Applicability and effectiveness of different decision making methods for seismic upgrading building structures

Nicola Caterino
Dipartimento per le Tecnologie, Università di Napoli Parthenope, Centro direzionale, isola C4, 80143 Napoli.

Iunio Iervolino, Gaetano Manfredi, Edoardo Cosenza
Dipartimento di Ingegneria Strutturale, Università di Napoli Federico II, via Claudio 21, 80125 Napoli.

Keywords: seismic retrofit, decision making, existing buildings

ABSTRACT
Different decision making methods, potentially useful to help who has to decide how seismically upgrade an existing building, are considered herein. They are compared in terms of suitability for the decision task, effectiveness, simplicity of use, degree of human intervention in the corresponding procedures.
A case-study consisting of an underdesigned RC structure allows to quantitatively highlight the main aspects related to the use of each decision procedure.
Two methods (TOPSIS and VIKOR), among those considered, seem to be more appropriate for solving the retrofit selection problem because of their capability to deal with each kind of judgement criteria, the clarity of their results and the reduced difficulty to deal with parameters and choices they involve.

1 INTRODUCTION

Starting from the assumption that it is not possible to identify, among those nowadays available, a retrofit technique better than the others in all cases, authors investigate herein the possibility of supporting who has to upgrade an existing structure (i.e. who has to decide how make it) in selecting the more suitable retrofit strategy for the specific case.

As both the number of criteria and the number of alternatives generally do not allow the decision maker to directly operate a rational choice that takes into account simultaneously all the several variables involved, the guided careful selection of the retrofit technique can be particularly important especially when the structure has an important role from the social-economic point of view. To this aim, Multi-Criteria Decision Making (MCDM) methods can give a significant help.

The main objective of the present work consists in investigating the applicability and effectiveness of different state-of-the-art MCDM methods for the seismic retrofit decision problem. These methods are compared one each other in terms of suitability for the particular considered decision task and according to some significant criteria like ease of applicability, reliability and robustness of the choice, degree of decision maker's influence on the results.

A case-study developed in a previous work by the same authors is used to apply and compare each method, also allowing to highlight the specific features of the considered procedures. Five different upgrade options are considered, three of those aiming at a seismic capacity enhancement, the last two providing a seismic demand reduction.

The decision making procedure (Caterino et al. 2008) adopted for the applications is made of: (1) un-retrofitted structure assessment, (2) design of the alternative interventions, (3) choice of the evaluation criteria, (4) weighting the criteria, (5) evaluation of alternatives, (6) application of a MCDM method to identify the best retrofit solution.

The criteria considered (i.e the different ways of evaluating the same solution, reflecting specific needs of the decision maker) are of both economical/social and technical types.

The case-study application leads to results can be generalized without reserve.

2 CASE-STUDY STRUCTURE

It is a three-storey reinforced concrete building (Figure 1) designed to be representative of pre-seismic code constructions in southern Europe (Fardis and Negro 2005).

Figure 1. 3D view of the case-study structure

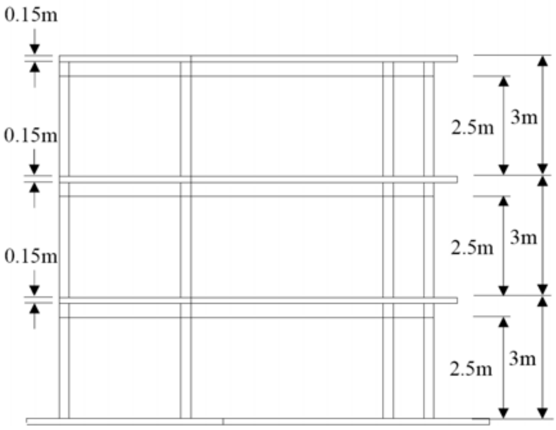

Figure 2. Front view of the case-study structure

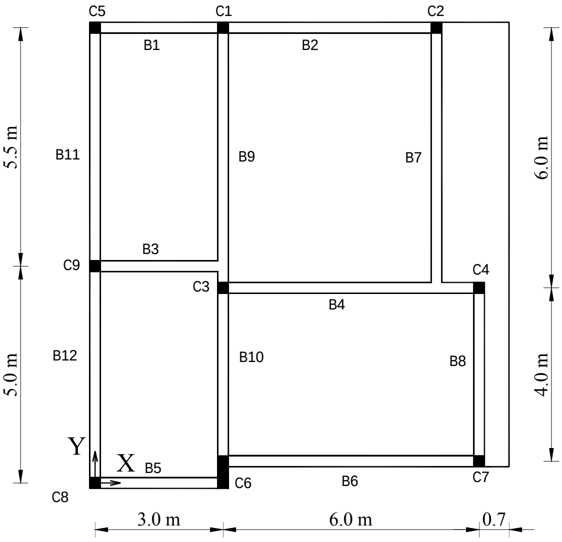

Figure 3. Plan of the case-study structure

The interstorey height is 3.0 m (Figure 2). The plan is irregular, as shown in Figure 3. All the columns have square cross section of 250x250 mm, except for column C6 which is 750×250 mm. The beams' depth is 500 mm; the slab thickness is 150 mm. The frame can be defined as a weak column-strong beam system, and is therefore far from the capacity design concepts. The reinforcement consists of smooth bars of 12 mm and 20 mm in diameter. Stirrups are smooth 8 mm diameter bars and are spaced by 200 mm in the beams, 250 mm in the columns. They are not continue in the joints.

Five different upgrade options (named A_1, A_2, …, A_5) are considered, three of those aiming at a seismic capacity enhancement, the last two providing a seismic demand reduction. A brief description of each one is given in the following.

2.1 *Alternative A_1: confinement by GFRP*

This strategy essentially aims at enhancing the building's global deformation capacity by increasing the ductility of plastic hinges without modifying their location. Externally bonded glass fibre reinforced polymers (GFRP) are used to adding a confinement action to the columns. Two layers of mono-directional glass fiber are used, except for column C6, strengthened by balanced four-directional glass fabric. GFRP sheets cover a partial length of the column at each end, except for C6 which is wrapped along its full length.

2.2 *Alternative A_2: steel bracing*

This intervention aims to increase the global strength of the structure without significant variation in terms of global ductility and at centring the stiffness in plan. Concentric diagonal X bracings were considered (Figure 4). The design aimed at bracing 2 parallel frames in each direction, for the regularity of stiffness in plant; at bracing alternating bays in plant, to distribute the large nodal actions among a larger number of columns; at bracing all the storeys, to keep the structure regular in elevation.

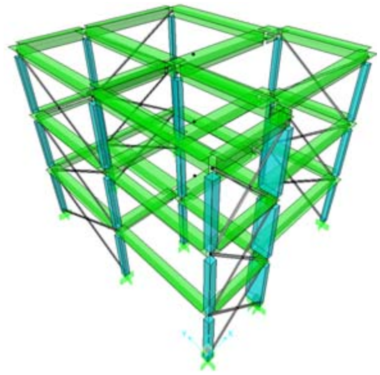

Figure 4. Alternative A_2: bracing configuration.

2.3 Alternative A_3: concrete jacketing of columns

This alternative consists of concrete jacketing of selected columns and results in the enhancement of both global strength and ductility of the structure, also aiming at centring strength in plan. Columns C1, C3 and C4 (Figure 3) ae strengthened by a concrete jacket 75 mm thick at each storey (50 MPa concrete, 8 ϕ 16 longitudinal bars, 8 mm stirrups with spacing 100-150 mm.

2.4 Alternative A_4: base isolation

This intervention is realized by installing an high-damping rubber bearing device for each column. It aims at lengthening the period of vibration of the building and enhance its dissipation capacity. Two different types of devices (type 1: “soft” rubber, diameter 400 mm, lateral stiffness K_h=480 kN/m; type 2: “normal” rubber, diameter 300 mm, K_h=710 kN/m) are considered and rationally placed in order to centre the building’s elastic stiffness in plan.

2.5 Alternative A_5: adding passive viscous dampers

Alternative A_5 consists of four viscous dampers installed at the first story of the building. It leads to the attenuation of the seismic demand through a drastic increasing of the dissipation capacity of the structural system. The intervention is concentrated at the first storey of the building in order to minimize di architectonic impact, even acting as a filter for the excitation given to the above structure. The devices (designed as linear viscous dampers, with constant equal to 1500 kNs/m), rigidly connected to the first floor, are linked to the base of the structure through steel concentric V-bracings (Figura 5).

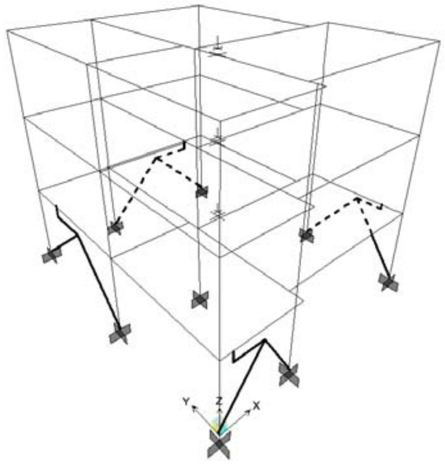

Figure 5. Alternative A_5: viscous dampers positioning.

3 DECISION PROCEDURE: PRELIMINARY STEPS

The decision making procedure, as said above, is the one proposed in Caterino et al. (2008): (1) un-retrofitted structure assessment, (2) design of the alternative interventions, (3) choice of the evaluation criteria, (4) weighting the criteria, (5) evaluation of alternatives, (6) application of a MCDM method to identify the best retrofit solution. Therefore, chosen and designed the alternatives of retrofit, this section intends to summarize the other steps of the procedures (3 to 5) needed to apply any MCDM method (step 6).

Eight criteria (named C_1, C_2,…, C_8) are considered to compare the alternatives. They are reported in Table 1, together with the weight of importance (w_j, j=1, 2, …,8; $\Sigma_j w_j$=1) assigned to each of them. The weights’ assignment procedure suggested by Saaty (1980) and based on eigenvalue’s theory is adopted. Refer to the above cited author’s work for further details.

Table 1. Evaluation criteria

Symbol	Description	Weight
C_1	Installation cost	0.073
C_2	Maintenance cost	0.172
C_3	Duration of works/disruption of use	0.073
C_4	Functional compatibility	0.280
C_5	Skilled labor requirement/needed technology level	0.026
C_6	Significance of the needed intervention at foundations	0.201
C_7	Significant Damage risk	0.035
C_8	Damage Limitation risk	0.141

Table 2 reports the so called *decision matrix* that collects the quantitative evaluation of each alternative according to each criterion (its generic element a_{ij} measures the performance of the alternative A_i in respect of criterion C_j). It is to underline that two criteria (C_4 and C_5) are qualitative and allows only linguistic judgments when alternatives are evaluated according to them; so these criteria required the additional operation consisting in the conversion of these linguistic variable into crisp numbers, which, again, may be found in the referenced work. It is also to be noted that all considered criteria are “cost” type, since the DM is interested to minimize the corresponding variables (time, cost, etc.), except for C_4 (functional compatibility) that represents a “benefit” type criterion.

Table 2 Decision matrix

	C_1 (€)	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	23	23	33	0.482	0.374	2.90	0.022	0.281
A_2	54	115	122	0.063	0.104	15.18	0.024	0.002
A_3	11	40	34	0.255	0.044	2.97	0.040	0.171
A_4	75	98	119	0.100	0.374	2.65	0.020	0.000
A_5	32	36	19	0.100	0.104	2.87	0.040	0.263
	[10^3 €]	[10^3 €]	[days]					

The decision matrix clearly shows that a rational tool to support the selection of the best alternative is needed as it is not evident which one is the optimal. In fact, for example, A_3 (concrete jacketing) requires the minimum cost of installation (criterion C_1), but corresponds to the highest risk of the Significant Damage limit state attainment (criterion C_7); A_1 (GFRP wrapping of columns and joints) guarantees the minimum maintenance costs (criterion C_2), but barely ensures the code's requirement about the non-structural elements protection required by the seismic code (criterion C_8); A_4 (base isolation) leads to the minimum intervention at foundation (criterion C_6) and the minimum risk of non-structural damage (criterion C_8), but needs many days to be realized (criterion C_3) and corresponds to the maximum cost for the installation (criterion C_1).

4 MCDM METHODS FOR SEISMIC RETROFITTING: A COMPARATIVE ANALYSIS

The following MCDM methods are considered for solving the decision problem:

- Weighted Sum Model (Fishburn 1967);
- Weighted Product Model (Bridgman 1922; Miller and Starr 1969);
- ELECTRE (Benayoun et al. 1966);
- TOPSIS (Hwang and Yoon 1981);
- MAUT (Edwards and Newman 1982);
- PROMETHEE (Brans and Vincke 1985).
- VIKOR (Opricovic 1998).

Each one will be briefly presented highlighting all the critical issues in respect to the specific decision problem. Their application to the case-study structure will support the comparison. Let *n* indicate, in general, the number of alternatives A_i and *m* that of criteria C_j.

4.1 Weighted Sum and Weighted Product Models

The Weighted Sum Model (WSM, Fishburn 1967) defines the optimal alternative as the one which corresponds to the "best" value (the maximum if all criteria are benefit-type criteria, the minimum if criteria are cost-type) of the weighted sum $\Sigma_j a_{ij} w_{ij}$. The model is formulated for problems in which all variables have the same physical dimensions, being based on the "additive utility" assumption. Moreover, for its correct application, all the criteria should be cost-type or all benefit-type. For these reasons, it seems to not be suitable for the focused problem generally involves very different types of criteria and variables.

Given two alternatives A_k and A_p, the Weighted Product Model (WPM, Bridgman 1922; Miller and Starr 1969), considers A_k better than A_p if the value of the product $\Pi_j(a_{kj}/a_{pj})^{wj}$ results to be larger than 1, if criteria are benefit-type, or lower than 1, if criteria are cost-type. The preferred alternative, if it exists, is simply the one in which the results are better than all the others. The method can also be applied to a multidimensional problem since it operates with performances ratios that automatically remove all the different units of measure. Nevertheless, the procedure may have the problem that when some alternatives show very different values in respect to a criterion (such that ratios result in having very high or very low values), it tends to rank the options in a way that is too much conditioned by that criterion, almost independently from the others and from the values of the criteria weights. This aspect, obviously, becomes particularly important when a null value is present in the decision matrix (as occurs, for example, in the assumed case-study; see Table 2). Moreover the WPM method is addressed to solve decision problems involving criteria of all the same type (cost or benefit).

4.2 ELECTRE method

The ELECTRE method (ELimination Et Choix Traduisant la REalité, Roy 1968) is based on the definition of outranking relations between alternatives, taken two at a time. According to the method, an alternative A_k outranks another one A_p ($A_k \rightarrow A_p$) if it shows performance values better or at least equal than those offered by A_p in respect of the majority of criteria and responds in a not so bad manner to the remaining criteria.

Firstly the decision matrix has to be normalized (substituting each a_{ij} element by the ratio between aij and the square root of the sum of the squared elements a_{kj} belonging to the same column) and weighted (by multiplying each value in the j-th column, with j=1, 2, …, *m*, by the weight w_j of the j-th criterion). After that, four sub-steps have to be carried out. Considering two alternatives A_k and A_p, the so called concordance set C_{kp} is defined as the one that groups all the criteria for which A_k results to be preferred to A_p or, at least, indifferent to it. The discordance set D_{kp}, conversely, includes all the remaining criteria. Then the concordance and discordance indices have to be defined. The generic concordance index c_{kp} between alternatives A_k and A_p is the sum of the weights of all criteria included in the concordance set defined above ($0 \leq c_{kp} \leq 1$) and represents how much A_k is to be preferred to A_p. The generic discordance index d_{kp}, instead, measures the maximum gap between performances of A_k and A_p in respect of criteria included in the discordance set D_{kp}. In order to know if the outranking relation $A_k \rightarrow A_p$ is true or false, it is needed the decision maker sets two threshold values $\underline{c}$ and $\underline{d}$ for the concordance indices and discordance indices respectively. Sometimes $\underline{c}$ and $\underline{d}$ are simply set equal to the mean value of the above-computed concordance and discordance indices respectively. The relation $A_k \rightarrow A_p$ is defined true if simultaneously results $c_{kp} \geq \underline{c}$ and $d_{kp} \leq \underline{d}$. For the case-study application, it is assumed for $\underline{c}$ and $\underline{d}$ the mean value of the concordance and discordance indexes ($\underline{c}=0.478$; $\underline{d}=0.689$). The retrofit option consisting in the GFRP wrapping (A_1) results to be the best one among the considered ones. Vice versa, the solution involving the steel bracing of the building (A_2) results to be "dominated" by each other.

The ELECTRE method often does not lead to the definition of only one solution emerging among the others, individuating a subset of solutions to be preferred in the initial set of available options. For this reason, the method is generally considered more suitable for decision problems characterized by not many criteria and several alternatives allowing to individuate a small subgroup of preferable options. The problem regarding the selection of the best seismic upgrade intervention of a given structure, generally does not have these characteristics. Designing and evaluating a very large number of retrofit alternatives would be too much expensive from the time and cost points of view. Moreover, in such a problem, the decision maker is interested only to know which alternative is better to implement, not to reduce the initial set of alternatives in a smallest one.

However, it is worth to note that the number of selected alternatives strongly depends on the threshold values $\underline{c}$ e $\underline{d}$ fixed by the decision maker. For the example under exam, it has been found that when $\underline{c}$ belongs to the interval [0, 0.5] and d to [0.5, 0.9], only one alternative (A_1) is selected. For values of $\underline{c}$ and $\underline{d}$ far from this intervals, instead, the number of selected alternatives quickly increase. On the other hand, may be not correct to consider all the possible couple of values $\underline{c}$ and $\underline{d}$ up to find the one that allows to select only one non-dominated solution, especially if this does not lead to fix more severe threshold values for the concordance and discordance tests.

4.3 *TOPSIS method*

The Technique for Order Preference by Similarity to Ideal Solution or TOPSIS method (Hwang and Yoon 1981) consists in identifying the best alternative among those in exam as the one having the shortest distance from a so called ideal solution A^* and the farthest distance from a so called negative-ideal solution A^-. Once the decision matrix has been normalized and weighted (as according to the ELECTRE method), A^* is obtained by taking for each criterion the best performance value among all the alternatives whereas the negative-ideal solution A^- is composed by the worst performances. Each alternative A_i ($i=1, 2, \ldots, n$), A^*, A^- can be geometrically represented as a point in a m-dimensional space where the generic j-th axes measures the weighted normalized performance of that alternative according to criterion C_j ($j=1, 2, \ldots, m$). Therefore it is possible to calculate the Euclidean distances S_i^* and S_i^- of alternative A_i from the ideal and negative-ideal solutions A^* and A^- respectively. Then the method defines relative closeness of alternative A_i to the ideal solution the following ratio $C_i^*=S_i^-/(S_i^-+S_i^*)$, the value of which is included in the interval [0, 1]. For $A_i=A^-$, results $S_{i-}=0$ and then $C_i^*=0$. For $A_i = A^*$, vice versa, $S_i^*=0$ and then $C_i^*=1$. The final ranking of the alternatives is made by considering the C_i^* value for each one. The best solution is that having the maximum C_i^* value.

In respect to the case-study (Table 3), the relative closeness of the five alternatives to the ideal one results to be $C_1^*=0.74$, $C_2^*=0.25$, $C_3^*=0.62$, $C_4^*=0.46$, $C_5^*=0.47$, leading to the following final ranking: $A_1 > A_3 > A_5 > A_4 > A_2$ (the symbol ">" stands for "better than").

Although deferring more comments to a final section where all the methods will be evaluated and compared one each other, it is important to observe that TOPSIS seems to be a procedure suitable to the decision problem about the seismic upgrade of under-designed structures since it allows to select only one solution as the "best" one and it is able to manage each kind of variables and each type of criteria.

Table 3 TOPSIS final results

	S_{i*}	S_{i-}	C_{i*}	Ranking
A_1	0.096	0.280	0.74	I
A_2	0.282	0.096	0.25	V
A_3	0.128	0.208	0.62	II
A_4	0.214	0.184	0.46	IV
A_5	0.209	0.183	0.47	III

4.4 MAUT method

The MAUT method (Multi-Attribute Utility Theory, Edwards and Newman 1982) is a decision analytic technique, which allows for the co-existence of judgment and objective measurement to capture the multidimensional nature of decision problems. After evaluating the alternatives in respect of each considered criterion and weighting the obtained values according to the relative importance of criteria, the method aggregates these "utility" measures to obtain an overall score for each option. The simplest way to perform this aggregation is taking the sum of the utility the generic alternative shows according to each criterion.

The application of MAUT to the case-study may start from the decision matrix of Table 2. In order to normalize the matrix, each element has to be divided by the larger value in the corresponding column. After that, each element, except for those belonging to the fourth column (corresponding to the benefit criterion C_4), is replaced by its complement to 1 in order to virtually have all benefit-criteria. This artifice is an arbitrary choice of the authors and it is required to associate to each variable an utility measure.

After weighting the obtained matrix by multiplying each value for the corresponding criterion weight, the matrix in Table 4 is assembled. The score (overall utility) of each alternative is calculated as the sum of the elements of the corresponding row (column 'Σ' in Table 11). Therefore, the ranking results to be: $A_1>A_3>A_5>A_4>A_2$.

Table 4 MAUT results

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	Σ
A_1	0.050	0.137	0.053	0.280	0.000	0.163	0.016	0.000	0.699
A_2	0.020	0.000	0.000	0.036	0.019	0.000	0.014	0.140	0.229
A_3	0.062	0.112	0.053	0.148	0.023	0.162	0.000	0.055	0.614
A_4	0.000	0.026	0.002	0.058	0.000	0.166	0.018	0.141	0.410
A_5	0.041	0.117	0.062	0.058	0.019	0.163	0.000	0.009	0.470

4.5 PROMETHEE method

The Preference Ranking Organization Methods for Enrichment Evaluations (PROMETHEE, Brans and Vincke 1985) is based on the comparison of each alternative with each other considering the deviations that alternatives show according to each criterion. Given its structure, the method allows to operate directly on the variables included in the decision matrix, without requiring any normalization. On the other hand, it is needed that each criterion is of the benefit type. This condition is always easily attainable by multiplying to -1 the variable measured according to cost criteria. This has been done for the case-study switching the sign of the elements of the decision matrix corresponding to the cost criteria (all of them except for C_4).

For each criterion C_j ($j=1, 2, \ldots, m$) a preference function $P_j(A_k, A_p)$ of alternative A_k to A_p has to be defined giving a value between 0 and *1*, increasing with the deviation $x=a_{kj}-a_{pj}$ between the performances of A_k and A_p in respect of C_j. A preference function is such that it results $P_j(A_k, A_p)=0$ if $x\leq 0$, whereas $P_j(A_k, A_p)=p(x)$ if $x>0$, given that $p(x)$ is a monotonically increasing function defined in the positive real domain and having values between 0 and 1. A null value of $p(x)=p(a_{kj}-a_{pj})$ means indifference between A_k and A_p from the point of view of criterion C_j. Values of $p(x)$ slightly greater than zero, closer than one or just equal to one mean a weak, strong or strict preference of A_k to A_p respectively. Standard $p(x)$ functions exist, they may be chosen depending on the particular criterion. Each type of function requires a different degree of involvement of the decision maker (DM) The function type I ($p(x)=1$ for each value of $x>0$) is the simplest one and does not require any intervention of the DM (Figure 6). The function II, instead, requires the DM fixes the parameter l (such that $p(x)=0$ for $x\leq l$ and $p(x)=1$ for $x>l$) that defines the magnitude of the interval of x in which the two alternatives under consideration have to be considered indifferent. The function type III ($p(x)=x/m$ for $x\leq m$ and $p(x)=1$ for $x>m$), through the definition of the parameter m, allows the DM expresses a preference of A_k to A_p linearly increasing with the deviation $x=a_{kj}-a_{pj}$, as far as x is smaller than m. For further details about the other, more complex, function types, please refer to Brans and Vincke (1985). Here it is only important to remark that types IV, V and VI require the definition of two (p and q), two (s and r) parameters and one parameter (σ) respectively.

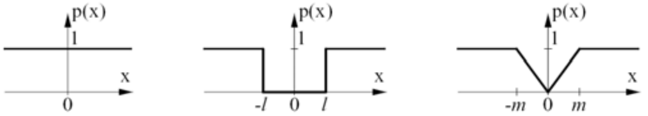

Figure 6. Criteria of type I, II and III respectively from left to right

The method was applied seven times to the case-study in order to investigate about the influence on the final result of all the involved parameters and choices. The first three preference function types are considered. For each application the same type of preference function is assumed for all the criteria. The threshold parameters l and m, needed to use preference functions II and III respectively, are fixed here in percentage terms (10%, 25% or 50%) with reference to the maximum gap among the performances of the five alternatives according to the particular criterion under exam.

After alternatives A_k and A_p has been evaluated in respect of each criterion, it is possible to evaluate the so called "preference index" $\pi(A_k, A_p)= \Sigma_j w_j P_j(A_k, A_p)$ where w_j is the weight of the j-th criterion. This index gives a measure of the global preference of A_k to A_p. After doing this for all couples of alternatives, the degree of "strength" (called "positive outranking flow") $\Phi^+(A_k)=\Sigma_p\pi(A_k , A_p)$ of each alternative Ak in respect to the others has to be evaluated whereas its degree of "weakness" is $\Phi^-(A_k)=\Sigma_p\pi(A_p, A_k)$ ("negative outranking flow"). The version of the method generally referred to as PROMETHEE I allows ranking the alternatives according to these rules: A_k is to be preferred to A_p if $\Phi^+(A_k)> \Phi^+(A_p)$ and $\Phi^-(Ak)< \Phi$-(A_p); it is indifferent to A_p if $\Phi^+(A_k)= \Phi^+(A_p)$ and $\Phi^-(A_k)= \Phi^-(A_p)$; otherwise A_k and A_p are incomparable.

Only the first application (carried out using the simplest preference function, type I) to the case-study leads to select one solution (A_1) dominating all the others. In all the other cases, at least two are the alternatives that result to be non-dominated by the others and non-comparable one each other. No application leads to a complete ranking of the alternatives. The influence of the chosen value for the threshold parameters l (function II) and m (function III) results to be significant. As could be logically forecasted, larger threshold values correspond to a greater indifference field in the comparison between two alternatives and a poorly defined classification.

Very often the PROMETHEE I method leads only to a partial classification of the alternatives. A modified version of the method (PROMETHEE II), defines a net outranking flow $\Phi(A_k)$ for each alternative as the difference $\Phi^+(A_k)$-$\Phi^-(A_k)$ and ranks the options assuming that Ak is to be preferred to A_p if $\Phi(A_k)> \Phi(A_p)$, indifferent if $\Phi(A_k)= \Phi(A_p)$. In this way, the method always allows ranking the alternatives in a complete manner. Obviously, the best alternative is the one having the greatest value of $\Phi(A_k)$. For the numerical case under exam, the resulting Φ values lead to the same final ranking for each of the seven applications done ($A_1 \rightarrow A_3 \rightarrow A_5 \rightarrow A_4 \rightarrow A_2$), not highlighting any significant influence of the particular chosen preference function and fixed parameters value.

4.6 *VIKOR method*

This method (VlseKriterijumska Optimizacija I Kompromisno Resenje, VIKOR, by Opricovic 1998) ranks the alternatives A_i (i=1, 2, …, *n*) according to the value of three scalar quantities (S_i, R_i e Q_i) that have to be calculated for each option. For each criterion C_j (j=1, 2, …, *m*), the best a_j^* and worst aj- performances among all the alternatives firstly have to be determined. Then S_i, R_i and Q_i values have to be assessed as follows:

$$S_i = \sum_{j=1}^{m} \frac{w_j(a_j^* - a_{ij})}{a_j^* - a_j^-} \quad ; \quad R_i = \max_j \left[\frac{w_j(a_j^* - a_{ij})}{a_j^* - a_j^-} \right] \qquad (1)$$

$$Q_i = \upsilon \frac{S_i - S^*}{S^- - S^*} + (1-\upsilon)\frac{R_i - R^*}{R^- - R^*} \qquad (2)$$

where is $S^*=\min(S_i)$, $S^-=\max(S_i)$, $R^*=\min(R_i)$, $R^-=\max(R_i)$. The parameter υ is fixed by the decision maker in the interval [0,1] giving a different weight of importance to each addend into the Qi expression. Practically $\upsilon>0.5$ is assumed when the decision maker wants to give more importance to the first term and hence to the global performance of the alternative in respect to the whole of the criteria. Using a υ value smaller than 0.5, instead, gives more weight to the second term that is related to the magnitude of the worst performances exhibit by alternatives in respect of each single criterion. When the two aspects are considered equally relevant, $\upsilon=0.5$ should be used.

For the case-study, starting from the decision matrix in Table 5, the S_i and R_i values are evaluated (Table 3). It results: $S^*=0.198$, $S^-=0.788$, $R^*=0.141$, $R^-=0.280$. The Q_i value is determined for each option, assuming $\upsilon=0.5$.

Table 5 S_i, R_i and Q_i values (υ=0,5) for each alternative

	S_i	R_i	Q_i
A_1	0.198	0.141	0.000
A_2	0.788	0.280	1.000
A_3	0.320	0.152	0.143
A_4	0.565	0.255	0.720
A_5	0.479	0.255	0.648
	$S^*=0.198$	$R^*=0.141$	
	$S^-=0.788$	$R^-=0.280$	

The method ranks the alternatives according to the Q_i values. The best option (A') is that with the smallest Q_i value, but only if the following two acceptance criteria are both satisfied:

1. "Acceptable advantage": it should be Q(A")-Q(A')≥DQ, where A" is the alternative having the second best Qi value and DQ is taken equal to the ratio 1/(*n*-1) depending on the number n of alternatives.

2. “Acceptable stability in decision making”: A’ should be the best also in terms of S_i value and/or R_i value.

If one of these conditions is not satisfied, it is not possible select directly the best solution of the set but a subset of preferable options can be defined, including in it A’ and A”, if only the second condition is not satisfied, or A’, A”, …, $A^{(N)}$ if the first condition is not satisfied, being $A^{(N)}$ the last option, in the ranking done by Q_i, for which it still results $Q(A^{(N)})-Q(A') < DQ$.

According to the Q_i values in Table 5 relative to the numerical example, the following classification is obtained: $A_1 > A_3 > A_5 > A_4 > A_2$. The evaluation of Q_i values is done again each time assuming a different υ value in the interval [0, 1] in order to investigate the actual influence of such a parameter on the results. The final ranking resulted to be independent from the chosen υ. This is due to the fact that the classifications obtained considering only the term $(S_i-S^*)/(S^--S^*)$, accounting for the global satisfaction of criteria, and only the term $(Ri-R^*)/(R^--R^*)$, accounting for the worst performance of each alternative in respect to the single criterion, are the same.

Since, for $\upsilon=0.5$, it results $Q(A_3)-Q(A_1)=0.143$ less than $DQ=1/(5-1)=0.250$, the first criterion of acceptability is not satisfied. In other words, considering the relatively small number of alternatives, the final score of solutions A_1 and A_3 are judged to be too much close and it is not possible to distinguish the best one between the two. Therefore, even if the second criterion is satisfied (A_1 is the best one also in terms of S_i only and R_i only), the final result of the VIKOR method consists in indicating the subset A_1, A_3 as a group of compromise solutions. Applying again the method excluding the A_2 alternative from the group leads to the ranking $A_1 > A_3 > A_5 > A_4$ with both the acceptability criteria satisfied, finally individuating A_1 as the best solution.

4.7 Comparison among the methods

All the examined MCDM methods result suitable for the focused decision problem, even if sometimes requiring artifices (e.g. MAUT). Only WSM and WPM are inapplicable since more appropriate for problems involving variables having homogeneous dimensions and criteria all of the same type. Table 6 summarizes the main informations obtained in the previous sections about MCDM methods applied to the seismic retrofit decision problem. The same table also indicates, with reference to the case-study, the results each method leads to, in terms of ranking of alternatives. Table 7, instead, summarizes informations included in the decision matrix (Table 2) and criteria weights (Table 1), also reporting the ranking of the alternatives as it would result according to a single criterion at a time. Alternatives are ranked in a very different manner depending on the considered point of view (i.e. criterion) so that the need of a decision support tool clearly emerges. All the applicable methods (see Table 6) lead to A_1 as the preferred retrofit option, with the exception of PROMETHEE I, that only allows a partial ranking.

In the following, useful comments about the examined MCDM methods are reported, addressing to understand which one is more suitable to solve the decision task under exam.

Table 6 MCDM methods examined: applicability to the seismic retrofit decision problem. Case-study results.

Method	Applicable?	Classification				
TOPSIS	Yes	A_1	A_3	A_5	A_4	A_2
WSM	No	N/A				
WPM	No	N/A				
ELECTRE	Yes	$A_1$to be preferred				
MAUT	Yes (*)	A_1	A_3	A_5	A_4	A_2
VIKOR	Yes	A_1 and A_3 to be preferred				
VIKOR (w/o A_2)	Yes	A_1	A_3	A_5	A_4	-
PROMETHEE I	Yes	Partial ranking				
PROMETHEE II	Yes	A_1	A_3	A_5	A_4	A_2

(*) Applicable using an artifice

Table 7. Case-study: considered criteria, relative weights and different ranking of the alternatives considering one criterion at a time.

		C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
		Install. cost (0.073)	Mainten. cost (0.172)	Duration works (0.073)	Compatib. (0.280)	Labour specializ. (0.026)	Foundations intervention (0.201)	SD risk (0.035)	DL risk (0.141)
ranking	I	A_3	A_1	A_5	A_1	A_3	A_4	A_4	A_4
	II	A_1	A_5	A_1	A_3	$A_2=A_5$	A_5	A_1	A_2
	III	A_5	A_3	A_3	$A_4=A_5$	$A_2=A_5$	A_1	A_2	A_3
	IV	A_2	A_4	A_4	$A_4=A_5$	$A_1=A_5$	A_3	$A_3=A_4$	A_5
	V	A_4	A_2	A_2	A_2	$A_1=A_5$	A_2	$A_3=A_4$	A_1

A_1=GFRP wrapping; A_2=steel bracing; A_3=RC jacketing; A_4=base isolation; A_5=viscous dampers.

The MAUT method cannot be applied to the problem directly. The cost-criteria have to be converted in equivalent benefit-type. For the case-study this was done replacing the performances values in respect to the cost-criteria with their complement to one. This artifice is an arbitrary choice of the authors required to associate to each variable a measure of utility. MAUT is herein applied in its simplest form, assuming that all the attribute utility functions are linear. As a consequence, no parameters have to be set.

The ELECTRE method is suitable for decision problems, like that under exam, involving non-homogeneous variables and different types of criteria. It often does not lead to the definition of only one solution emerging among the others (except when, as for the examined case-study, an alternative clearly outclasses the others, even according to concordance and discordance tests separately considered), individuating a subset of solutions to be preferred in the initial set of available options. Applying the method to this subset again does not modify the result.

The structure of PROMETHEE method (versions I and II) allows a direct application to the considered problem. It does not require the normalization of the decision matrix variables but requires that all the criteria are benefit type. When the last condition is not satisfied (as in the case-study), the method allows the equal satisfaction of it simply by changing the sign of all the performance values relative to the cost-type criteria, without affecting the results. This method is easily adaptable to each kind of conditions. It allows the association of a different preference model to each criterion, each one being characterized by a certain degree of complexity and a given involvement of parameters to be fixed by the decision maker (DM). PROMETHEE I is essentially addressed to give only a partial ranking of the alternatives, as the application to the case-study confirmed. Actually often two or more options result in being non-comparable to each other. The version II of the method was ideated just as an evolution of the version I aimed at giving a complete ranking of the alternatives. It always allows the comparison of each pair of alternatives, independently from the particular operating conditions.

The TOPSIS and VIKOR methods allow the use of variables with different units of measure and criteria of different type. If applied starting from previously evaluated decision matrix and criteria weights, they lead to the final result almost without requiring the DM's intervention (except for the definition of the υ parameter of the VIKOR method). They approach the decision problem in a similar manner; both define, explicitly or not, an ideal solution ad-hoc combining the best performances of the alternatives according to each criterion and assume the "distance" of each alternative to the ideal one as a partial measure of the desirability of that option. VIKOR leads to the ranking also considering the degree of satisfaction of each single criterion and allows to give a different weight to the global performance to the whole of criteria and the individual response to the single criterion. TOPSIS, instead, considers, together with the distance from the ideal alternative, the distance from a so called negative-ideal option obtained combining the worst performances of alternatives in respect to the single criterion.

The TOPSIS and VIKOR methods use different normalization techniques for the variables in the decision matrix; the first one a vector normalization, the second one a linear normalization. After the final ranking using the TOPSIS (according to the C_i values) and the VIKOR (according to the Q_i values) methods are obtained, a marked difference between the two procedures is recognized. The VIKOR method checks whether the first ranked alternative can be considered "better enough" than the others by checking if the second alternative is far enough from the first one, and if the preferred alternative results in terms of Q_i are the best also in terms of global performance in respect to the whole of criteria only (S_i) and/or in terms of the performance offered to each single criterion (R_i). If these tests are not passed, the first ranked alternative cannot be defined the best in absolute terms but, together with some of the following ones, composes a subgroup of options to be considered preferable to the remaining ones. TOPSIS, instead, does not include such checks of acceptability for the obtained results.

5 CONCLUSIONS

The analyses shown in the paper may be of help may be of help in the case of managing one or more existing buildings to be upgraded to resist seismic actions. Decisional procedures like the MCDM methods clearly may support the selection of the most suitable intervention of retrofit. Herein many well-known decision methods are compared in order to understand which one can be suggested to the practitioner has to take the above decision. After investigating the actual applicability and effectiveness of each method, the study pointed out limits, advantages and disadvantages related to the application of each method and tried to synthetically compare them according to the main practical aspects.

The MAUT method, applied in its simplest version, does not require the DM fixing any parameter. A drawback is that the assumption (of all linear utility functions) the method is based on is unlikely to be realistic for a wide range of attribute measures. MAUT always allows to completely rank the alternatives. On the other hand, it needs all the variables in the decision matrix to be measures of the utility each option leads to in respect to each criterion: when cost-criteria are involved, this condition is not satisfied. For the case-study showed herein, the authors made an artifice aiming at converting the cost-criteria in equivalent benefit ones.

PROMETHEE I method has a clear approach to the decision problem and a degree of complexity depending on how the decision maker wants to model the *preference function* according to each criterion, but the method very often does not lead to a complete ranking of alternatives, actually not solving the given problem. The version II of the same method, instead, always allows a complete ranking of options, but it leads to a loss of a considerable part of information by taking the difference of the positive and negative outranking flows (Brans and Vincke 1985; Fulop 2005).

Given their flexibility of use and the general validity of the principles governing their procedures, the ELECTRE, TOPSIS and VIKOR methods can easily applied to solve the considered problem. Nevertheless ELECTRE often is not able to give a complete ranking of the alternatives rather selecting a subset of options to be considered preferable to the remaining ones. For this reason, ELECTRE may be considered more suitable for decision problems characterized by not many criteria and several alternatives, allowing to individuate a small subset of preferable options (Lootsma 1990). The problem regarding the selection of the preferred seismic upgrade intervention of a given structure generally does not have these characteristics. Roughly speaking, the number of retrofit options to be compared may not be larger than five or six, considering that each alternative intervention has to be designed with an adequate detail and evaluated from each point of view. Furthermore, in order to make as effective as possible a comparison among the alternatives, adopting several judgment criteria is generally preferable. Moreover, the result ELECTRE leads to is generally strongly dependent on the threshold $\underline{c}$ and $\underline{d}$ values fixed by the decision maker. These parameters may not be easily understood by practitioners (Brans and Vincke 1985).

TOPSIS and VIKOR have many common aspects in their general approach, their difference being a possibility that the second one gives to explicitly account for the degree of satisfaction of a single criterion besides the global performance to the whole of criteria and for the double check of acceptability for the final solution VIKOR imposes. The capability of these methods to manage each kind of judgement criteria and variables, the clarity of their results and the reduced difficulty to deal with parameters and choices they involve lead to conclude that these two methods results to be, among those investigated, the most suitable to the focused decision task.

REFERENCES

Brans, J. P., Vincke, P., 1985. A Preference Ranking Organization Method (The PROMETHEE Method for Multiple Criteria Decision Making), *Management Science*, **31**(6): 647 – 656.

Bridgman, P.W., 1922. *Dimensional Analysis*, Yale University Press: New Haven, CT.

Caterino, N., Iervolino, I., Manfredi, G., Cosenza, E., 2008. Multi-Criteria Decision Making for Seismic Retrofitting of RC Structure, *Journal of Earthquake Engineering*, **12**: 1-29.

Edwards, W., Newman, J. R., *Multiattribute Evaluation*: Sage Publications Inc.

Fardis, M.N., Negro, P., 2005. Seismic Performance Assessment and Rehabilitation of Existing Buildings, *Proceedings of the SPEAR International Workshop*, Ispra, Varese, Italy.

Fishburn, P. C., 1967. *Additive Utilities with Incomplete Product Set: Applications to Priorities and Assignments*, Operations Research Society of America (ORSA), Baltimore.

Fulop, J., 2005. *Introduction to Decision Making Methods, Working Paper*, Laboratory of Operations Research and Decision Systems (LORDS), WP05-06.

Hwang, C.L., Yoon, K., 1981, *Multiple Attribute Decision Making*, Lecture Notes in Economics and Mathematical Systems 186, Springer-Verlag: Berlin, Germany.

Lootsma, F. A., 1990. *The French and the American School in Multi-Criteria Decision Analysis*, Recherche Operationnele/Operations Research, Vol. 24, No. 3, pp. 263-285.

Miller, D. W., Starr, M. K., 1969. *Executive Decisions and Operation Research*, Prentice-Hall, Inc: Englewood Cliffs, NJ.

Opricovic, S., 1998. *Multicriteria Optimization of Civil Engineering Systems*, Faculty of Civil Engineering, Belgrade, Serbia.

Roy, B., 1968. Classement et choix en présence de points de vue multiples (la méthode ELECTRE), *Revue Francaise d'Informatique e de Recherche Opérationelle*, **8**, 57-75.

Saaty, T.L., 1980. *The Analytic Hierarchy Process*, McGraw-Hill, New York, NY, USA.