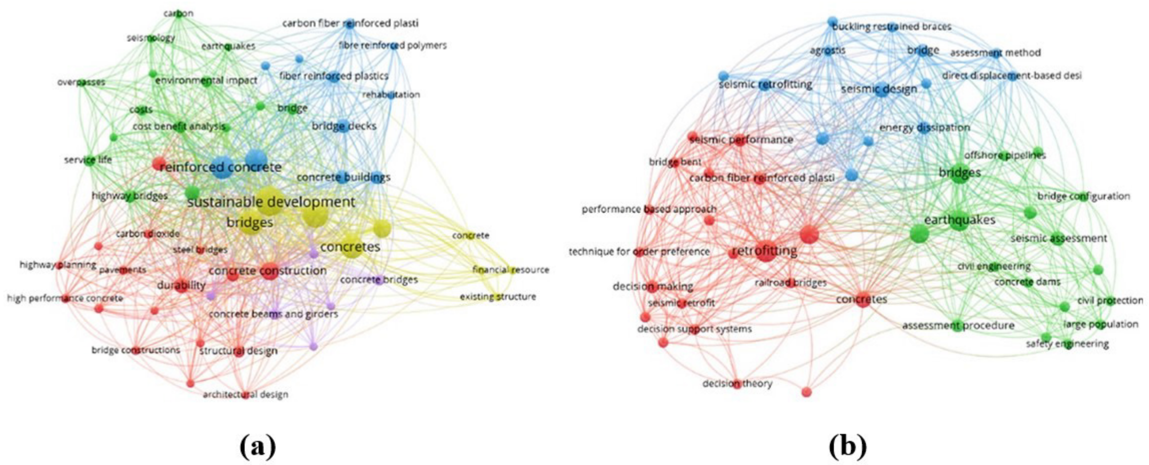


Figure 1. Sustainable retrofitting assessment scientometric: **(a)** data for bridges: in blue the mix design, in yellow the costs and composition, in red the structural analysis and in green the seismic assessment; **(b)** data for bridges with multi-criteria decision analysis. In blue, there is the mix design, in red and green the seismic analysis.

Only a few studies in the two groups extracted thanks to the second search are specifically relevant to sustainability. One uses decision-making to integrate seismic loss, sustainability and resilience. The approach is defined as innovative because it has not yet been extensively developed for the selection of the best intervention alternative from a long-term perspective [11].

To varying degrees, Multiple Attribute Decision Making (MADM) techniques have been applied throughout each stage of the bridge's life cycle as support for engineers and contractors. In the event of intervention on existing structures, each repairing strategy may present different benefits but also significant drawbacks that must be considered. Therefore, the multitude of solutions in the state-of-the-art may lead to an ineffective or even incorrect design decision.

A general overview of MADM analysis applied to bridges' sustainability is provided in [12], where the authors examine about 77 manuscripts classifying them into 4 main categories (planning and design, construction, operation and maintenance, demolition and recycling). According to this study, the maintenance phase emerges as the most investigated while Fuzzy logic and Analytical Hierarchy Process (AHP) techniques have emerged as the most employed approaches. Regarding the use of multi-criteria analysis techniques to compare alternative retrofitting options, they have been used to face many problems: to select material for the repair of structural concrete [4], to compare repair projects [13], to assess corrosion damage [14] and risk [15], etc. Only a small number of researches are available on the ranking and classification method used to assess the priority of the bridge to be repaired [16].

2 METHODOLOGY

The evaluation of four different alternatives for the sustainable repair of a bridge's' column is carried out via an innovative procedure in the world of infrastructure. The following approach aims to compare alternatives from a sustainability point of view considering environmental, social, economic and structural aspects.

The research methodology is then summarized as follows:

1. The repair interventions are designed;
2. The alternatives are modelled through the BIM technology to extract the schedule of the quantities and all the data necessary for the successive evaluations;

3. The most sustainable alternative is established via multi-criterial analyses, in particular, the AHP approach with the implementation of MIVES (Modelo Integrado de Valor para Evaluaciòn Sostenible);
4. Python code is developed to carry out the analysis.

These steps are necessary to quantify the sustainability of the selected alternatives and to obtain an index that allows comparison and a recommended and most suitable solution.

The non-exhaustive legislation (which does not specify a single methodology, even when it mentions it) and the challenge of selecting multi-criteria analysis that should be developed by the individual user with a team of decision experts are likely the reasons why multi-criteria analysis is still rarely used today (as evidenced in the literature) in this particular field.

2.1 Case study

An actual RC bridge located in Sardinia (Italy), in particular one column, as shown in Figure 2, serves as the case study for this research. The deck is made of simple multi-span precast concrete girders, which are supported by rigid frame columns. The analysed column has a circular cross-section with a 1200 mm diameter and its height is equal to 3850 mm (up to the cap). The bridge column is built of normal strength concrete (NSC), whose nominal compressive strength and associated strain are equivalent to 30 MPa and 0.2 percent, respectively, while the softening branch reaches zero stress at a strain value of 0.4 percent. The axial force on a single column is estimated to be 4500 kN, and the concrete cover has a depth of 40 mm. Twenty rebars with a diameter of 24 mm are arranged in a single concentric circular layer while transverse reinforcement is provided by a spiral with dimensions of 12 mm in diameter and 250 mm in pitch, respectively. The uncorroded reinforcing steel bars' yielding stress, ultimate stress, and corresponding strain are 536 MPa, 649 MPa, and 11.6%. The repairing interventions herein presented are designed by analysing the pier only in the transverse direction, therefore it is effectively modelled as a cantilever element (by neglecting the effect due to the frame).

2.2 Repair methods

(1) *Column replacement:* the first option involves the removal of the severely damaged pier and its replacement with a new one designed as the original without providing for a code adaptation (Figure 3a).

(2) *Rebar replacement:* the second intervention approach has been proposed to repair earthquake and corrosion-damaged piers in recent years [17]–[23].

The procedure is implemented as follows:

- The external layer of concrete is removed to allow for the replacement of damaged longitudinal rebars as well as to stop the corrosion of new steel rebars. The repaired zone extends along the column height and deeper than the original reinforcement's rear face. The height of the intervention area is assumed to equal to 2_{Lp} (length of the plastic hinge), while the depth of the removed concrete area is equal to 110 mm. To adequately distribute the tensions at the pier footing, the repaired zone must also be expanded into the foundation.
- To improve the bond between old and new concrete sections, the surface of the concrete core is prepared.
- The damaged longitudinal rebars are cut and replaced with new machined steel rebars. $\alpha = A_m/A_s$ stands for the turning factor (here assumed to be equal to 0.6) where A_m and A_s are machined and the original rebar cross-section area, respectively. Bar replacement occurs mainly in two steps: firstly, the couplers (i.e., steel equal angles) are placed on the backside of the old rebars while the new machined steel rebar segments are first aligned with the existing rebars, then the coupler and the ends of the rebars are welded together.
- Part of the original longitudinal reinforcement within the intervention area can be eventually replaced with new unmachined steel rebars.
- Lastly, covering is accomplished using Ultra-high Performance Fibre-Reinforced Concrete (UHPFRC) [24] by arranging the formwork and casting the UHPFRC. Once enough time has passed, the formwork is removed. UHPFRC gains strength quite quickly, which cuts down on the total amount of time needed to complete the repair intervention.

It should be noted that the application of UHPFRC greatly improves the shear capacity, allowing the removal of the corroded transverse reinforcement in the repaired zone without replacement. Lastly, the UHPFRC's extremely low diffusion coefficient practically blocks chloride from penetrating concrete, which prevents the corrosion of steel reinforcement close to the repaired zone (Figure 3b).

(3) *FRP jacketing:* in the third scenario, the repairing intervention is designed according to He et al. [25]. In the cited paper, the authors propose a rapid intervention technique for seriously damaged columns, with fractured or buckled

reinforcing bars. The repairing solution aim at restoring the column strength associated with the peak load of the original un-corroded pier (Figure 3c) and the original concrete confinement. The intervention is designed on the assumption that identical works, timing and "comparable" materials are utilised. The repair mortar is a normal strength concrete with a compressive strength of 37 MPa. The CFRP strengthening system is made up of carbon fibre tow sheets consisting of unidirectional fibres with the following properties: ultimate tensile strength of 3800 MPa; tensile modulus of 227 GPa; ultimate rupture strain of 0.0167; and nominal thickness of 0.165 mm per ply. The stress-strain relationship of the fibres is linear-elastic until rupture.

In the case of U-shape or wrapping, the contribution of the FRP reinforcement system can be estimated according to CNR-DT 200 [26], [27], and so, based on the Mörsch model, $V_{Rd,f,}$ can be calculated by the following Equation 2:

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

where d = the height of the section, f_{fed} = the effective strength of the reinforcement system, t_f = the thickness of the FRP reinforcement system, b_f = the width of the strips, p_f = the pitch of the strips (in the case of strips placed adjacent to each other, b_f/p_f =1.0 is assumed), γ_{Rd} = the partial coefficient given in Table 1-3 of the CNR-DT 200 (for shear/torsion is equal to 1,20). The f_{fed} has been evaluated choosing an effective strain in the CFP equal to 0.004. Hence, by assuming $V_{Rd,f}$ equal to the difference between the target resistance and the resistance of the damaged column, by inverting Equation 1 it was possible to calculate t_f, i.e. the thickness of FRP needed. The application of the FRP intends to re-establish also the confinement given by the transverse reinforcement in the damaged section (evaluated according to Mander et al. [28]), so the confinement pressure given by the wrapping system has been evaluated according to the following Equation 3 given by DCR-DT 200 [26], [27]:

$$f_1 = \frac{1}{2} \cdot \rho_f \cdot E_t \cdot \varepsilon_{fr,rid} \tag{3}$$

Where ρ_f = ratio of reinforcement, dependent on the shape of the section and the type of application, E_f = modulus of elasticity of the material in the direction of the fibres, $\varepsilon_{fr,rid}$ = reduced strain of the fibre-reinforced composite.

CFRP has been applied also with longitudinal fibres to compensate the loss of strength related to the fracture or buckling of longitudinal rebars. Because of uncertainty regarding the capacity of the existing longitudinal reinforcement, all the bars are severed and the required layers of CFRP are calculated by assuming that they will provide all of the resistant moment. As a result of the design outcomes, 10 vertical and 3 horizontal layers were used. A crucial aspect is to guarantee enough bond length to the CFRP wrap, avoiding premature failure mechanism in the strengthening system. For this reason, a metal anchorage system is designed to secure the longitudinal reinforcement at the crucial section at the base of the cantilever column. Details of the system are shown in Figure 3c.

(4) Concrete jacketing: this methodology has been proposed by Lehman et al. [29] to repair extensively damaged bridge columns. It entails installing a strong jacket to the damaged part of the pier, forcing new flexural hinging of the jacket. The jacket is designed to have comparable flexural strength to the original cross section. Damaged concrete to a depth of 110 mm of the column is removed while the remaining area of the intervention height of the existing column is roughened to encourage shear transfer. Given the uncertainties of the capacity of the damaged reinforcement, all the original longitudinal bars are severed and the fractured spiral is removed. Due to jacketing the base section thickens to a diameter of 1600 mm and it is reinforced by 15ϕ20 longitudinal rebars and a new column spiral with diameter and pitch equal to 12 mm and 100 mm, respectively. The jacket length L_j of 1800 mm is chosen to make it unlike that the column would yield above the jacket. The original column diameter is 400 mm smaller than the jacket diameter. The repair design strategy is depicted in Figure 3d.

The alternatives were thus modelled with BIM technology to extract the schedules of quantities (Figure 2-3). The modelling involved the creation of individual parametric elements, built according to the seven dimensions by UNI 11337 [30]. The level of details (LOD) geometry is equal to F and G depending on the elements since the degradation state has been only partially replicated. Only the deck turns out to be a LOD D (Figure 2).

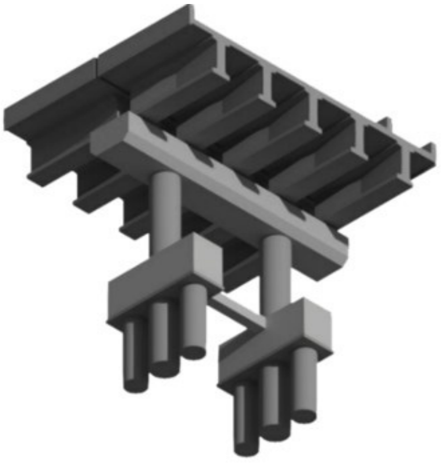


Figure 2. Modelling of the current condition of the pier.

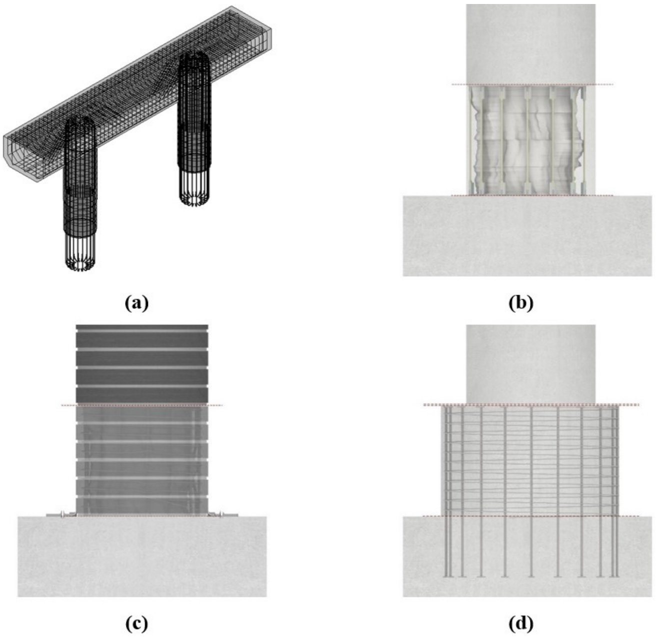


Figure 3. Modelling of the four alternatives: **(a)** complete replacement of the pier, **(b)** rebars replacement with UHPFRC cover, **(c)** CFRP wrapping, **(d)** concrete base jacketing

2.2 Multi-Criteria Decision Making

The decision-making analysis is a technique applied in many fields to determine the goals to be achieved and the optimal methodology to be used [31].

This systematic process is described by several steps that are respectively: the identification of the problem; the selection of criteria; the evaluation of alternatives; the final choice of the best alternative for that specific problem [32].

The multi-criteria analysis is applied to the most disparate subjects, from economy to teaching, with specific types of analysis considered more suitable for different fields [33].

The literature on this procedure is represented by a very wide range of publications resulting in detailed and specific papers for each hypothetical application. In particular, in the architectural field, there are countless applications that such an interesting methodology can have [34].

Often the multi-criteria analysis is employed in Economics to select investment for instance, but it has currently a little application in the infrastructures field. Despite these premises, the uses it has and could have are innumerable and can lead, for example, to: optimization of structural decisions; greater understanding of alternatives; higher efficiency of buildings; greater sustainability of the entire life cycle of the bridge retrofitting projects.

The multi-criteria decision-making process, also known as MCDM (or MCDA multi-criteria decision analysis), is based on mathematical and analytical analyses that the decision-maker does to rank and select the best alternatives for solving a problem.

There are different types of analysis, but the main difference is between single-criteria and multi-criteria. Usually, the second one is used as it examines more options, finding the best one. A standard model used for these analyses is that of a systematic approach to evaluation, choosing priorities and selecting the best one [35].

2.3 Analytical Hierarchy Process

Decision-making through the use of analytical hierarchy is a technique for decision support in complex environments where many variables or criteria are considered in the prioritization and selection of alternatives [36].

The AHP was developed in the 1970s by Thomas L. Saaty and its application starts with a problem that is divided into a hierarchy of criteria so it can be more easily analysed and compared independently. Secondly, it must be constructed according to a logical hierarchy so that decision-makers can systematically evaluate and weight alternatives by making pair comparisons for each of the chosen criteria. The AHP approach, also compared to other MADM methodologies, allows giving a mathematical value to a judgment, to conduct coherent and valid comparisons. A decision tree is defined, with the criteria to be taken into account in assessing the chosen alternatives. Each criterion and tree branch will be assigned a weight [37],[38]. The tree is consequently divided into three parts: the macro categories called Requirements, the sub-criteria (or Criteria) and the so-called Indicators (more specific groupings). Each of the latter will then be assigned a value associated with each alternative (Figure 4).

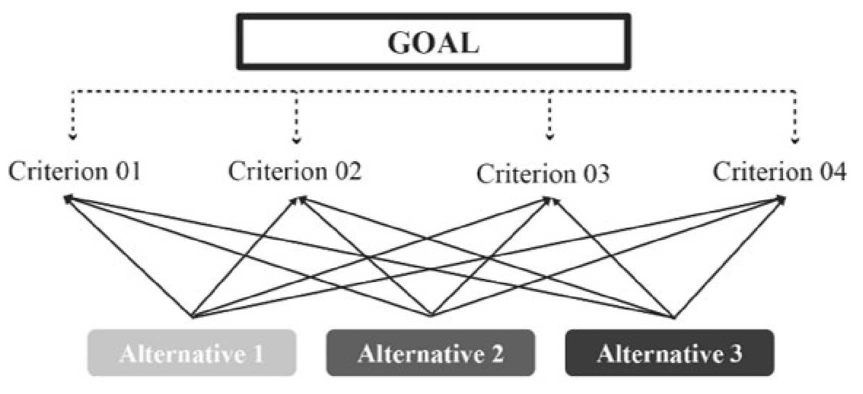


Figure 4. Flowchart showing how the AHP method works as pairwise comparison. Once the goal and the decision tree have been established, the alternatives are evaluated according to each criterion, weighted according to the importance of the goal.

The goal is to obtain a Sustainability Index (SI) that is given by the following Equation 4:

$$SI = \sum_{i=1}^{n} \alpha \cdot \beta \cdot \gamma \cdot (V_i) \quad (4)$$

Where n = total number of indicators; α = requirement weight (%); β = criterion weight (%); γ= indicator weight (%); V_i = is the so-called value index, taken by value function (%).

The weights are obtained from the AHP approach and the value index from the MIVES value function as the following chart explains (Figure 5).

In the state-of-the-art, there are various types of decision trees to assess the sustainability of concrete structures and infrastructures, mainly elaborated by Spanish Universities through teams of experts who have evaluated the weights of each criterion according to data collected and personal experience.

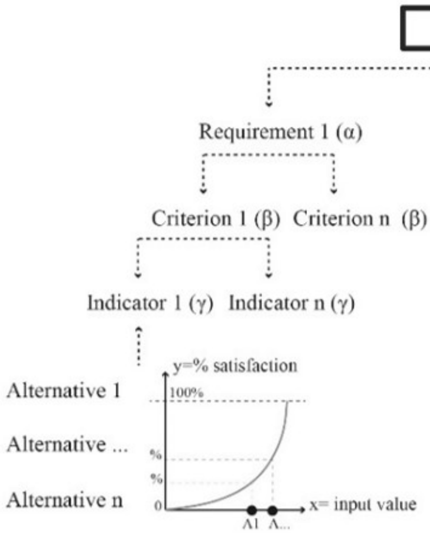


Figure 5. Decision tree taken as example with weights assigned and the value function correlated. It shows the association between value functions and indicators.

In the following image the selected criteria used to evaluate the different alternatives of intervention are specified (Figure 6):

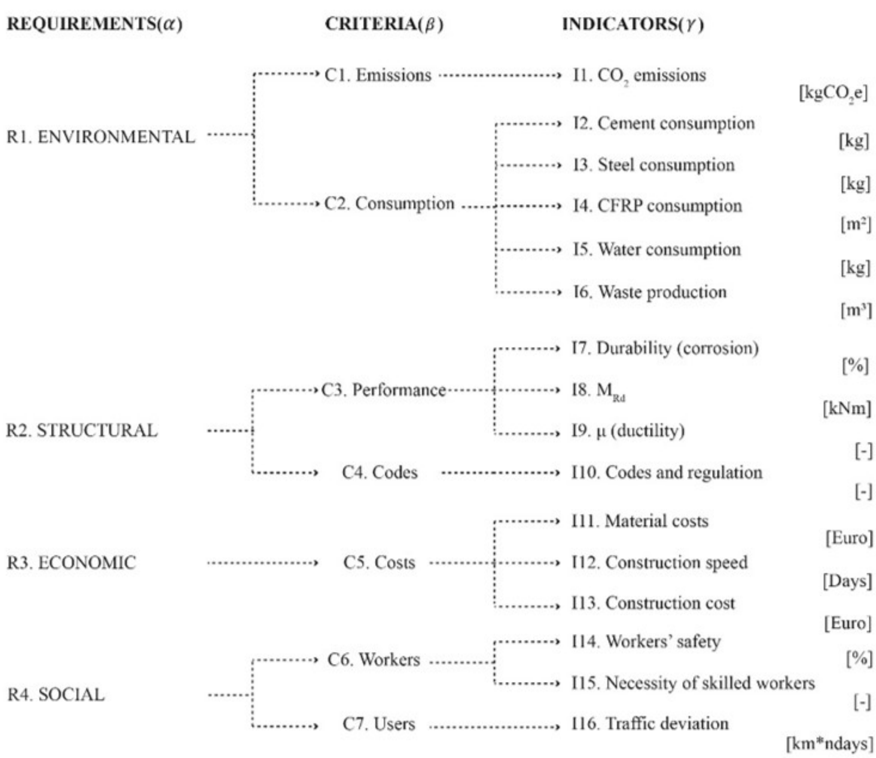


Figure 6. Decision tree for the considered study case, subdivided into Requirements (four clusters), Criteria (seven clusters) and Indicators (eighteen clusters).

The criteria selection methods refer to the assessment of the life cycle assessment of concrete infrastructures, evaluating macro-categories of economic, social and environmental indices, plus the structural component that is rarely considered. At this point the weights for each selected criterion must be established, making a comparison between the criteria themselves and defining the hierarchy. The weights expressed in percentages are verified and constructed through the matrix method (as explained later). Each of the steps, from the sub-criteria to the requirements of the macro-categories, is weighed through a specific function.

The values are taken as follows.

For each step, the decision maker derives a weight to evaluate each alternative. Once these steps have been carried out, it is necessary to get the summation of all obtained values to estimate the choice considered better through the parameters taken into consideration for every different alternative.

The most common comparison currently used to make judgments is still the one proposed by Saaty [37]. By assigning values ranging from 1 to 9 (possibly using odd numbers to increase the difference in judgments), the scale determines the relative importance of an alternative over another alternative [38].

The goal is to create a criteria comparison matrix according to the next model in Table 1.

Table 1. Criteria comparison following the AHP method.

	Criterion 1	**Criterion 2**
Criterion 1	1	rating
Criterion 2	1/rating (reciprocal)	1

Given an ordered pair of objects (n_i,n_j) of a level, the decision-maker expresses a judgment of comparison (n_{ij}) as follows (Equation 5):

$$n_{ij} = \frac{1}{n_{ji}} \text{with } n_{ii} = 1 \forall i \quad (5)$$

At the end of the process, a weight is assigned to each level and the sum of the weights must be equal to 100% (Equation 6).

$$w = [w1, \dots, wi, \dots, wj, \dots, wn], \sum_{i=1}^{n} wi = 1 \quad (6)$$

When the valuation method proposed by Saaty et al. is used, it is necessary to verify the so-called Consistency Ratio (CR), if it is less than 0.10, it is considered valid.

CR is a ratio between CI (Consistency index) and RI (Ratio Index).

In general, RI is a fixed number linked to the number of criteria (Table 2).

Table 2. RI reference values considering N as number of criteria.

N	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The matrix is considered always valid if the number of criteria is equal to one or two because the CR factor is usually used for complex matrices that need to be verified.

Once the decision tree and the weight have been elaborated, it is necessary to find the value function for each indicator, to assign an analytical validity and a precise preference. The V-value to be multiplied at the incidence calculated with the AHP methodology should therefore be obtained.

2.4 MIVES approach

The last step of this research involves the MIVES technique (Modelo Integrado de cuantificacion de Valor para Edificacion Sostenibles), developed by Spanish universities and institutions (UPC, UPV and Labein Tecnalia). While the AHP method finds weight through matrix calculation, the MIVES approach finds the satisfaction value of each alternative through the study of an algorithm [39]. It is therefore necessary to calculate a value function for each indicator considered. Typical value functions can be: increasing or decreasing (monotony); S-shaped, linear, concave or convex (form). Other types of curves (such as the Gauss bell or parabola) can also be considered for particular cases. Monotony and form of functions are discretionary, according to the literature and the experience of decision makers.

The first step for creating functions is to consider the following parameters (Table 3).

Table 3. Possible monotonies and shapes of the functions.

Monotony	Shape
Increasing	Linear
Decreasing	Convex
	Concave
	S-shaped

The x-values for the reference indicator shall be set in the abscissa axis. The values of the extremes, x_{min} and x_{max}, are fixed and then the range that contains the trend of the function is established.

In the axis of the ordinates are inserted the maximum and minimum values of approval, which are always equal to 1 and 0, corresponding to 100% and 0% of satisfaction linked to the choice of the given alternative.

For instance, knowing the limit values of the function, the shape can be decided based on whether the decision maker wants the most collected data near the extremes (S-shape, as a combination between concave and convex) or constants (linear), etc.

Monotony is decided according to the liking of extreme values. For example, economic values curve is usually decreasing while carbon dioxide consumption may be increasing

The goal is to find the algorithm that finds the following two functions (Equation 7):

$$V_{ind} = A + B \cdot \left(1 - \mathrm{e}^{-k \cdot \left(\frac{|x - xmin|}{C}\right)^{P}}\right) \tag{7}$$

where B is obtained by Equation 8:

$$B = \frac{1}{\left(1 - \mathrm{e}^{-k \cdot \left(\frac{|xmax - xmin|}{C}\right)}\right)} \tag{8}$$

where unknown values have discretionary ranges depending on the curve the operator wants to obtain, x_{min} = the minimum x-axis of the space within which the interventions take place for the indicator under evaluation; x = the quantification of the indicator under evaluation (different or otherwise, for each intervention), P = the form factor that defines whether the curve is concave, convex, linear or an "S" shape: concave curves are obtained for values of P < 1, convex and "S" shaped forms for P > 1 and almost straight lines for values of P = 1. In addition, P gives an approximation of the slope of the curve at the inflection point. C approximates the x-axis of the inflection point. k approximates the ordinate of the inflection point. B is the factor that allows the function to be maintained within the value range of 0 to 1. A is usually equal to zero. If it is not equal to zero, the function is translated according to y, by a value equal to A [40], [41].

Parameters are chosen according to the monotony and the shape, as follows (Table 4 and 5).

Table 4. Parameters for 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

Table 5. Parameters for 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

The first step is then the decision of the boundary ranges, x_{min} and x_{max}, to establish the domain of value functions. As alternatives deal with an existing column, maximum and minimum values cannot be derived from regulations or best practices. There are few case studies in the literature with alternatives for repair of the existing structures, so there are no predetermined procedures to understand how to select the extreme values. It emerged that among the four options considered, each time two of them should represent the extremes. This assumption is experimental and with this article, authors want to emphasize the possibility of intervening in the existing structures through the AHP multi-criteria analysis with the MIVES implementation. Chosen values are further described in the following section.

2.5 Indicators description

The values of the indicators for each alternative are evaluated as follows:

1. Emissions related to the production of cement include the first three steps declared in the Environmental Product Declaration (EPD) of the product (corresponding to the A1-A3 phases) of the Buzzi Unicem plant and published in "Report Cementi 2021" [42]. The reference factory is located in Sardinia, near the city of Nuoro. The emissions are taken equal to 862 [kgCO_2e] (Siniscola factory average), slightly above the company's national average. The emissions parameter has also been included in the BIM environment modelling, to build the model following the seven dimensions. The emissions related to the A4 phase are then estimated and added to the total. The emissions related to the transport from the manufacturer to the batching plant, and from the latter to the construction site are estimated by evaluating the number of trucks (heavy vehicles) used for each alternative. The calculation refers to Commission Regulation EU 2017/2400 of 12 December 2017. The new VETCO software was used, an application developed by the European Commission and already became mandatory in 2019 for some categories of heavy vehicles. The vehicles hypothesized to be used in the case study can be classified in category 4 (truck carrying more than 16 tons), with an axle arrangement of four and a weight of about 40 tons. Regarding steel products emissions, they are taken from the environmental product declaration of an Italian steel company. The values include stages A1 to A4. Finally, emissions associated with the FRP production stages are deduced from the literature [43].
2. Data referring to the volume of the concrete are extracted from the BIM model (Figure 7). Knowing the data related to the mix design and the specific weight, it was possible to obtain the kg of cement needed.

Schedule of structural columns

A	B	C	D	E	F	G	H
Family	Volume	Pile diameter	Pile height	Reinforcement volume	Volume dep	Cost	Emission CO2
Pile	4.31 m³	1.200	3.850	111029.29 cm³	4.19 m³	€716.50	1084.72
Pile 2	4.31 m³	1.200	3.850	111029.29 cm³	4.19 m³	€716.50	1084.72
Total 2	8.61 m³			222058.59 cm³	8.39 m³	€1433.00	2169.44

Figure 7. Schedule example taken by BIM modelling of the elements. Each parameter has references and formulas inside to obtain the shown values.

3. Regarding the consumption of steel, all the rebars necessary for the realization of various interventions are modelled in a BIM environment and the kg of material used are obtained.
4. Modelling the CFRP components proved challenging. To get the intended result (the surface used), it is required to model a structural wall element and insert as many as the number of layers designed. CFRP modelling, like several other actions on the current structures, has several limitations in the BIM environment.
5. The water consumption is equal to a percentage of the selected mix design.
6. The production of waste is based on the simple calculation of the volumes involved in the disposal of the demolished portions.

7. Figure 8a shows the time-dependent evolution of the chloride-induced corrosion, expressed as the loss of reinforcement section or the ratio between corroded section A_{pt} and original bar section A'_s, predicted from multi-physics FE-based simulations for each intervention methodology [44]. As regards the first option, the replacement of the pier with a new one designed as the original without providing for a regulatory adaptation, there will be a loss of the reinforcement area after 50 years of about 11%. In Alternative 2, ultra-high performance concrete is used as repair materials, in this way, thanks to its great compactness, increasing the durability of RC members subjected to corrosive conditions. In this instance, the chloride penetration into the concrete is prevented since the diffusion coefficient is two to three orders of magnitude lower than that of ordinary strength concrete. Therefore, the results of Figure 8a, where rebar cross sections over time, are reasonable. It should be mentioned that the FRP jacketing used in Alternative 3, in addition to recovering the mechanical performance of the pier, can also serve to improve its durability as the external wrapping can significantly reduce the corrosion rate. Consequently, results do not show reduction of rebar cross sections also in Alternative 3. Finally, the intervention number four appears to have the worst behaviour when exposed to a corrosive environment. This is because the new bars placed in the repaired zone at the base have a smaller diameter (20 mm) than the original ones (24 mm). Subsequently, it has been estimated that the rebars will lose 15% of their cross section after 50 years.

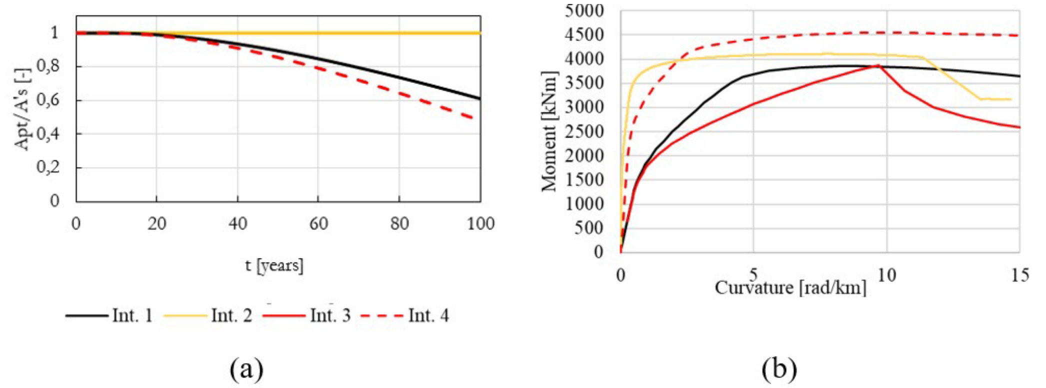


Figure 8. (a) Rebar section reduction over time (b) moment-curvature at the time of the repairment.

8. The model's structural criterion evaluates the structural capabilities of various interventional options. The variables taken into account are the retrofitting's capability to enhance durability, strength (load bearing capacity) and ductility. The repairs of the column are designed to restore the resistant moment of the original un-corroded pier. However, the engineering of the solutions meant that the final results are slightly different from the target values. There are slight differences in the resistant moment among the four solutions, with values ranging from 3868 to 4546 kNm (Figure 8b).
9. On the other hand, the differences when it comes to ductility are not minor. In particular, it should be noted that due to the material's brittle behaviour, the ductility was set to 0 in the case of the FRP intervention.
10. The presence of codes and regulations is considered a fundamental parameter and often overlooked. The importance of its inclusion refers to the difficulty of designing retrofitting interventions. It is indicated with zero the absence of current legislation and with one the presence. An intermediate parameter equal to 0.5 to consider the presence of non-prescriptive guidelines at the International level for CFRP (UNI EN 1015-12 2002; ASTM D 7234 2005) and Italian (CNR-DT 200 R1/2013 introduced in 2014 [26]).
11. Material costs are computed in the BIM environment by adding the cost parameter to each element created. The prices are taken from the Sardinia region's price list for construction. However, some costs that are not predicted in the latter are hypothesised by using instances from the literature or comparable items on the market. This is the case of the mechanical connectors that anchor the vertical FRP to the base of the pier. Similarly, as this product is not currently marketed in Italy, the cost of UHPFRC is estimated to be five times the price of an NSC [45].
12. As the duration of construction work is closely related to construction costs, it is considered a relevant parameter. The data are taken from literature [24], [25], [29] and only the actual days of work were considered, resulting in 10 days for the first alternative, and four for the remaining, respectively.

13. The regional construction price list for Sardinia is used to determine the construction costs, which also include safety costs. The construction site is designed and all the processes are planned, including safety equipment, site arrangements, the electrical panel, the scaffolding, etc. As the cost of machined reinforcing bars is not mentioned in the price list, reference is made to a similar procedure whose price is in the price list of a company in the steel industry.
14. The value of the safety risk for the workers is evaluated according to T. U. 81/08 and the modalities of the drafting of the document of Risk Assessment. This calculation refers to the Risk Matrix (Table 6), where it is possible to balance the probability of occurrence of a dangerous event and the damage it would cause.

Table 6. Values related to the risk matrix.

Risk	Improbable	Unlikely	Probable	Most likely
[R]	[P1]	[P2]	[P3]	[P4]
Slight damage	LOW	LOW	MEDIUM	MEDIUM
[E1]	[P1]X[E1]=1	[P2]X[E1]=2	[P3]X[E1]=3	[P4]X[E1]=4
Significant damage	LOW	MEDIUM	HIGH	HIGH
[E2]	[P1]X[E2]=2	[P2]X[E2]=4	[P3]X[E2]=6	[P4]X[E2]=8
Serious damage	MEDIUM	HIGH	HIGH	VERY HIGH
[E3]	[P1]X[E3]=3	[P2]X[E3]=6	[P3]X[E3]=9	[P4]X[E3]=12
Very serious damage	MEDIUM	HIGH	VERY HIGH	VERY HIGH
[E4]	[P1]X[E4]=4	[P2]X[E4]=8	[P3]X[E4]=12	[P4]X[E4]=16

The matrix allows obtaining values that, multiplied by reduction factors (Table 7) and summed among all the expected works, allows to calculate the percentage of risk. The risks considered are: falling and sliding; soar; falling of materials from above; failure of mechanical parts of machinery; contacts with machines or machines in motion; collapse or replenishment of deposited materials; disarmament; electrocution; electrocution due to the use of electrical equipment; jets, splashes; investment; manual handling of loads, powders, fibres; splinters, punctures, cuts, abrasions, wounds; overturning of the subsidence medium; noise; vibrations.

Table 7. Values related to risk reduction [46].

Preventive and protective measures implemented	k
General information training	0.95
Specific training	0.9
Category PPE training	1.0
Operating procedures and instructions	0.9
First aid and emergency	1.0
Health surveillance	0.9
Accidents missed accidents and near miss	0.9
PPE / DPC	0.8
Total attenuation coefficient (Ktot)	0.5

15. The ease of finding qualified and skilled workers is equal to zero to indicate situations in which it is considered particularly easy and there is no need for workers with special certifications, equal to one to underline greater difficulties. As for the regulations, an intermediate value has been inserted.
16. The traffic deviation is calculated considering the distance between Oristano (the closest city centre) and the bridge endpoint. To get to the latter there is only provincial road 56. The time of closure of the infrastructure (30 days for the first alternative, 10 for the second, 7 for the third and 10 also for the last one) is assessed and multiplied by the kilometres of the journey to account for the traffic deviation (1.8 km). This value is chosen because it is possible to derive as a result the CO_2 emissions, the journey time and the cost of fuel.

It is then elaborated the following table with the grouped values for all the Indicators of each alternative (Table 8).

Table 8. The values of each alternative to be associated with each indicator are given. Each time two values will be considered as x_{min} and x_{max}.

Indicators	Units	A1	A2	A3	A4
I1. CO_2 emissions	[kgCO_2eq]	12110.81	589.36	521.70	1029.91
I2. Cement consumption	[kg]	10584.00	683.71	605.22	1194.79
I3. Steel consumption	[kg]	4066.30	244.83	296.94	238.13
I4. CFRP consumption	[m^2]	0.00	0.00	21.11	0.00
I5. Water consumption	[kg]	5292.00	108.70	89.10	468.00
I6. Waste production	[m^3]	26.57	0.66	0.66	0.39
I7. Durability (corrosion)	[%]	0.89	1.00	1.00	0.85
I8. M_{Rd}	[kNm]	3947.00	4087.00	3868.90	4546.00
I9. μ (ductility)	[%]	5.50	8.39	4.04	6.35
I10. Codes and regulation	-	1.00	0.00	0.50	0.00
I11. Material costs	[Euro]	9415.71	1045.30	35707.92	1163.16
I12. Construction speed	[days]	10.00	4.00	4.00	4.00
I13. Construction cost (including safety cost)	[Euro]	31348.71	17666.00	53732.40	17266.40
I14. Workers' safety	-	0.32	0.28	0.27	0.26
I15. Necessity of skilled workers	-	0.00	1.00	0.50	0.00
I16. Traffic deviation	[Km*n_{days}]	54.00	18.00	12.60	18.00

3 ANALYSIS AND RESULTS

Once the hierarchies, weights and extreme values are established, a code in Python language is setup to carry out the analysis and to find the most sustainable alternative based on the opinion expressed by the decision makers. In order to determine which of the proposed interventions is suitable for each of the four requirements α—environmental (R1), structural (R2), economic (R3), and social (R4)—each requirement is first investigated separately. Following this initial study, the authors combined the requirements by assigning them different weights to properly appreciate how they affect the ranking and the optimum solution. Conversely, the weights assigned to each criterion and indicator remained constant throughout the investigation. Specifically, the analysis starts with the structural requirement, which is discussed in detail, including the specifics of the code and the procedure followed to assign a value function curve and how the satisfaction values for each indicator is obtained. Each requirement is described separately below. All the first acronyms expressed in uppercase on Python have been indicated in lowercase to facilitate the algorithm and avoid mistakes.

3.1 Structural

The structural requirement (R2) is divided into 2 criteria, Performance (C3) and Codes (C4), respectively. These are further separated into 4 indicators: durability (I7), resistant moment MRd (I8), and ductility (I9) for criterion C3, and codes and regulations (I10) for criterion C4. The structural performances values are obtained from the sectional analysis carried out in Opensees for each intervention, as previous described in Section 2.5. The presence of codes and regulations is taken into account by indicating with zero the absence of current legislation and with 1 the presence. An intermediate parameter equal to 0.5 to consider the presence of non-prescriptive.

Values of approval are obtained to carry out the MIVES analysis by describing them as functions of each indication as shown in Figure 9 (the "suggested" curve is automatically processed by the algorithm, while the "chosen" is the curve selected by the decision maker).

On the x-axis are reported the values of each indicator, ranging between the minimum and maximum values obtained thought the analysis for each parameter. As the weight and the value of approval are established, the MIVES analysis is performed though the python code as shown in Figure 10.

The matrix with preferences is identified as 'pcm'. The weights, expressed through vectors, are indicated as 'weights' and follow the order of the decision tree. The consistency index is denoted by 'cr' as a number. Finally, the values associated with each final indicator are expressed as a vector with the alternatives in order (alternative 1 to the first place, alternative 2 to the second,…). The outcomes for the structural requirements are presented below (labelled as SI or sustainability index). The second alternative which includes the rebar replacement with UHPFRC cover resulted to be the more sustainable option when it comes to structural requirement.

SI 1 = 0.224 + 0.044 + 0.246 + 0.170 = 0.684

SI 2 = 0.373 + 0.052 + 0.373 + 0.000 = 0.798

SI 3 = 0.373 + 0.040 + 0.146 + 0.087 = 0.646

SI 4 = 0.179 + 0.083 + 0.298 + 0.000 = 0.560

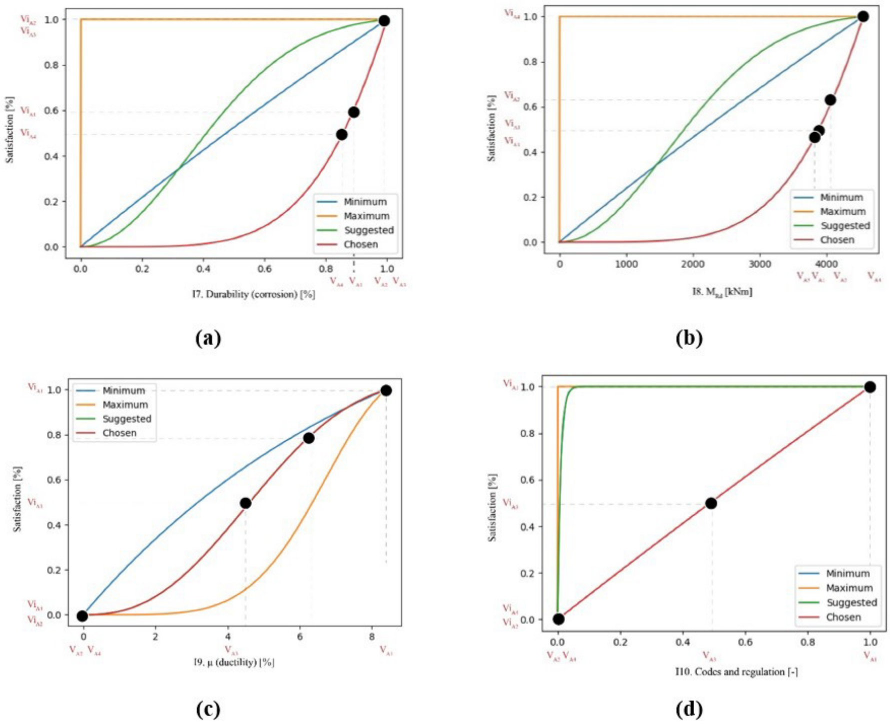


Figure 9. Value function curves for: **(a)** indicator I7, with a convex shape and increasing monotony (chosen parameters are: p_c= 5.0, c_c = 0.5 and k_c = 0.01), **(b)** indicator I8, with a convex shape and increasing monotony (chosen parameters are: p_c= 5.0, c_c = 2200.0 and k_c = 0.01), **(c)** indicator I9, with a s-shaped shape and increasing monotony (chosen parameters are: p_c= 2.5, c_c = 4.19505 and k_c = 0.5), **(d)** indicator I10, with a linear shape and increasing monotony (chosen parameters are: p_c= 1.0, c_c = 0.001 and k_c = 0.0001).

```
[[{'parent_criterion': 'result', 'level': 0, 'level name': 'requirements',
'names': ['r2'], 'pcm': array([[1.]]), 'weights': [1.0], 'cr': 0}],

[{'parent_criterion': 'r2', 'level': 1, 'level name': 'criteria', 'names':
['c3', 'c4'], 'pcm': array([[1. , 5. ],
                            [0.2, 1. ]]),
'weights': [0.833, 0.166], 'cr': 0}],

[{'parent_criterion': 'c3', 'level': 2, 'level name': 'indicators', 'names':
['i7', 'i8', 'i9'], 'pcm': array([[1.  , 4.  , 1.  ],
                                  [0.25, 1.  , 0.25],
                                  [1.  , 4.  , 1.  ]]),
'weights': [0.444, 0.111, 0.444], 'cr': 0.0,
'values': [[0.597, 1.0, 1.0, 0.483], [0.540, 0.632, 0.493, 1.0], [0.665, 1.0,
0.388, 0.803]]},

{'parent_criterion': 'c4', 'level': 2, 'level name': 'indicators', 'names':
['i10'], 'pcm': array([[1.]]),
'weights': [1.0],
'cr': 0,
'values': [[1.0, 0.0, 0.512, 0.0]]}]]c
```

Figure 10. Algorithm results for structural requirement.

3.2 Environmental

The environmental requirement (R1) is divided into 2 criteria, Emissions (C1) and Consumption (C2), respectively, and in six indicators (I1. CO2 Emissions, I2. Cement Consumption, I3. Steel consumption, I4. CFRP consumption, I5. Water consumption, I6. Waste production) (Figure 11).

Regarding environmental requirement the most sustainable choice, according to the decisions taken, is again the second alternative. All alternatives, except the first, give however valid results. Values obtained for the alternative 1 are often used as extreme values of the functions, representing 0% of the satisfaction.

SI 1 = 0.000 + 0.000 + 0.000 + 0.036 + 0.000 + 0.000 = 0.036

SI 2 = 0.465 + 0.170 + 0.131 + 0.036 + 0.077 + 0.036 = 0.915

SI 3 = 0.470 + 0.172 + 0.125 + 0.000 + 0.078 + 0.036 = 0.881

SI 4 = 0.430 + 0.168 + 0.133 + 0.036 + 0.068 + 0.036 = 0.871

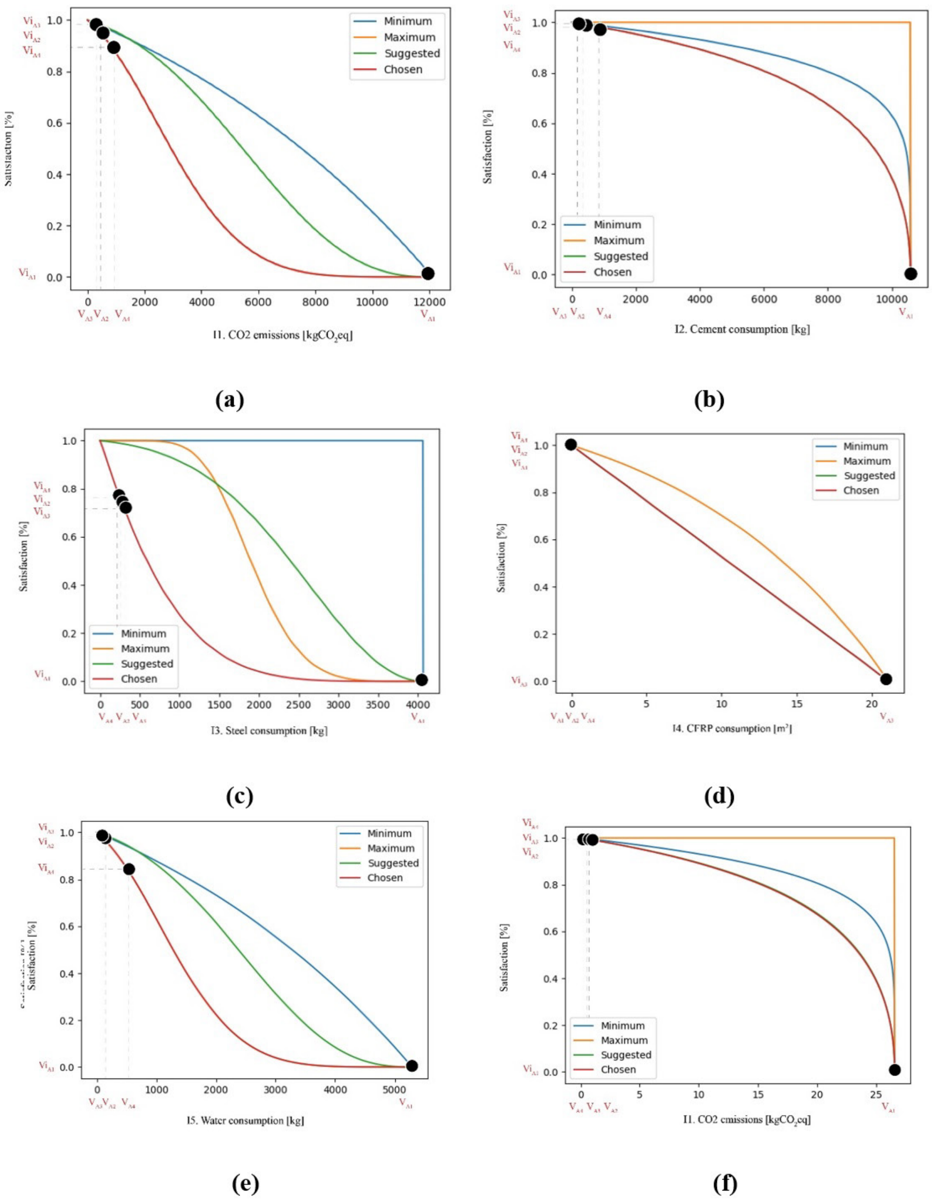


Figure 11. Value function curves for: **(a)** indicator I1, with a s-shaped shape and decreasing monotony (p_c= 5.0, c_c = 9688.0 and k_c = 0.8), **(b)** indicator I2, with a concave shape and decreasing monotony (p_c=0.5, c_c = 2646.0 and k_c = 0.75), **(c)** indicator I3, with a convex shape and decreasing monotony (p_c= 5.0, c_c = 2000.0 and k_c = 0.01), **(d)** indicator I4, with a linear shape and decreasing monotony (p_c= 1.0, c_c = 21.11 and k_c = 0.01), **(e)** indicator I5, with a s-shaped shape and decreasing monotony (p_c= 5.0, c_c = 4233.0 and k_c = 0.8), **(f)** indicator I6, with a concave shape and decreasing monotony (p_c= 0.5, c_c = 7.0 and k_c = 0.75).

3.3 Economic

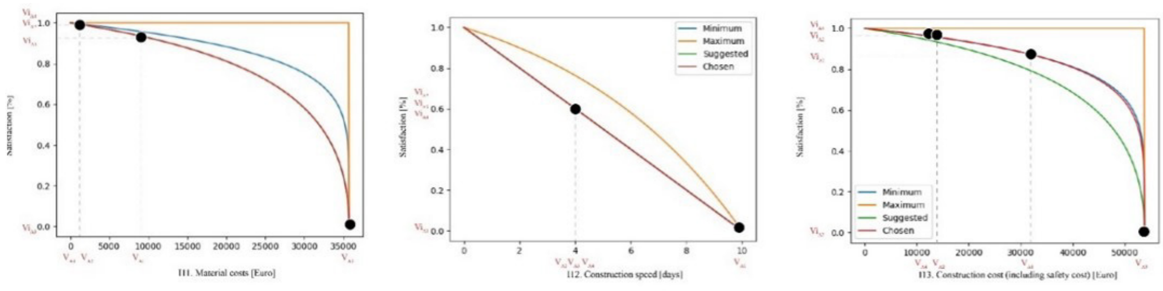
The economic requirement (R3) comprehends the criterion C5. Costs further organized in three indicators: I11. Material costs, I12. Construction speed, I13. Construction costs (Figure 12). SI values show two most suitable alternative: the second one and the fourth alternative, where the column is strengthened by a concrete base jacketing.

SI 1 = 0.372 + 0.000 + 0.348 = 0.720

SI 2 = 0.396 + 0.120 + 0.376 = 0.892

SI 3 = 0.000 + 0.120 + 0.000 = 0.120

SI 4 = 0.396 + 0.120 + 0.376 = 0.892



(a) **(b)** **(c)**

Figure 12. Value function curves for: **(a)** indicator I11, with a concave shape and decreasing monotony (p_c= 0.5, c_c = 8927.0 and k_c = 0.75), (b) indicator I12, with a linear shape and decreasing monotony (p_c= 1.0, c_c = 10.0 and k_c = 0.01), **(c)** indicator I3, with a concave shape and decreasing monotony (p_c= 0.25, c_c = 15000.0 and k_c = 0.75).

3.4 Social

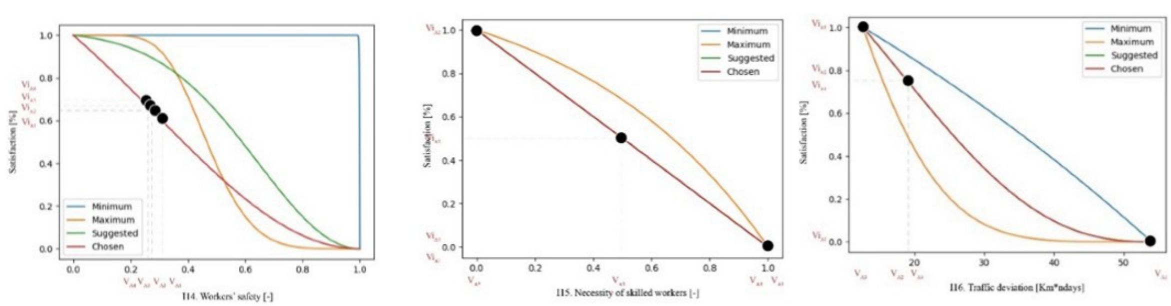
The social requirement (R4) is divided in two criteria, C6. Workers and C7. Users, respectively, and three indicators, I14. Workers' safety, I15. Necessity of skilled workers, I16. Traffic deviation (Figure 13). The most suitable alternative is the fourth.

SI 1 = 0.36 + 0.13 + 0.0000 = 0.49

SI 2 = 0.40 + 0.00 + 0.20 = 0.60

SI 3 = 0.41 + 0.06 + 0.25 = 0.72

SI 4 = 0.41 + 0.13 + 0.20 = 0.74



(a) **(b)** **(c)**

Figure 13. Value function curves for: (a) indicator I14, with a convex shape and decreasing monotony (p_c= 2.00, c_c = 0.10 and k_c = 0.01), (b) indicator I15, with a linear shape and decreasing monotony (p_sp = 1.00, c_sp = 1.00 and k_sp = 0.01), (c) indicator I16, with a convex shape and decreasing monotony (p_sp = 2.50, c_sp = 33.30 and k_sp = 0.50).

4 DISCUSSION

As previously stated, it is crucial to consider a variety of factors while carrying out structural rehabilitation, including both the problem of sustainability and the commonly encountered problem of cost reduction. Contrary to common belief, the themes are not necessarily in opposition to one another. As a result, it is possible to identify a solution that addresses both while utilizing limited resources, consuming less energy, and cutting costs. The application of this methodology is an innovative and relevant evaluation that, involving both widespread and theoretical solutions for the rehabilitation of R.C. bridge column, has rarely been made.

After comparing the alternatives individually, a first sensitivity attempt is made by assuming three potential weight combinations for the requirements. Through matrix study, more in-depth sensitivity analysis can be seen as a future development. As a result of having to conduct the analysis with a small group of decision-making professionals, the weights have been varied to give a general and impersonal point of view. The weights' variation has suggested in fact that further study is required to determine whether the results are reliable. Although the results themselves are not particularly remarkable, they do enable the reader to comprehend the analysis and research methodology.

Based on literature using MIVES and AHP for structures in RC, the authors decided to assess (Scenario1) the environmental requirement equal to 40%, economic equal to 40%, social equal to 14% and structural equal to 6% (Table 9). For the first evaluation the best intervention turns out to be the second, so the indices are verified to see if it changed the final judgment. About the second assessment (Scenario 2), changing the weights and using for the environmental requirement= 40%, economic= 32%, social= 10% and structural= 18%, the second one (alternative A2) results in in the best, with Alternative 4 following. Scenario 3 is evaluated using for the environmental requirement= 30%, economic= 42%, social= 10% and structural= 18%, where the most suitable one is, also in this case, the second one.

Table 9. Different scenarios with SI results.

	Scenario 1	Scenario 2	Scenario 3
SI 1	0.542	0.546	0.485
SI 2	0.855	0.844	0.853
SI 3	0.540	0.567	0.503
SI 4	0.842	0.809	0.780

By changing the weights, it is possible to appreciate the dynamics that cause one alternative to be characterized as more sustainable than the others. It is also possible to identify alternatives that are acceptable in multiple scenarios and those that result less sustainable in all or many scenarios. The sustainability indices (defined, as mentioned previously, with SI) are compared, which include the ratings obtained according to the values, for each index, and their multiplication by the weights of each branch of the decision tree. The three different scenarios have been chosen because they show possible preferences of the clients, designers, users, and other stakeholders, and plausible choices of the decision maker based on what it is requested to deepen in a given situation and what is meant in a specific one with sustainability. Consequently, SI are first analysed individually (considering the other requirements with a value equal to 0%) and then all the requirements are considered together. This could give a broader view. Taking the requirements individually (with each equal to 100%), it is clear how the second alternative (replacement of the bars), results to be the most sustainable in three requirements out of four (environmental and economic structural on a par), is the most suitable. For the social aspect, this solution results second only to the A4 intervention, which involves a concrete base jacketing; nonetheless, they are comparable from an economic perspective. These initial analyses suggest that there is already a clear preference for two alternatives (A2 and A4) over the others (A1 and A3). This is likely due to complete replacement A1 being the least efficient solution in most value functions (without considering the weights) because of the large consumption of material compared to the others. Intervention with the CFRP results unfavourable mainly because of costs, but also because of considerable emissions. Despite being the most common in practice, A1 and A3 should be discarded. This demonstrates how even more complex interventions may turn out to be the most cost-effective and environment friendly if properly investigated. Evidently, weight addition seems to support earlier analyses. Even after weights are added, the options that were ranked as optimal are still preferable. Despite this, there is a slight but significant preference for the A2 choice over the A4 alternative in the third scenario. On the contrary, two final values (SI2 and SI4) in the first scenario are closer because the social factor is given more weight than the structural one while the social and economic aspects are assumed equally. In fact, the two choices are very close for SI in the three analyses carried out. It is evident how modifying the importance of a requirement allows to vary the result. It must therefore be clear what the goal should be, in terms of sustainability, to avoid ambiguous and inconsistent results. In the second scenario, the results remain unchanged. In fact, by increasing the preference for the structural requirement, the gap between alternative A2 and A4 increases. In the last analysis, however, the single criterion that determines whether the two options are equally acceptable differs. As consequence, the A2 alternative that involve replacing the bars is confirmed as the best choice. The second alternative, therefore, despite being the most challenging from a technological point of view, has proved to be the most sustainable overall and the most suitable from all points of view analysed.

The best alternative is an interesting example of how new retrofit solutions may be advantageous and sustainable, and how they can eventually replace rehabilitations options more conventional and ineffective from both an economic and environmental perspective. The replacement of the bars (alternative A2) is a valid option as it tends to consider long-term sustainability and increases awareness on the maintenance issue. In fact, the corroded bars, due not only to the strength but also to the ductility reduction, could cause serious long-term local and global damage if not replaced. Corrosion is still one of the most sensitive issues for infrastructure, as it leads to leakage of resistant section and ductility, causing a domino effect to the mechanical strength of the structure. Through matrix study, more in-depth sensitivity analysis can be seen as a future development.

5 CONCLUSIONS

In this paper a multi-criteria decision making approach is applied to assess the sustainability of bridge’s column rehabilitation techniques. The analysis allows to rank the four rehabilitation solutions considered and select among them the intervention that most closely match the desired outcome. Therefore, this method enables all parties involved, including clients, designers, users, and other stakeholders, to select the intervention that is appropriate for the needs that must be addressed beforehand.

The primary subject of this article is sustainability, which is examined from a variety of perspectives, including those related to the environment, which is frequently investigated, the economy, which is always considered critical, society, and technology (usually not considered). This article has taken 16 indicators into account (referred to in paragraph 2.5). More of aspects were evaluated by the authors, who then ranked them. This serves to restrict the analysis to get less dispersed results and because raising the parameters decreases the experts' reliability.

The aesthetic component is undoubtedly an interesting aspect that was neglected. Replacement of the pier (A1) and replacement of the bars (A2) solutions have less impact than the other two options (A3 and A4). Future environmental considerations could also be integrated in the future, such as: noise pollution, chemical one and dust.

The repairing alternatives examined have been proposed by researchers to repair columns severely damaged. Each intervention has been properly designed, modelled, analysed and applied to a real case study in order to go forward with the bill of quantities, safety costs and appreciate the social impacts on workers. CO_2 emissions quantities for each material involved have been taken from product's environmental product declaration. Transport scenarios have been imagined evaluating CO_2 emissions due to transportation.

The MIVES analysis performed has a great deal of potential as it enables individuals or groups of individuals to evaluate new constructions or interventions on existing structures to preserve the environment and cut costs. To fully comprehend the changes in values and the impact that the weights have, the authors employed a novel approach by first looking at the requirements without the assigned weights and then with them. The sensitivity of the decision maker is a crucial component of the suggested technique. Obviously, the goal to be achieved must be clear from the outset and the choices, both in terms of weights and values, must always be consistent and coherent. Nevertheless, it is necessary to stress the importance of sensitivity analysis to assess the variation in the results (SI) and to understand if they reflect the initial decisions.

In this preliminary study, the number of decision makers being rather limited, a new tool was introduced that allowed to establish a range within defining the valuable functions. As results, the authors defined minimum, maximum and recommended curves by the algorithm. To comprehend the effectiveness of the method, however, more research and development are required. The results collected show how the studies conducted are sensitive to the desired outcome as well as the viewpoint of the experts. This strategy is consequently discretionary and delicate. Nevertheless, in the opinion of the authors it is interesting that replacement of the reinforcing bars was recommended in each of the hypothetical scenarios despite being the less known and seemingly more difficult alternative to implement. Future advances will involve the integration of additional costs and sustainability factors across the entire life cycle of the structure.

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