Multi-Criteria Decision Methods for Structural Modification Interventions: Vertical Addition and Seismic Retrofitting

Conference Paper

DOI: 10.4203/ccp.96.173

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Multi-Criteria Decision Methods for structural modification interventions: vertical addition and seismic retrofitting

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Abstract

In the framework of structural modification interventions of existing buildings, in this paper the application of three different MCDM methods has been done aiming at establishing the optimal solutions for both seismic upgrading of existing reinforced concrete frames and vertical addition of existing masonry buildings. The analysis results have shown that all analysed methods always provide aluminium shear panels and cold-formed constructive systems are optimal solutions for seismic retrofitting and vertical addition purposes, respectively.

Keywords: MCDM methods, existing buildings, vertical addition, seismic retrofitting, experimental tests, FEM analyses.

1 Introduction

In the last years the construction market in Italy has focused the attention on the restoration of existing buildings rather than the edification of new constructions. This activity has been dictated from the necessity to upgrade buildings either designed to withstand vertical loads only or subjected to either a new seismic classification or a change of use, therefore requiring an increased load bearing capacity. To this purpose, new seismic analysis rules have been implemented, they making several changes to the regulatory framework for existing buildings, namely both considering the design at the ultimate limit state and taking into account deformations and displacements as design parameters. When these rules are related to new buildings, the designer should guarantee a given performance of such constructions under earthquake, which should be able to attain a predicted performance level. This aim is more difficult to be pursued for existing buildings, where the primary target is to increase their seismic safety, by using also all necessary measures to ensure the safety of human life.

Common intervention techniques modifying the performance level of an existing building are aimed at its retrofitting or vertical addition, which are made either to provide resistance under earthquakes, when a not seismic designed is performed, or to increase its seismic behaviour, respectively.

Within this field, innovative intervention techniques are very popular and available in a large number, they being differentiated each other also for the various difficulties of application. However, a macroscopic subdivision among them can be made: some systems alter the seismic demand in terms of Peak Ground Acceleration (PGA) and, therefore, reduce the horizontal seismic force, whereas other systems improve the structural response offered under seism.

A significant number of these techniques has been used for retrofitting some real full-scale 3D RC frames, as it will be shown in the Section 2.

On the other hand, different innovative and traditional constructive systems are used to increase the number of floors of existing buildings. The effectiveness of these interventions in improving the base building behaviour, represented by a masonry building typical of the urban tissue of a generic Italian town, is shown in Section 5.

In both structural modification applications, the best solution for retrofitting and vertical addition purposes has been individuated by applying three different Multi-Criteria Decision Making (MCDM) methods (Topsis, Electre and Vikor), which have always provided the same solution as a winner of the competition.

2 The multi-criteria decision methods (MCDM)

The Multi-Criteria Decision Making (MCDM) methods are mathematical tools that allow to solve a decision problem by individuating the best alternative meeting a given number of criteria. Therefore, a multi-criteria analysis is the formulation of the convenience opinion of an intervention according to most criteria, examined independently or interactively.

All decision problems regarding a multi-criteria evaluation are analysed by considering the following elements:

- A "goal" or a set of "goal", which represent the general aim to be achieved.
- A Decision Maker (DM) or a group of decision makers (DMs) involved in the selection process, who are responsible of the evaluation procedure.
- A set of decisional alternatives, which are the fundamental elements of the evaluation and selection process.
- A set of evaluation, used by DMs to evaluate the performance of alternatives.
- The preferences of DMs, which are typically expressed in terms of weights assigned to the evaluation criteria;
- A set of scores, expressing the value of the alternative i with respect to the criterion j, which are the elements of the decision matrix D.

In particular, any MCDM method is based on two basic elements, that is the decision matrix D, where the performance of different alternatives with respect to each criteria is reported, and the criteria weight vector, which provides the importance that the DM, or the group of DM, give to each selected criterion.

Three MCDM methods have been used in the present paper.

First of all, the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method [1] has been applied thanks to its easy of application. This method allows to represent the various alternatives as points of a vector space having dimensions equal to the number of criteria, so that the performance of different solutions become the coordinates in the assumed vector space. Therefore, it is a very practical method to immediately identify the best solution and create a ranking among all alternatives considered.

Afterwards, the ELECTRE (ELimination and Choice Traslating Reality) method [2], which provides relationship of dominance (outranking) among various options, and the VIKOR method [3], which provides, as the TOPSIS method makes, a ranking among the alternatives under consideration, have been applied.

A detailed description of the three methods used is reported as follows.

The TOPSIS method creates two additional alternatives that guide the DM to choose the best alternative among those considered. These two ideal alternatives are the best solution (A^+), that is the one having the best performance over all criteria, and the worst one (A^-). So, the solution of the decision problem is represented by the alternative having, in the same way, the minimum distance from A^+ and the maximum distance from A^-.

The first practical step of the method requires that the decision matrix *D* should be written in a not-dimensional way in order to compare each other the criteria with different units. This gives rise to the matrix *R*, which is constituted by parameters r_{ij} calculated as follow:

$$r_{ij} = \frac{a_{ij}}{\sqrt{\sum_{k=1}^{n} a_{kj}^2}} \tag{1}$$

where a_{ij} are elements of the decision matrix.

In this way all the matrix elements are without measurement units.

Later on, the weighted decision matrix *V* composed of elements v_{ij} is achieved by multiplying the elements of the matrix *R* for the criteria weight vector ω_j according to the following relationship:

$$v_{ij} = \omega_j \times r_{ij} \tag{2}$$

At this point, the method requires the determination of the two ideal alternatives. All the alternatives considered, together with the two ideal ones, are considered as virtual points, whose coordinates are their performance against the established criteria.

As a next step of the method, the distances among each alternative and the ideal ones are calculated. So, the list of preference among alternatives can be generated by considering the following parameters:

$$\begin{aligned} S_{i^+} &= \sqrt{\sum_{1}^{m} j\,(v_{ij} - v_{j^+})^2} \quad per \quad i = 1, 2, \ldots\ldots\ldots n \\ S_{i^-} &= \sqrt{\sum_{1}^{m} j\,(v_{ij} - v_{j^-})^2} \quad per \quad i = 1, 2, \ldots\ldots\ldots n \end{aligned} \tag{3}$$

and taking as best solution the alternative having the minimum value of the factor C_{i+}, calculated as follows:

$$C_{i^+} = \frac{S_{i-}}{S_{i-} + S_{i*}} \tag{4}$$

In general, MCDM methods are used to help the DM or a group of DMs to make objective choices not influenced by the responsible of the evaluation process. In order to test the validity of the achieved results, the weight of each single criterion, taken one by one, is varied from 0 to 1, leaving all others unchanged, aiming at verifying if the ranking is changed or not. This proves the stability of the solution found.

The absolute change of the generic weight able to reach a solution other than the one identified with the chosen weights, is indicated with the *Absolute Top* (*AT*) , where “absolute" means that there is an absolute change of value and "top" indicates that this change modifies the top of the alternative ranking. Then, for each criterion, by dividing *AT* for the criterion weight, the *Percentage Top* (*PT*), which represents the weight change that should modify the first solution in the ranking, is obtained.

The measure of the stability of the solution is made by calculating the sensitivity parameter, achieved as reciprocal of the corresponding *PT* value. The solution will be more stable as much as more the *PT* values are high.

In this context, robust criteria are defined when the change of the AT values does not provoke a change of the solution of the decision problem. So, robust criteria are, of course, no sensitive to the definition of the final solution, since their weight variation does not change the classification. Therefore, when a large number of criteria are stable and *PT* values are high, it is possible to declare that the outcome of the decision problem is sufficiently sure and is little influenced by the personal choices of the DM.

On the other hand, the ELECTRE method has the ultimate goal to build the so-called outranking relationships (domination relationship) among considered alternatives.

The alternatives are defined as dominated if there is another alternative that responds better towards one or more criteria.

The method involves binary comparisons among alternatives with respect to each criterion. The set of relationships can be either complete or there may be a failure, when the DM has not given any preference for an alternative over another.

The application of the method follows simple steps, similar to the TOPSIS method ones. As a first step, the decision matrix is normalised according to the relationship (1). Afterwards, the weighted decision matrix is calculated on the basis of the expression (2), which provides v_{ij} values.

Then, the concordance set C_{kp} and the divergence set D_{kp} are determined. The concordance set of an alternative A_k with respect to the alternative A_p is composed by the criteria where the v_{kj} parameter of the matrix V is greater than the corresponding v_{pj} value.

At this point the concordance index is calculated as sum of criteria weights contained in the concordance set:

$$c_{kp} = \sum_{j \in C_{kp}} \omega_j \quad for \quad j = 1,2,.......m \tag{5}$$

whereas the divergence index is determined on the basis of the following equation:

$$d_{kp} = \frac{\max\limits_{j \in D_{kp}} \left| y_{kj} - y_{pj} \right|}{\max\limits_{j} \left| y_{kj} - y_{pj} \right|} \tag{6}$$

The concordance index expresses the importance of the alternative A_k with respect to the alternative A_p, while the divergence one has the opposite meaning.

The next step consists on the determination of other threshold parameters used to impose the outclassed relationship. These parameters are the concordance threshold S_c:

$$S_c = \frac{1}{n(n-1)} \sum_{\substack{k=1 \\ k \neq p}}^{n} \sum_{\substack{p=1 \\ p \neq k}}^{n} c_{kp} \tag{7}$$

and the discrepancy threshold S_d:

$$S_d = \frac{1}{n(n-1)} \sum_{\substack{k=1 \\ k \neq p}}^{n} \sum_{\substack{p=1 \\ p \neq k}}^{n} d_{kp} \tag{8}$$

The outclassed relationship is expressed as follows:

$$A_k \text{ outclasses } A_p \text{ if and only if } c_{kp} \geq S_c \text{ and } d_{kp} \leq S_d \tag{9}$$

This relationship allows to create an additional matrix E, which will individuate either the alternative dominating all others or to eliminate a group of alternatives dominated by the remaining ones. This matrix is built by putting either one, if the outclassed relationship is satisfied, or zero, when the relationship is not fulfilled. From the matrix E the columns with at least one unitary element should be eliminated, since these alternatives are dominated from others.

Finally, the method VIKOR or compromise ranking method is based on measurements of three scalar parameters that will generate the ranking of alternatives.

It begins with the definition of the best (a_{j+}) and the worst (a_{j-}) performances of each alternative against the same criteria j. When these performances are known, the calculation of scalar parameters S_i and R_i is performed as follows:

$$S_i = \sum_{j=1}^{m} \frac{\omega_j (a_{j^+} - a_{ij})}{a_{j^+} - a_{j^-}} \quad ; \quad R_i = \max_j \left[\frac{\omega_j (a_{j^+} - a_{ij})}{a_{j^+} - a_{j^-}} \right] \tag{10}$$

where ω_j represents the weight of criteria.

The knowledge of the above two scalars allows for the determination, for each alternative, of the scalar parameter Q_i:

$$Q_i = \upsilon \frac{S_i - S^+}{S^- + S^+} + (1-\upsilon)\frac{R_i - R^+}{R^- + R^+} \tag{11}$$

where:

$$S^* = \min_i S_i \quad ; \quad S^- = \max_i S_i \; ;$$

$$\upsilon = 0.5 \tag{12}$$

$$R^* = \min_i R_i \quad ; \quad R^- = \max_i R_i \; ;$$

From Q_i it is possible to proceed to generate the ranking of alternatives.

The best alternative, called compromise solution A', is the one with the lowest value of Q_i.

3 Selection of the optimum seismic retrofitting system of a real RC structure

3.1 The experimental campaign ILVA-IDEM

The possibility of increasing the knowledge on the retrofitting of existing RC buildings has represented the main objective of the experimental activity performed in the period 2000-2005 by the research group headed by Prof. F. M. Mazzolani on a real structure located within the ex steel mill of Bagnoli in Naples and destined to be demolished.

The purpose of the experimental campaign, called "ILVA-IDEM" (acronym of ILVA Intelligent DEMolition"), was to evaluate and compare each other the results deriving from the use of a variety of retrofitting techniques of existing structures based on metallic materials. The detailed contents of this wide experimental, numerical and theoretical activity are reported in [4].

The original structure was not designed to withstand any horizontal loads, since its erection was made when the area of Bagnoli was not considered as a seismic prone zone. For this reason, the structure was designed to sustain vertical loads only.

The building (Figure 1) had a rectangular lengthened plan shape (41.6m×6.50m) and it developed on two floors with a first and second floor heights on the ground of 3.55m and 6.81m, respectively. It was composed by twenty-six 30x30 cm columns and beams located along the building perimeter only supporting hollow tiles mixed slabs. Inverse T-beams were used as foundation of the building. In order to increase the potential number of specimens and to test different upgrading solutions, slabs were cut at the first and second floor, in such a way to divide the whole building into six separate simple structures to be analysed. Before the cutting of the slabs, both the internal partitions and the external claddings of the building were removed.

Seven different retrofitting techniques, which represents the alternatives (A) for the application of MCDM methods, have been considered to retrofit the structural sub-units:

1. Base isolation with rubber bearings (BI) (A1)
2. Buckling Restrained Bracings (BRB) (A2)
3. Carbon-Fibre Reinforced Polymers (C-FRP) (A3)

4. Eccentric Bracings (EB) (A4)
5. Shape Memory Alloy (SMA) bracings (A5)
6. Steel Shear Panels (SSP) (A6)
7. Aluminium Shear Panels (ASP) (A7)

Each technique has been associated to a given structural sub-unit, as shown in Figure 2, where it is noticed that in the sixth module the staircase of the building and was located and, therefore, this sub-structure was not used to host any anti-seismic device.

Figure 1. The building tested within the ILVA-IDEM research project before experimentation.

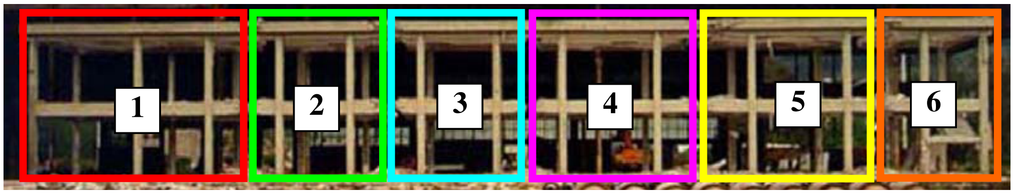

Figure 2. Techniques under study: 1) BI; 2) BRB; 3) C-FRP; 4) EB; 5) SMA, SSP and ASP.

The base isolation system is able to reduce the seismic demand, while all the others allow for increasing the seismic capacity of the building, which should be at least equal to the demand required by the earthquake. The base isolation system has been submitted to free vibration and ambient vibration tests. Instead, static inelastic tests have been carried out for all the other systems. Differently from other techniques, the SMA bracing system was tested both statically and dynamically (free vibration).

In the following, a summary of test results is given, also showing a final comparison among them.

First of all, the base isolation system with circular cross-section rubber bearings has been inserted into the module with six columns by cutting preliminarily the ground floor columns at their base and, subsequently, by connecting their ends by means of X-shaped steel bracings in order to create a stiff base diaphragm.

Free vibration tests have been carried out on both the original (fixed) structure and the base isolated one. Namely, the free vibration properties of the fixed structure have been measured by using both ambient and impact-induced vibrations, the latter produced by means of a special pendulum mass impacting columns. The base-isolated structure has been tested with the same methodology for measuring elastic vibration properties. Additionally, the efficiency of the base isolation system has been tested by imposing a horizontal lateral displacement to the structure and then leaving it to freely vibrate. Both acceleration and displacement transducers were used. Figure 3 illustrates the base-isolated structure, the maximum lateral deformation of the rubber bearing, the displacement transducer and the structure displacements measured during the release tests.

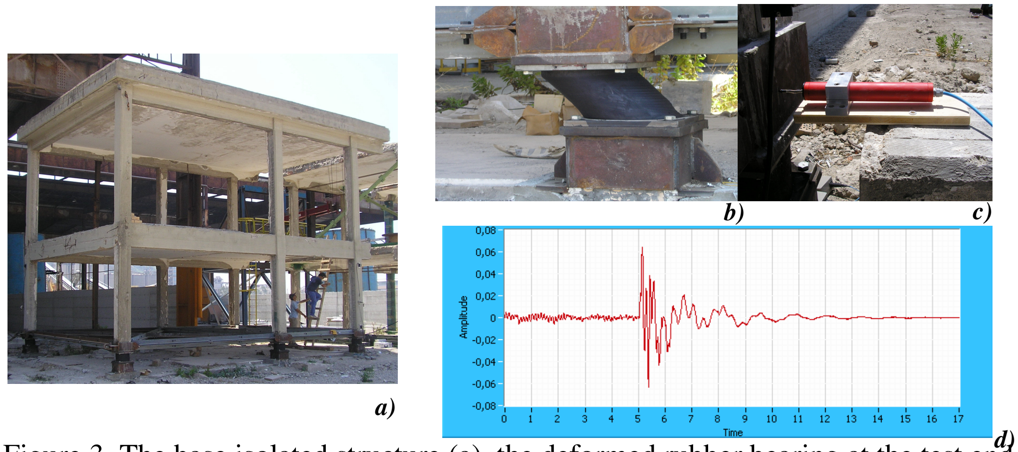

Figure 3. The base isolated structure (a), the deformed rubber bearing at the test end (b), the displacement transducer (c) and the displacement vs. time diagram of the retrofitted structure (d).

Figure 4a illustrates the sub-structure equipped with BRBs. As it can be seen, the BRBs were placed in number of two for each story, in such a way to form a story X-bracing, but with braces placed in different vertical planes. This arrangement allows for an indirect evaluation of the difference between the tension and compression response of the braces by measuring the story torsion rotation.

The tested BRBs belong to the ‘only-steel’ type, with the core made of one single steel plate (25mm x 10 mm) and two restraining rectangular steel tubes (100mm x 50mm x 5mm).

Two tests have been carried out, differing only for some detailing of the end portions of the yielding core. The first type of BRB tested is shown in Figure 4b. As it can be seen, the tube walls are in direct contact with the internal core, while a couple of internal plates welded to the tube walls are used to complete the restraining action. The design gap between the restraining plates and the yielding core was 0.5mm. During testing there was clear yielding of the BRB core both in tension and compression. The force- displacement diagram is shown in Figure 4c. The second type of BRB tested is shown in Figure 4d. Two main changes were made with respect to the first test. The BRB internal core was now tapered in a more gradual manner, in such a way to give larger rotational restraint at the BRB end. In addition, the gap between the core plate and the restraining elements was now fixed equal to 1mm, in order to avoid rigid-body relative movements and to get a more uniform strain distribution in the core plate. Besides, the new BRBs were conceived as fully detachable, by joining the two restraining tubes together by means of bolted stiffened elements. This allowed the BRB to be opened for inspection and monitoring at the end of the test. The force displacement diagram is shown in Figure 4e.

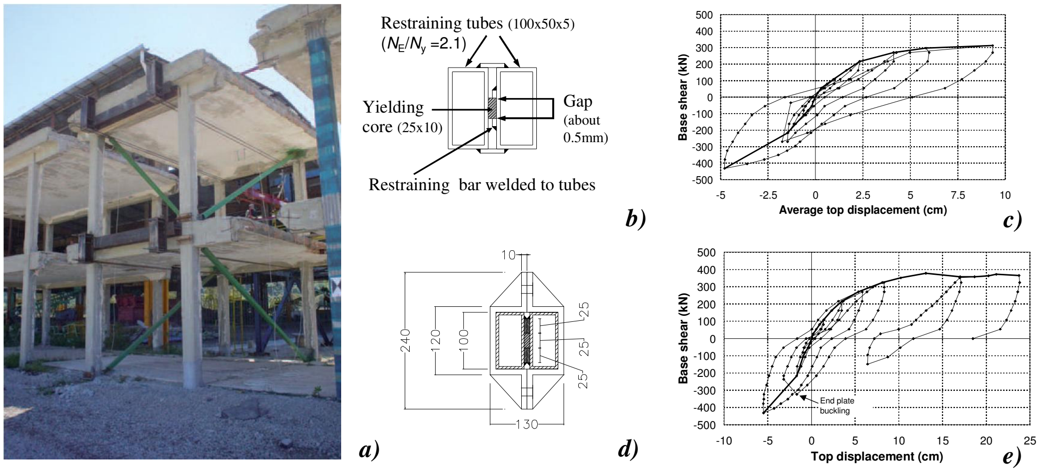

Figure 4. The structure equipped with BRB (a): BRB type 1 (b), results of the test n. 1 (c), BRB type 2 (d) and results of the test n. 2 (e).

The sub-structure on which C-FRP were applied is shown in Figure 5a. It was first tested in its original condition up to the formation of a column-sway collapse mechanism. Then, the structure was repaired and subsequently strengthened. The strengthening system consisted of longitudinal C-FRP pultruded strips, externally bonded to the RC columns, and transverse C-FRP confining sheets. The longitudinal strips were designed in such a way to increase the plastic strength of columns, with the objective to move the formation of plastic hinges from columns to beams. On the other hand, the transverse C-FRP sheets were designed for the additional shear strength required by the flexural enhancement.

The original (bare) RC sub-structure was tested under a monotonic increasing roof displacement, while the upgraded structure was tested under load reversals. Figure 5b illustrates the column-sway and the beam-sway mechanisms exhibited by the original RC structure. Figure 5c shows the comparison of response between the original and upgraded structures, illustrating the measured base-shear versus top-story lateral displacement relationships (both positive and negative envelopes are given for the cyclic test on the upgraded structure). As it can be observed, a significant improvement of the seismic performance has been obtained from all points of view (stiffness, strength, ductility).

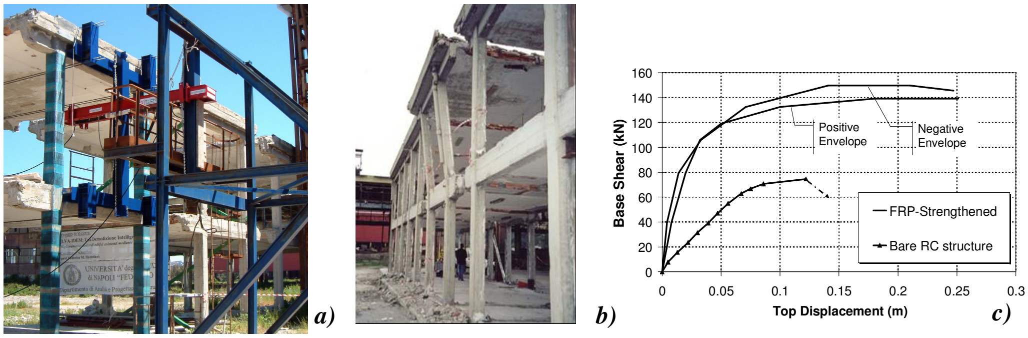

Figure 5. The structure retrofitted with C-FRP (a), the collapse mechanism of the bare structure (b) and the summary of test results (c).

Figure 6a illustrates the typology of the EB system adopted for seismic retrofitting. Three tests have been carried out, using always the same RC frame, while the link cross-section and some connection details have been changed.

The first bracing system subjected to test was designed according to the Eurocode 8 provisions, but neglecting capacity design criteria. Experimental evidence showed link-to-diagonal connection failure, as it was well expected.

The second test was carried out with the link having the same geometrical properties as in the first test, but link end connections were strengthened by assuming that they must carry a shear force equal to 1.5 times the link plastic strength V_p. The ratio between the nominal shear strength of the connection and the plastic strength of the link was now $V_{j,Rk}/V_p = 1.89$. Notwithstanding, the test showed shear failure of link-to-diagonal connection bolts and again a relatively small plastic deformation of links, thus indicating link over-strength larger than expected.

The third test was carried out using a built-up steel section as shear link. In fact, due to the impossibility to change the link-to-diagonals connection and because of the need to increase the ratio $V_{j,Rk}/V_p$ in order to increase the plastic deformation capacity of the system, it was required to reduce the link plastic strength. So, the ratio $V_{j,Rk}/V_p$ was assumed equal to 2.84.

Test results showed significant plastic deformation of links, but once again failure ultimately occurred with the (predominantly) shear rupture of link-to-diagonals connection bolts. However, in this last test the total shear angle of link plus connections resulted in a value of about 31% (some slipping in the link-to-RC slab top connection occurred, but it is deemed to have a minor effect).

The experimental response, expressed as a relationship between base shear and top floor displacement, is shown in Figure 6b for the first test, in Figure 6c for the second tests and Figure 6d for the third test. Figure 6e shows the collapse mode detected in the third test.

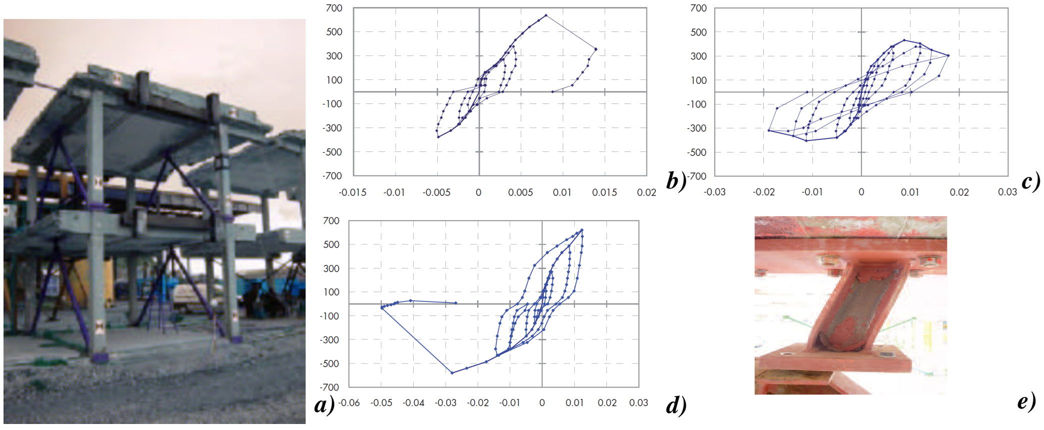

Figure 6. The structure reinforced with EBF (a), shear-displacement diagrams related to test n. 1 (b), test n. 2 (c), and test n. 3 (d) and link-to-diagonal bolts failure in the test n. 3 (e).

Later on, the research group of the University of Basilicata, based on the results of previous studies, proved the effectiveness of NiTi SMA-based bracings for retrofitting purposes. The in-situ activity consisted of push-over and cyclic tests, as well as release tests. Figure 7a shows the SMA braces mounted on the structure. Figure 7b gives the results of the free vibration test, showing the reduction of displacement and the increase of damping obtained in the retrofitted structure as respect to the bare RC structure.

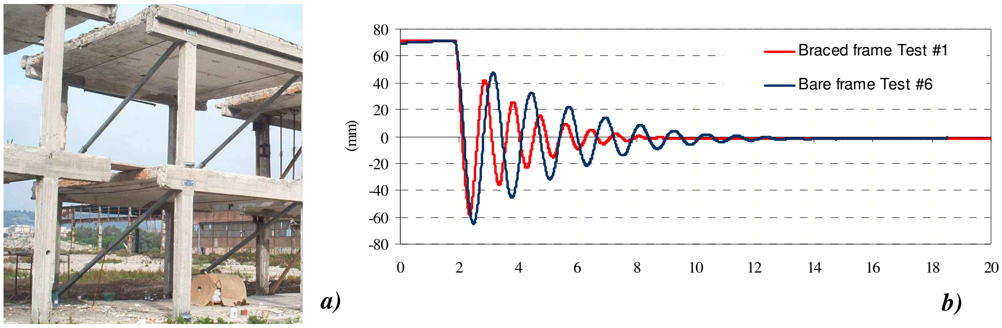

Figure 7. SMA bracings inserted into the module n.5 (a) and time history displacement diagram comparison between the bare structure and the retrofitted one (b)

Shear panels (SP) made of aluminium alloy and steel have been used as retrofitting system of the sub-structure depicted in Figure 8a. This structure was already tested in the transversal direction for evaluating the effectiveness of SMA braces. After reparation, it was used for testing the shear panel system in the longitudinal direction, avoiding the transversal sway of the first floor by using a couple of transversal X-braces. Then, the bare RC structure was preliminarily tested in the longitudinal direction, without reaching the collapse of the system, by means of a pushover test, employing two hydraulic jacks able to apply a total force of 30 tons and connected to an appropriate steel retaining structure. This test was done in order to know the stiffness of the original structure. A couple of shear panels was inserted into the r.c. frame by means of surrounding hinged steel frames at the first floor. The steel frame columns were connected to r.c. foundation beams by means of four UPN 220 profiles, adequately stiffened by reinforcing steel plates, and six threaded passing M16 bars. The transfer of the forces carried by the steel panel to the r.c. beams was guaranteed by two UPN220 profiles. The final configuration of the applied systems is represented in Figures 8b and c. The effectives of the proposed upgrading intervention has been proved by the execution of two experimental cyclic tests.

The response of the retrofitted structure was significantly improved in both cases, showing an increase of both initial stiffness and ultimate strength, as it is shown in Figure 8d, where the envelope curves of experimental tests are plotted. Also the deformation capacity of the structure appeared to be very large, without the involvement of any brittle collapse mode up to a deformation amplitude corresponding to an inter-storey drift greater than 3.5%. However it was evident as in both cases a combined dissipative mechanism between plastic hinges in the beamto-column joints of the r.c. frame and plastic deformation of tensioned diagonals of the applied shear panels occurred.

In conclusion, it should be observed that the dissipation capacity of the structure retrofitted with aluminium shear panels was more satisfactory than the one endowed with steel plates, due to the excellent hysteretic characteristics of the used aluminium alloy.

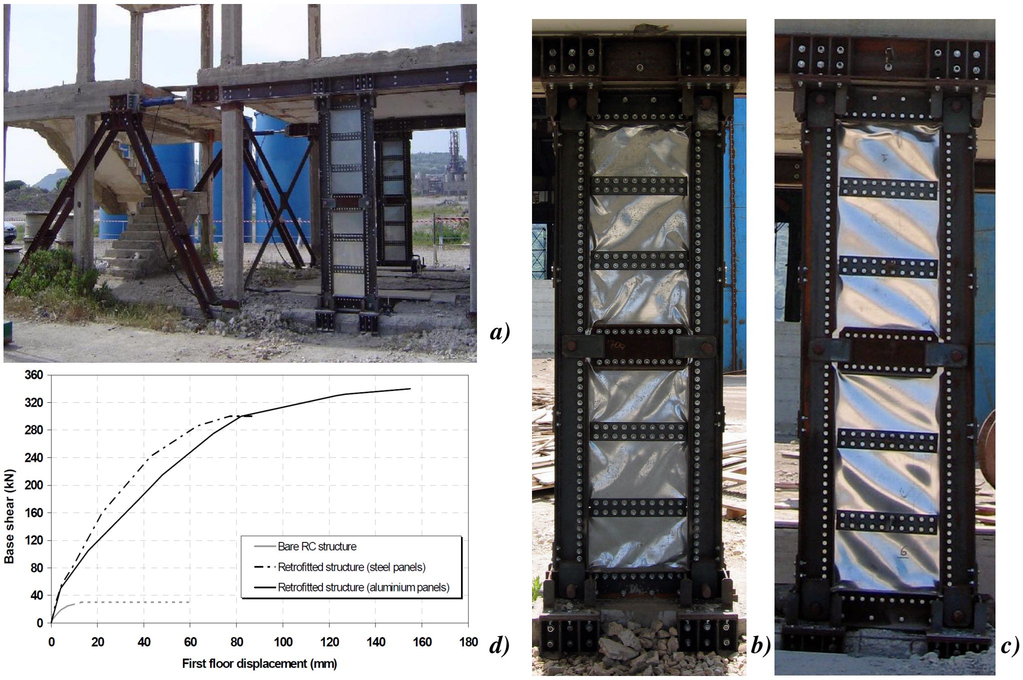

Figure 8. The sub-structure retrofitted with metal shear panels (a), final deformed shape of tested steel (b) and aluminium (c) devices and comparison between the bare structure response and the behaviour of upgraded structures (d).

Figure 9 shows a comparison of the experimental results on the five upgrading systems (C-FRP, EB, BRB, SSP and ASP) examined by the research group of the University of Naples, also illustrating the improvement of response with reference to the bare RC structure. Actually, the four tested RC structures are slightly different for their in-plan dimensions, but their lateral-load response can be assumed to be fairly the same because it is governed by the four square-section columns, which are identically reinforced. As it can be seen and it could be expected, steel bracings, both EB and BRB, and shear panels are generally able to produce very large increase of stiffness and strength, while the C-FRP system appreciably increased the lateral displacement capacity of the structure but with a low increase in strength (about 2 times). The second type of tested BRB, however, reached a maximum displacement approximately equal to that one of the C-FRP upgraded structure. In Figure 9, the event of a brittle rupture has been highlighted with a star. The maximum increase in load bearing capacity has been reached with EB from 5.5 to 8 times the original value of the bare structure. In case of BRB the increment is averagely 4.25 times, very similar as in case of SP (about 4 times).

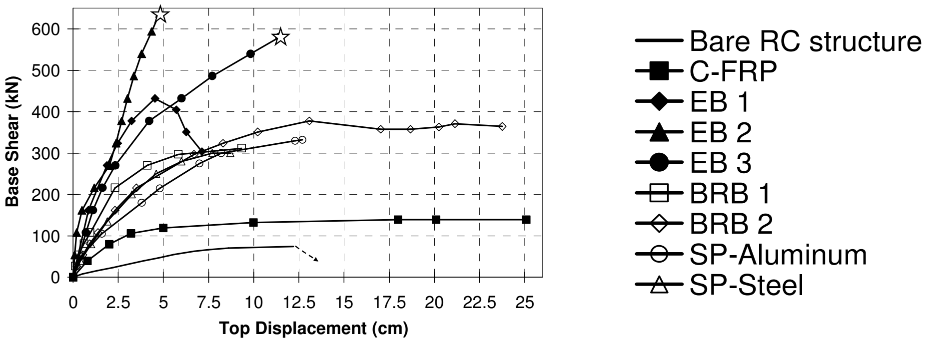

Figure 9. Comparison among responses of retrofitted structures.

3.2 The used alternatives and criteria

The alternatives, which represent the rows of the decision matrix, are the different anti-seismic techniques described in the previous Section.

Seven performance criteria have been considered, they being distinguished into quantitative criteria, which are those that express the opinion of the generic alternative with a number, and qualitative criteria, which give a verbal assessment to be converted into a number for being included in the decision matrix *D*.

The quantitative criteria are:

1) Cost of the intervention, which is usually one of the most important requirement to be observed when a retrofitting design is performed. It is a cost criterion that should be minimised as much as possible.
2) Reduction of vulnerability, determined as the ratio between the maximum PGA sustained by the retrofitted structure and the one of the bare structure. It is a benefit criterion that should be maximised as much as possible.

On the other hand, the qualitative criteria are:

1) Feasibility of the intervention, which includes all those impediments that can arise for the realization of a particular type of intervention, namely the availability of workmanship, materials and technologies. It is a criterion of benefit and the preferences of DMs, expressed as verbal judgement, should be transformed into numbers in order to be placed in the decision matrix.
2) Disturbance to the occupiers, which is a criterion essential if a retrofitting intervention within a building in use is of concern. In fact, depending on the intervention type, either the removal of the occupants or the displacement of production that takes place there can occur or not.
3) Functional and aesthetic compatibility: the aesthetic component of the intervention and the functionality, which are very important topics when the structure is used especially for residential purposes, represent a benefit criterion expressed into verbal way.
4) Reversibility, which is the capacity of a given alternative to be removed from the building when other interventions are requested. It is a benefit criterion and, therefore, the preference is devoted to techniques having this prerequisite.

5) Protection from damage, which is related to the need of preserving the integrity of the anti-seismic devices throughout the life of the structure. Among the different alternatives, the one providing both the better security, and, over time, a constant capacity response, should be individuated. It is a qualitative benefit criterion.

3.3 The criteria weight vector and the decision matrix

All MCDM methods require two elements to be applied: the criteria weight vector of criteria, which represents the importance that DM gives to different criteria, and the decision matrix, which contains the performance of individual alternatives towards the considered criteria.

In the current analysis case the weights of the criteria have been determined by using the AHP method developed by Saaty (Table 1) [5]. After weights are assigned to the various criteria, the decision matrix can be implemented, as shown in Table 2.

Table 1. Weights of criteria.

Criterion		Weight	Weight (%)
Cost of the intervention	C1	0.070	7.00
Feasibility of the intervention	C2	0.050	5.00
Disturbance to occupiers	C3	0.200	20.00
Functional and aesthetic compatibility	C4	0.100	10.00
Reversibility	C5	0.350	35.00
Reduction of vulnerability	C6	0.200	20.00
Protection from damage	C7	0.030	3.00

Table 2. The decision matrix *D*.

Alternative		Criterion						
		C1	C2	C3	C4	C5	C6	C7
Base isolation	A1	€ 36,359.66	0.024	0.317	0.036	0.025	2.450	0.404
Buckling restrained bracings	A2	€ 2,649.22	0.039	0.069	0.321	0.154	2.420	0.074
Carbon fibre-reinforced polymers	A3	€ 42,821.28	0.167	0.296	0.058	0.044	1.000	0.028
Eccentric bracings	A4	€ 1,537.68	0.083	0.059	0.097	0.114	2.560	0.187
Shape memory alloy bracings	A5	€ 49,000.00	0.058	0.034	0.100	0.084	2.680	0.065
Steel shear panels	A6	€ 12,466.85	0.324	0.114	0.196	0.276	2.140	0.129
Aluminium shear panels	A7	€ 13,010.83	0.305	0.110	0.192	0.303	2.430	0.114

3.4 Solution of the decisional problem

3.4.1 The TOPSIS method

Once defined the two above basic elements, firstly the TOPSIS method has been employed to solve the decisional problem.

So, starting from the matrix *D*, the matrix *R*, having elements without measurement units, has been achieved (Table 3) and, consequently, also the matrix *V* has been determined (Table 4).

Therefore, the ideal alternatives have been individuated (Table 5) and the ranking of alternatives has been determined on the basis of the distance of each retrofitting technique from ideal ones (Table 6).

Finally, from the sensitivity analysis the stability of the solution found has been proved due to the presence of one robust criterion (C6) and very high values of *PT* parameters for the other criteria (Table 7).

Table 3. The matrix *R*.

	C1	C2	C3	C4	C5	C6	C7
A1	0.4737	0.0495	0.6712	0.0797	0.0542	0.4023	0.8281
A2	0.0345	0.0789	0.1461	0.7136	0.3322	0.3974	0.1518
A3	0.5579	0.3430	0.6276	0.1293	0.0943	0.1642	0.0566
A4	0.0200	0.1695	0.1258	0.2158	0.2468	0.4204	0.3827
A5	0.6384	0.1186	0.0730	0.2215	0.1820	0.4401	0.1331
A6	0.1624	0.6629	0.2415	0.4349	0.5962	0.3514	0.2639
A7	0.1695	0.6256	0.2340	0.4277	0.6545	0.3991	0.2328

Table 4. The matrix *V*.

	C1	C2	C3	C4	C5	C6	C7
A1	0.0332	0.0025	0.1342	0.0080	0.0190	0.0805	0.0248
A2	0.0024	0.0039	0.0292	0.0714	0.1163	0.0795	0.0046
A3	0.0391	0.0171	0.1255	0.0129	0.0330	0.0328	0.0017
A4	0.0014	0.0085	0.0252	0.0216	0.0864	0.0841	0.0115
A5	0.0447	0.0059	0.0146	0.0222	0.0637	0.0880	0.0040
A6	0.0114	0.0331	0.0483	0.0435	0.2087	0.0703	0.0079
A7	0.0119	0.0313	0.0468	0.0428	0.2291	0.0798	0.0070

Table 5. The virtual alternatives.

	C1	C2	C3	C4	C5	C6	C7
A^+	0.0014	0.0331	0.0146	0.0714	0.2291	0.0880	0.0248
A^-	0.0447	0.0025	0.1342	0.0080	0.0190	0.0328	0.0017

Table 6: Ranking of alternatives according to the TOPSIS method.

Alternative			C_i^*
First	A 7	Aluminium shear panels	0.831
Second	A 6	Steel shear panels	0.799
Third	A 2	Buckling restrained bracings	0.586
Fourth	A 4	Eccentric bracings	0.486
Fifth	A 5	Shape memory alloy bracings	0.436
Sixth	A 1	Base isolation	0.176
Seventh	A 3	Carbon-fibre reinforced polymers	0.087

Table 7. Sensitivity analysis.

Criteria	Weight	AT	PT (%)	Sensitivity
C1	0.070	0.585	836	0.001
C2	0.050	0.579	1158	0.001
C3	0.200	0.542	271	0.004
C4	0.100	0.640	640	0.002
C5	0.350	0.320	91	0.011
C6	0.200	-	-	-
C7	0.030	0.334	1113	0.001

3.4.2 The ELECTRE method

First, the application of the method has led to the determination of matrixes *R* and *V*, reported in Tables 8 and 9, respectively.

Table 8. The matrix *R*.

	C1	C2	C3	C4	C5	C6	C7
A1	0.4737	0.0495	0.6712	0.0797	0.0542	0.4023	0.8281
A2	0.0345	0.0789	0.1461	0.7136	0.3322	0.3974	0.1518
A3	0.5579	0.3430	0.6276	0.1293	0.0943	0.1642	0.0566
A4	0.0200	0.1695	0.1258	0.2158	0.2468	0.4204	0.3827
A5	0.6384	0.1186	0.0730	0.2215	0.1820	0.4401	0.1331
A6	0.1624	0.6629	0.2415	0.4349	0.5962	0.3514	0.2639
A7	0.1695	0.6256	0.2340	0.4277	0.6545	0.3991	0.2328

Table 9. The matrix *Y*.

	C1	C2	C3	C4	C5	C6	C7
A1	0.0332	0.0025	0.1342	0.0080	0.0190	0.0805	0.0248
A2	0.0024	0.0039	0.0292	0.0714	0.1163	0.0795	0.0046
A3	0.0391	0.0171	0.1255	0.0129	0.0330	0.0328	0.0017
A4	0.0014	0.0085	0.0252	0.0216	0.0864	0.0841	0.0115
A5	0.0447	0.0059	0.0146	0.0222	0.0637	0.0880	0.0040
A6	0.0114	0.0331	0.0483	0.0435	0.2087	0.0703	0.0079
A7	0.0119	0.0313	0.0468	0.0428	0.2291	0.0798	0.0070

The end phase of the method allows for the definition of the matrix E, which provides the solution of the MCDM problem (Table 10).

Table 10. The matrix *E*.

	A1	A2	A3	A4	A5	A6	A7
A1	0	0	0	0	0	0	0
A2	1	0	1	1	1	0	0
A3	0	0	0	0	0	0	0
A4	0	0	0	0	1	0	0
A5	0	0	0	0	0	0	0
A6	1	1	1	1	1	0	0
A7	1	1	1	1	1	1	0

From the analysis it is shown that the dominant alternative is A7, that is aluminium shear panels, as already found by the TOPSIS method. After this solution, the preference can be attributed to SSP (2nd place), BRB (3rd place), BI, C-FRP and EB (4th place) and SMA (5th place).

3.4.3 The VIKOR method

The first step of the VIKOR method is based on the determination of two scalar parameters, that is S_i and R_i (Table 11).

Table 11. The scalar parameters S_i and R_i.

	Alternative	S_i	R_i
A1	Base isolation	0.7787	0.3500
A2	Buckling restrained bracings	0.3188	0.1879
A3	Carbon fibre-reinforced polymers	0.9212	0.3267
A4	Eccentric bracings	0.4057	0.2377
A5	Shape memory alloy bracings	0.4945	0.2755
A6	Steel shear panels	0.2366	0.0643
A7	Aluminium shear panels	0.1718	0.0538

Afterwards, the definition of another scalar parameter Q_i for each alternative allows for finding both the solution of the decisional problem, it having the minimum value of Q_i, and the classification of different retrofitting systems considered (Table 12).

As in the two previous analysis cases, shear panels made of aluminium alloys represent the best solution for resolving the MCDM problem.

Table 12. Ranking of alternatives according to the VIKOR method.

Alternative			Q_i
First	A 7	Aluminium shear panels	0.000
Second	A 6	Steel shear panels	0.061
Third	A 2	Buckling restrained bracings	0.325
Fourth	A 4	Eccentric bracings	0.466
Fifth	A 5	Shape memory alloy bracings	0.590
Sixth	A 1	Base isolation	0.905
Seventh	A 3	Carbon fibre-reinforced polymers	0.961

4 Choose of the optimum technology for vertical addition of masonry buildings

4.1 Super-elevation of existing buildings

The MCDM has been also used to select the best technique for vertical addition of existing masonry buildings.

A single structural masonry unit extrapolated from a building in line, representative of the building heritage built in Naples at the beginning of '900, has been selected as a study case. This building, made of tuff stones, is developed on two storeys having inter-storey height of 3.20 m and covering an area of about 120 m^2. A 3D view of the study masonry unit is depicted in Figure 10.

On this masonry building the design of a super-elevated floor has been conceived. To this purpose, the following different constructive technologies have been foreseen:

- glued laminated timber (Fig. 10b);
- reinforced concrete (Fig. 10c);
- hot-rolled steel (Fig. 10d);
- tuff masonry (Fig. 10e);
- cold formed steel (Fig. 10f).

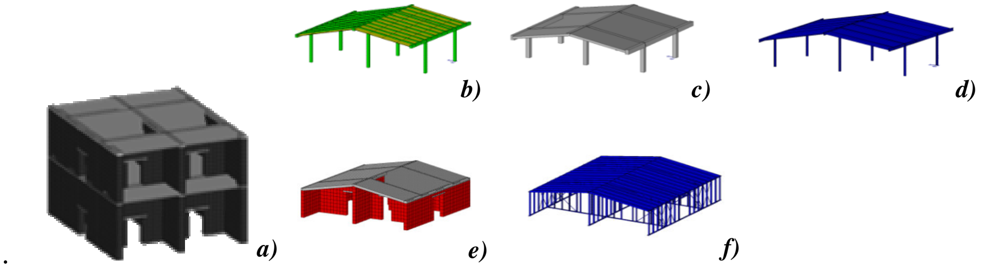

Figure 10. The study masonry structural unit (a) and construction systems for vertical addition (from b to f).

So, other than traditional construction technologies (r.c., ordinary steel and masonry systems), also innovative ones, represented by cold-formed steel systems and glued laminated timber structures, have been considered.

The glued laminated timber is preferred to timber, which was used in the past for erection of floors, since it allows to obtain sections of general shape with minimal defects and high structural performance. The possibility of reducing the dimensions of the vertical addition structure members has led in some cases to the use of reinforced concrete. A solution widely used also for the retrofitting of existing buildings is the one based on hot-rolled steel elements, organized into either moment resisting frames or pinned ones. Finally, an innovative solution that combines the use of light materials with structural types which distribute the vertical loads uniformly on all the masonry walls, is represented by the use of cold-formed systems.

The result of the performed study, framed within a more large research activity carried out by some of the Authors [6], is to use the same MCDM methods already applied in the previous Section in order to assess the vertical addition construction system providing the best performance.

4.2 The basic elements of MCDM methods

The alternatives of MCDM methods are the various technologies used for vertical addition purpose, which have been previously listed.

Instead, about considered criteria, it is important to underline that not only economic and structural parameters have been taken into account, but also environmental factors correlated to the reduction of pollution correlated to the production of different structural systems have been assessed.

In particular, the following criteria have been used in the current applications:

- Life Cycle Assessment (LCA), which is an analysis method that evaluates a set of interactions that the vertical addition structure has with the environment, considering its whole life cycle, from cradle to grave.
- Environmental Performance Index (EPI), which is another criterion that allows for an environmental judgement about the various alternatives. More in detail, it is the amount of energy actually consumed or expected to be needed to meet the different needs associated with a standard use of the building.
- Cost of the vertical addition, which has been assessed taking into account the updated price list of the Campania Region for building systems.
- Maximum vertical load Q_{veff}, which represents the maximum load sustained by the masonry piers of the base building.
- Peak Ground Acceleration (PGA), which represents the maximum acceleration reached by the vertical addition system.

As already declared, the two elements necessary for the application of MCDM methods, that is the criterion weight vector and the decision matrix, are reported in Tables 13 and 14, respectively.

Table 13. Weights of criteria.

Criterion		Weight	Weight (%)
LCA	C1	0.080	8.00%
EPi	C2	0.050	5.00%
Cost of the vertical addition system	C3	0.370	37.00%
$Q_{v\ eff}$	C4	0.200	20.00%
PGA	C5	0.300	30.00%

Table 14. The decision matrix *D*.

Alternative		*LCA*	*EPi*	Cost of the vertical addition system	$Q_{v\ eff}$	*PGA*
		-	kWm/m^2 year	€/m^2	KN/m^2	m/s^2
		C1	C2	C3	C4	C5
Glued laminated timber	A1	0.2096	162.80	€ 174.00	6.16	0.1680
Reinforced concrete	A2	0.8766	149.80	€ 85.62	2.50	0.1760
Hot-rolled steel	A3	0.5731	195.70	€ 95.48	5.85	0.1600
Tuff masonry	A4	0.8405	168.30	€ 103.92	10.50	0.1340
Cold formed steel	A5	0.5731	183.60	€ 111.94	13.19	0.1800

4.3 Solution of the problem

4.3.1 The TOPSIS method

The same steps already accomplished in the previous application have been followed, they leading to the definition of the matrix R (Table 15) and the matrix V (Table 16), the creation of both the two virtual alternatives (Table 17) and the ranking of alternatives (Table 18) and, finally, the execution of the sensitivity analysis (Table 19), in order to evaluate the impartiality of the found solution.

Table 15. The matrix *R*.

	C1	C2	C3	C4	C5
A1	0.1421	0.4214	0.6574	0.3235	0.4570
A2	0.5943	0.3877	0.3235	0.1313	0.4787
A3	0.3885	0.5065	0.3607	0.3072	0.4352
A4	0.5698	0.4356	0.3926	0.5514	0.3645
A5	0.3885	0.4752	0.4229	0.6926	0.4896

Table 16. The matrix *V*.

	C1	C2	C3	C4	C5
A1	0.0114	0.0211	0.2432	0.0647	0.1371
A2	0.0475	0.0194	0.1197	0.0263	0.1436
A3	0.0311	0.0253	0.1335	0.0614	0.1306
A4	0.0456	0.0218	0.1453	0.1103	0.1093
A5	0.0311	0.0238	0.1565	0.1385	0.1469

Table 17. The virtual alternatives.

	C1	C2	C3	C4	C5
A^+	0.0475	0.0194	0.1197	0.1385	0.1469
A^-	0.0114	0.0253	0.2432	0.0263	0.1093

Table 18. Ranking of alternatives according to the TOPSIS method.

Alternative			C_i^*
First	A 5	Cold formed steel	0.785
Second	A 4	Tuff masonry	0.714
Third	A 3	Hot-rolled steel	0.592
Fourth	A 2	Reinforced concrete	0.543
Fifth	A 1	Glued laminated timber	0.242

Table 19. Sensitivity analysis.

Criterion	Weight	AT	PT (%)	Sensitivity
C1	0.076	0.339	443	0.002
C2	0.048	-	-	-
C3	0.156	-	-	-
C4	0.268	0.235	88	0.011
C5	0.451	-	-	-

From the last analysis phase, where three robust criteria are individuated, it has been demonstrated that cold-formed systems are the optimal solution for vertical addition of existing masonry buildings.

5.3.2 The ELECTRE method

First, the application of the method has led to the determination of matrixes *R* and *V*, reported in Tables 20 and 21, respectively.

Table 20. The matrix *R*.

	C1	C2	C3	C4	C5
A1	0.1421	0.4214	0.6574	0.3235	0.4570
A2	0.5943	0.3877	0.3235	0.1313	0.4787
A3	0.3885	0.5065	0.3607	0.3072	0.4352
A4	0.5698	0.4356	0.3926	0.5514	0.3645
A5	0.3885	0.4752	0.4229	0.6926	0.4896

Table 21. The matrix *V*.

	C1	C2	C3	C4	C5
A1	0.0114	0.0211	0.2432	0.0647	0.1371
A2	0.0475	0.0194	0.1197	0.0263	0.1436
A3	0.0311	0.0253	0.1335	0.0614	0.1306
A4	0.0456	0.0218	0.1453	0.1103	0.1093
A5	0.0311	0.0238	0.1565	0.1385	0.1469

Table 22. The matrix *E*.

	A1	A2	A3	A4	A5
A1	0	1	1	1	0
A2	0	0	0	0	0
A3	0	1	0	0	0
A4	0	1	0	0	0
A5	0	1	1	1	0

From the analysis of the matrix *E* it is shown that the dominant alternatives for vertical addition are cold-formed and glued laminated timber, followed by masonry and steel (2nd place) and reinforced concrete (3rd place).

5.3.3 The VIKOR method

From this method, the scalar parameters S_i and R_i have been firstly calculated, as shown in Table 23.

Afterwards, the ranking of alternatives is established by means of the parameter Q_i. In particular, the optimal solution is always represented by the cold-formed steel system, which has the lowest value of Q_i.

Table 23. The scalar parameters S_i and R_i.

	Alternative	S_i	R_i
A1	Glued laminated timber	0.6156	0.3700
A2	Reinforced concrete	0.3561	0.2000
A3	Hot-rolled steel	0.3526	0.1373
A4	Tuff masonry	0.5325	0.3000
A5	Cold formed steel	0.1670	0.1102

Table 24. Ranking of alternatives according to the VIKOR method.

Rank			Q_i
First	A 5	Cold formed steel	0.000
Second	A 3	Hot-rolled steel	0.259
Third	A 2	Reinforced concrete	0.384
Fourth	A 4	Tuff masonry	0.773
Fifth	A 1	Glued laminated timber	1.000

5 Conclusions

In the current paper the problem of structural modification interventions of existing masonry buildings has been faced with reference to two types of operations, namely seismic retrofitting and vertical addition. In both cases different solutions have been analysed and the best one has been selected by means of the application of three MCDM methods.

The first intervention has been studied on the basis of the results of an experimental campaign performed on a real full-scale 3D RC structure. All the applied methods have provided the same result, that is the dominating role exerted by aluminium shear panels.

On the other hand, the second intervention typology has seen the vertical addition of an existing masonry structural unit by means of traditional and innovative technologies. The results of the carried out study, achieved by using the same three methods examined for establishing the optimum seismic retrofitting technique of the existing RC structure, have provided as best solution the systems made by cold-formed steel thanks to their prerequisites, such as lightness, economy and sustainability.

Even if sensitivity analyses, performed in both applications, have provided very stable solutions, it is clear that the best alternative to solve structural modification problems mainly depends on the weights assigned to criteria. For this reason, the next step of the study is to make a parametric analysis by changing the criteria weights in order to establish in a more exact way the optimal solution of treated MCDM problems.

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