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Comparative Analysis of Multi-Criteria Decision-Making Methods for Seismic Structural Retrofitting

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Abstract: *The selection of a strategy to seismically upgrade an existing building is a difficult problem. In fact, several different technologies are available to this aim nowadays. Furthermore, many generally conflicting options have to be considered to assess the performance of each alternative. Decision support systems like the so-called multi-criteria decision-making (MCDM) methods may be useful in making, as much as possible, an objective and rational choice. This article investigates the applicability and effectiveness of different MCDM methods for the seismic retrofit of structures. Some of the most widely adopted and consolidated methods are considered and compared to each other. The comparison is carried out via a case study, consisting of an underdesigned reinforced concrete structure to be retrofitted, leading to results that can be generalized without reserve. 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 judgment criteria, the clarity of their results, and the reduced difficulty to deal with parameters and choices they involve.*

1 OBJECTIVES OF THE STUDY

Seismic retrofitting is one of the most common and effective approaches aimed at the reduction of seismic risk for existing buildings. It essentially consists of the realization of interventions such that the seismic capacity of the structure is greater than the seismic demand at the site.

In the last years, a significant amount of resources have been invested to support the research regarding the application of innovative materials and technologies for the upgrading and control of the structural performances in seismic areas so that several possible retrofit options are now available to practitioners. Starting from the likely assumption that it is not possible to identify a retrofit technique better than the others in all cases, the authors investigated in a previous work the possibility of supporting who has to upgrade an existing structure (or, more precisely, who has to decide how to make it)

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in selecting the more suitable retrofit strategy for the specific case of interest. It has been shown that, to this aim, multi-criteria decision-making (MCDM) methods can give a significant help (Caterino et al., 2008). These methods are commonly used in fields different from structural engineering, for example, for the resources allocation planning (Ogryczak, 2007), for the selection of the best medical therapy for a patient (Pérez Encinas et al., 1998; Ehrgott and Burjony, 2001), or to locate a special facility (Queiruga et al., 2008).

The main objective of the present work consists of investigating the applicability and effectiveness of different state-of-the-art MCDM methods for the seismic retrofitting decision problem. Selected procedures are compared to each other in terms of suitability for the considered task and according to some significant aspects as ease of use, reliability, and robustness of the choice, and the degree of the decision maker's involvement in the procedure.

A case study developed in a previous work by the same authors is used to apply and compare each method. It refers to an existing underdesigned structure and allows assessing the specific features of each MCDM procedure. It is a three-story reinforced concrete (RC) building representative of preseismic code constructions in southern Europe. Five alternative retrofit interventions are designed and analyzed by MCDM methods, considering eight different criteria of evaluation.

2 BACKGROUND

A great deal of research, as well as some building codes, shows how many different kinds of retrofit strategies are available to upgrade substandard structures nowadays (ATC-40, 1996; Sugano, 1996; FEMA, 1997; Mohele, 2000; FIB, 2003). Some researchers also show possible applications of the MCDM methods for structures, even in seismic zones, but almost always with reference to the design of new constructions (Beck et al., 1999; Irfanoglu, 2000; Liu et al., 2004; Salajegheh and Heidari, 2004). Similarly, cost optimization procedures are nowadays used for structural design, also including life cycle cost considerations (Sarma and Adeli, 1998, 2000a, b, 2002). Such procedures are also proposed to select the preferred intervention for specific existing structures (e.g., bridges), aiming at the time planning of the maintenance to preserve the reliability of the structural system (Augusti et al., 1998) or at the structural assessment in the case of concurrent risks (Adey et al., 2003).

Other literature is focused on decisional methods aimed at the allocation of limited resources for the realization of rehabilitation projects for structures and infrastructures, showing that multi-criteria procedures may be used to address the comparative analysis of different strategies aimed at the reduction of social and economical costs in regions subjected to natural risks (Opricovic and Tzeng, 2002; Shohet and Perelstein, 2004). On the other hand, Nuti and Vanzi (2003) try to answer the question about the social and economical convenience related to the seismic retrofit of an existing building.

Recently, the MCDM methods have been applied by the authors to the seismic retrofit selection problem (Caterino et al., 2007, 2008). The main results of these two previous articles, needed for the readability of the present work, are summarized in Section 4.

3 MCDM GENERAL ASPECTS AND CRITICAL ISSUES

Let $A_i (i = 1, 2, \ldots, n)$ be a finite group of alternative decisions (solutions), $C_j (j = 1, 2, \ldots, m)$ a finite set of criteria in respect to which performances of each feasible action have to be assessed, and $w_j (j = 1, 2, \ldots, m)$ the relative importance (weight) of each criterion to the final decision. The multi-criteria decision problem consists of determining the *optimal* solution among alternatives A_i, that is, the one showing the highest degree of desirability with respect to all the criteria.

The criteria are generally conflicting with each other or representing trade-offs. In most cases, there is no solution that satisfies all criteria simultaneously. In fact, criteria can be generally distinguished as "benefit" type, when the decision maker (DM) is interested in maximizing the evaluation of alternatives according to them, and "cost" type, when the DM wants to minimize them.

Before applying any MCDM methods, all the alternatives have to be evaluated according to each criterion. This requires the qualitative variables to be converted into crisp numbers and the criteria weights to be determined. In fact, the so-called decision matrix **A** (having n by m dimensions) may be assembled, assuming the generic element a_{ij} as the performance of the alternative A_i in respect to criterion C_j.

The evaluation of the alternatives according to the different criteria generally involves variables characterized by different units of measure. In these cases, a normalization of the involved variables may be needed.

Qualitative criteria are often also involved in the decision process. This kind of criteria, by definition, requires evaluation through linguistic judgment. As a consequence, the conversion of these qualitative evaluations in equivalent crisp numbers is needed to completely define the decision matrix.

As discussed, MCDM methods need the definition of a “weight” for each criterion expressing the relative importance of it in respect to the others. This is one of the most critical phases of the decision procedure requiring a synthetic and quantitative measure of the decision maker’s preference about each performance target.

4 SYNTHESIS OF PREVIOUS WORK AND SELECTED CASE STUDY

To make the subsequent sections clear to the reader, herein a brief description of the main contents of two previous articles written by the authors about the MCDM topic is given (Caterino et al., 2007, 2008).

In the cited articles a stepwise procedure consisting of six phases was proposed to approach the problem of the selection of the preferred solution to seismically upgrade an existing structure. It was applied to a case study consisting of a three-story RC building not adequately resisting seismic actions. The TOPSIS MCDM method (Hwang and Yoon, 1981) was chosen to perform the sixth and last step. The same case study is also adopted herein, using other MCDM methods, so the steps from 1 to 5 are still valid. For this reason they are briefly described herein. It is worth underlining that the resulting decision matrix and criteria weights (Tables 1 and 2) obtained by these steps represent the starting point for the application of any MCDM method considered.

Step 1: Seismic evaluation of the building as is.

To assess the seismic performance, a nonlinear static analysis of a lumped plasticity model of the building was performed considering the rotational properties of the plastic hinges according to the OPCM 3431 (2005) Italian code. The building does not satisfy the significant damage (SD) limit state and barely withstands the damage limitation (DL) limit state.

Step 2: Definition and design of the group of alternative retrofit solutions.

A total of five upgrade options are considered, three of those aiming at a seismic capacity enhancement, the last two providing a seismic demand reduction. In the following they will be indicated as alternatives A_1, A_2, A_3, A_4, and A_5, respectively. A_1 consists of confinement by glass fiber reinforced plastic (GFRP) of columns and joints and results in an increase of the building displacement capacity; A_2 provides a global strength (and stiffness) enhancement by adding steel braces; A_3 is the concrete jacketing of selected columns, which provides a partial but simultaneous enhancement of strength and ductility; the base isolation of the structure is referred to as alternative A_4 and results in the reduction of the seismic forces through the lengthening of the fundamental period of vibration of the structure; finally, A_5 consists of installing four viscous dampers at the first story of the building and produces the attenuation of the seismic demand through a drastic increasing of the dissipation capacity of the structural system.

Table 1
Evaluation criteria and weights

Symbol	*Description*	*Weight*
C_1	Installation cost	0.073
C_2	Maintenance cost	0.172
C_3	Duration of work/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
Decision matrix

	C_1 (€)	C_2 (€)	C_3 (days)	C_4	C_5	C_6	C_7	C_8
A_1	23,096	23,206	33	0.482	0.374	2.90	0.022	0.281
A_2	53,979	115,037	122	0.063	0.104	15.18	0.024	0.002
A_3	11,175	40,353	34	0.255	0.044	2.97	0.040	0.171
A_4	74,675	97,884	119	0.100	0.374	2.65	0.020	0.000
A_5	32,309	36,472	19	0.100	0.104	2.87	0.040	0.263

Steps 3 and 4: Definition and weighting of criteria.

The building focused in the application is supposed to be residential and the DM to be the owner. The considered criteria are those reported in Table 1.

Table 1 also reports (last column) the weight w_j assigned to each criterion C_j $(j = 1, 2, \dots, 8)$. They are expressed in relative terms $(\Sigma_j w_j = 1)$ and are derived starting from the DM’s preference using a procedure based on eigenvalue’s theory. A *one-level hierarchy* for the criteria and the *independence* among them is assumed (Saaty, 1980).

Note that generally the criteria depend on the peculiarities of the building, on its destination of use, on the decision maker’s profile as well as on the kind of competing retrofit options involved. For instance, all the five alternatives listed herein are passive retrofit systems, while active and/or semi-active control devices could also be considered (Jiang and Adeli, 2008a, b). In such a case other criteria should be included, reflecting the special performances of these kinds of interventions in respect to the others.

Step 5: Evaluation of alternatives.

Table 2 reports the decision matrix that collects the quantitative evaluation of the alternatives according to each criterion. 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. These criteria required the adoption of a special procedure (based on pairwise comparisons among the alternatives) to obtain a numerical measure of the options' performance in respect to them. It is also to be noted that all considered criteria are cost-type, because the DM is interested to minimize the corresponding variables (time, cost, etc.), except for C_4 (functional compatibility) that represents a benefit-type criterion.

The decision matrix clearly shows that a rational tool to support the selection of the preferred alternative is needed. For example, A_3 (reinforced 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 nonstructural elements protection (criterion C_8); A_4 (base isolation) leads to the minimum intervention at foundation (criterion C_6) and the minimum risk of nonstructural 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).

Step 6: Selection of the preferred solution.

As stated above, the TOPSIS (technique for order preference by similarity to ideal solution; Hwang and Yoon, 1981) method was used in Caterino et al. (2008). According to the method, first all the a_{ij} values in the decision matrix (Table 2) have to be normalized using the expression (1) and weighted by multiplying it by the weight w_j of the j-th criterion (Table 3).

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

The preferred alternative is the one having the shortest distance from an *ideal* solution A^* and the farthest distance from a *negative-ideal* solution A^-. The fictitious alternative A^* can be obtained by taking from each criterion the best performance value among all the alternatives; conversely, the negative-ideal solution A^- is composed of the worst performances (Table 4).

Table 3
Weighted normalized decision matrix according to TOPSIS (Caterino et al., 2007)

	C₁	*C₂*	*C₃*	*C₄*	*C₅*	*C₆*	*C₇*	*C₈*
A_1	0.017	0.025	0.014	0.238	0.018	0.036	0.011	0.094
A_2	0.039	0.122	0.050	0.031	0.005	0.188	0.012	0.001
A_3	0.008	0.043	0.014	0.126	0.002	0.037	0.021	0.057
A_4	0.054	0.104	0.049	0.050	0.018	0.033	0.010	0.000
A_5	0.023	0.039	0.008	0.050	0.005	0.036	0.021	0.088

Table 4
Ideal A^* and negative-ideal A^- solutions

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A^*	0.008	0.025	0.008	0.238	0.002	0.033	0.010	0.000
A^-	0.054	0.122	0.050	0.031	0.018	0.188	0.021	0.094

Table 5
Absolute S_i^*, S_i^-, and relative C_i^* distances for each alternative: final ranking

	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

Each alternative $A_i (i = 1, 2, \ldots, 5)$, A^*, A^- can be geometrically represented as a point in an eight-dimensional space where the generic j-th axes measure the weighted normalized performance of that alternative according to criterion C_j ($j = 1, 2, \ldots, 8$). 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. The method defines relative closeness of alternative A_i to the ideal solution for 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 preferred solution is that having the maximum C_i^* value. Table 5 reports the values of the distances S_i^*, S_i^-, and C_i^* for each alternative and the consequent final ranking of the five options. This result can be resumed as $A_1 > A_3 > A_5 > A_4 > A_2$ (where the symbol "$>$" stands for "better than").

5 COMPARATIVE ANALYSIS OF MCDM METHODS

The following MCDM methods having a single decision maker are considered herein and also compared with the TOPSIS method used in the previous work and summarized above:

- Weighted sum model (Fishburn, 1967)
- Weighted product model (Bridgman, 1922; Miller and Starr, 1969)
- ELECTRE (Benayoun et al., 1966)
- 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.

5.1 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 and the minimum if criteria are cost-type) of the weighted sum $\Sigma_j a_{ij} w_{ij}$ (see the meaning of the symbols in Section 3). 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 $\Pi_j (a_{kj}/a_{pj})^{wj}$ is 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 because 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, e.g., 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).

5.2 ELECTRE method

The original ELECTRE method (ELimination Et Choix Traduisant la REalité) is attributed to Benayoun et al. (1966). It is generally labelled as "ELECTRE I" because several different versions of the ELECTRE method were subsequently given: ELECTRE II (Roy and Bertier, 1971), ELECTRE III (Roy, 1978), ELECTRE IV (Hugonnard and Roy, 1982), ELECTRE IS (Roy and Skalka, 1984), ELECTRE A (unpublished for confidential reasons; it was made to solve a specific decision problem of an important banking company), and ELECTRE TRI (Yu, 1992). Herein only the ELECTRE I version is considered and referred to simply as "ELECTRE" method.

ELECTRE 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 if it shows performance values better or at least equal to those offered by A_p in respect to the majority of criteria and responds acceptably to the remaining criteria (the outranking relation is generally indicated with $A_k \to A_p$ or $A_k S A_p$).

To apply this method, the decision matrix (generally written in a normalized form) has to be weighted. This has to be done as for the TOPSIS method, so the weighted normalized decision matrix according to ELECTRE is still the one in Table 3. After that three stages have to be carried out.

Stage 1: Concordance and discordance set.

Considering two generic alternatives A_k and A_p, the concordance set C_{kp} is defined as the group of criteria for which A_k is preferred to A_p or, at least, indifferent to it. The discordance set D_{kp} includes all the remaining criteria.

Stage 2: Concordance and discordance matrices.

They are squared matrices of order n, where n is number of alternatives. The generic concordance matrix element c_{kp} (concordance index) between alternatives A_k and A_p is the sum of the weights of all criteria included in the concordance set ($0 \leq c_{kp} \leq 1$) and represents how much A_k is to be preferred to A_p. The generic element d_{kp} (discordance index) of the discordance matrix, instead, measures the maximum gap between performances of A_k and A_p in respect to criteria included in the discordance set. Indicating with y_{ij} the generic element of the weighted normalized decision matrix, d_{kp}, can be expressed as in the Equation (2). Tables 6 and 7 report these two matrices as they result for the case study. For instance, the comparison between alternatives A_1 (retrofit by GFRP) and A_3 (RC jacketing) leads to the following value for the c_{13} and

Table 6
Concordance matrix

	A_1	A_2	A_3	A_4	A_5
A_1	–	0.834	0.761	0.598	0.560
A_2	0.167	–	0.176	0.099	0.176
A_3	0.240	0.825	–	0.624	0.520
A_4	0.403	0.902	0.377	–	0.657
A_5	0.441	0.825	0.481	0.344	–

Table 7
Discordance matrix

	A_1	A_2	A_3	A_4	A_5
A_1	–	0.451	0.139	0.499	0.068
A_2	1.000	–	1.000	1.000	1.000
A_3	1.000	0.374	–	0.752	0.081
A_4	1.000	0.096	1.000	–	0.740
A_5	1.000	0.573	1.000	1.000	–

Table 8
Auxiliary matrix for concordance test

	A_1	A_2	A_3	A_4	A_5
A_1	–	1	1	1	1
A_2	0	–	0	0	0
A_3	0	1	–	1	1
A_4	0	1	0	–	1
A_5	0	1	1	0	–

Table 9
Auxiliary matrix for discordance test

	A_1	A_2	A_3	A_4	A_5
A_1	–	1	1	1	1
A_2	0	–	0	0	0
A_3	0	1	–	0	1
A_4	0	1	0	–	0
A_5	0	1	0	0	–

d_{13} indices: $c_{13} = w_2 + w_3 + w_4 + w_6 + w_7 = 0.761$; $d_{13} = 0.0156/0.1123 = 0.139$.

$$d_{kp} = \frac{\max\limits_{j \in D_{kp}} \left| y_{kj} - y_{pj} \right|}{\max\limits_{j} \left| y_{kj} - y_{pj} \right|} \tag{2}$$

Stage 3: Outranking relations and identification of the preferred alternative.

To know if the outranking relation $A_k \rightarrow A_p$ is true or false, it is necessary to set two threshold values c and d for the concordance indices and discordance indices, respectively. These values have to be fixed *a priori* by the decision maker. Sometimes c and 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 $c_{kp} \geq c$ (in this case the concordance test is passed) and $d_{kp} \leq d$ (the discordance test passed) simultaneously result.

For the case study application, the mean value of the concordance and discordance indexes ($c = 0.478$; $d = 0.689$) is first assumed for c and d. To make easily understandable the results given by the comparison among the elements in the matrices of concordance and discordance, two auxiliary Boolean matrices are written. The first one is a 5 by 5 matrix obtained by substituting each element c_{kp} in the concordance matrix with the value 1 if the concordance test is passed ($c_{kp} \geq c$) and 0 otherwise (Table 8). The second matrix is again squared by order 5 and is obtained by substituting at each element d_{kp} of the discordance matrix, the value 1 if the discordance test is passed ($d_{kp} \leq d$), and 0 otherwise (Table 9). Alternatives outranked by at least one of the others have to be eliminated. After that, if only one option remains, it is defined as the preferred of the set. Vice versa, all the alternatives remaining in the set have to be defined as “preferable” to the others. For the numerical application shown here, alternatives are ranked using a concordance–discordance (aggregate dominance) Boolean matrix obtained by an element-to-element product of the concordance and discordance matrices. This new matrix is such that if the element in position (k, p) results in being equal to 1, it means that for the outranking relation $A_k \rightarrow A_p$ both concordance and discordance tests passed and the relation $A_k \rightarrow A_p$ is to be considered true; if it is equal to 0, it means that at least one of the two tests failed. This matrix is reported in Table 10. The absence of any null element in the first row indicates the retrofit by GFRP (A_1) as the preferred alternative intervention among the considered ones. Vice versa, the solution involving the steel bracing of the building (A_2) results outranked by each other and thus results in being the worst one.

Generally speaking, the number of selected alternatives strongly depends on the threshold values c and

Table 10
Aggregate dominance matrix

	A_1	A_2	A_3	A_4	A_5
A_1	–	1	1	1	1
A_2	0	–	0	0	0
A_3	0	1	–	0	1
A_4	0	1	0	–	0
A_5	0	1	0	0	–

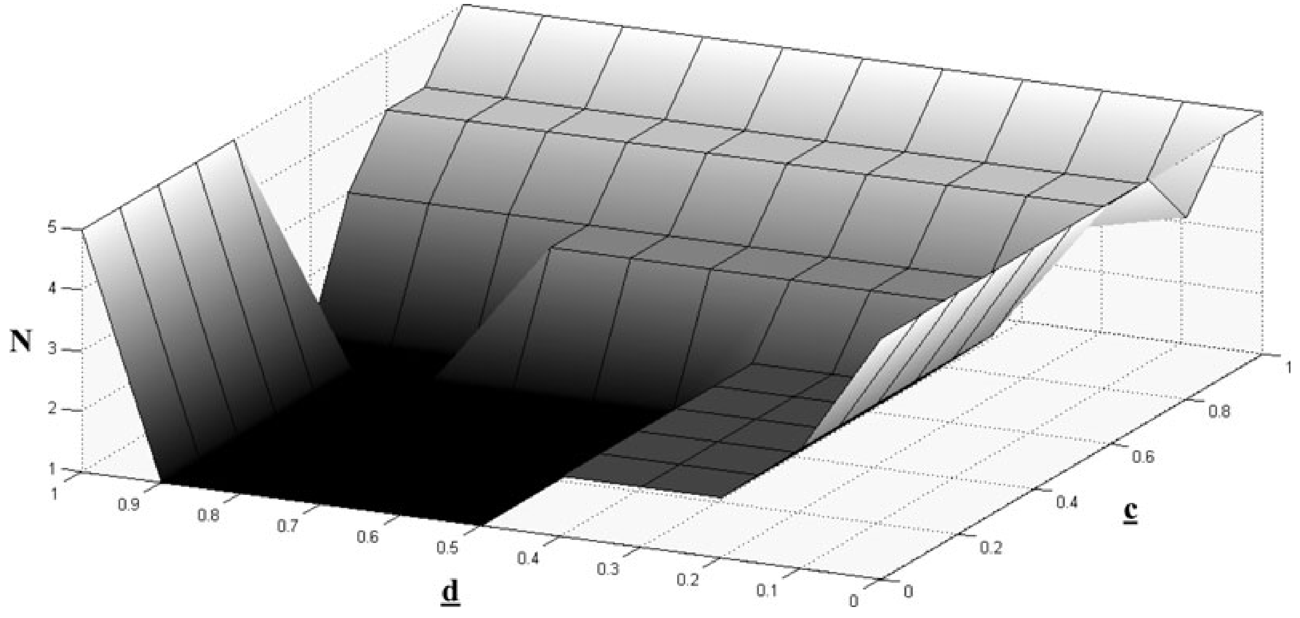

Fig. 1. Influence of threshold values c and d on the number (N) of alternatives belonging to the kernel.

d fixed by the decision maker. For the example under exam, Figure 1 helps better understand that. The represented surface is determined associating to each of 121 different couples of values (c, d), the corresponding number of preferred alternatives, selected via ELECTRE. One can observe that when 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 c and d far from these intervals, instead, the number of selected alternatives quickly increases. This can be explained by observing that a bigger value of threshold c and a lower value of d (i.e., a higher requirement for going to a conclusion, a higher significance of this conclusion) lead to a lower number of outranking relations; it is more difficult to differentiate solutions and the kernel results to be larger. In other words, the method is such that higher significance goes with less reduced kernel, and a reduced kernel goes with a lower significance of the results.

5.3 MAUT method

The MAUT (multi-attribute utility theory; Edwards and Newman, 1982) method is a decision analytic technique, which allows for the coexistence of judgment and objective measurement to capture the multidimensional nature of decision problems. After evaluating the alternatives in respect to 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. 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 a utility measure.

After weighting the obtained matrix by multiplying each value for the corresponding criterion weight, the matrix in Table 11 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 is $A_1 > A_3 > A_5 > A_4 > A_2$.

5.4 PROMETHEE method

The preference ranking organization method for enrichment evaluations (PROMETHEE) was proposed by Brans and Vincke in 1985. It is based on the comparison of alternatives considering the deviations that alternatives show according to each criterion. Given its structure, the method allows the direct operation on the variables included in the decision matrix, without requiring any normalization. On the other hand, it is necessary that each criterion is of the benefit-type. This

Table 11
Weighted normalized decision matrix according to MAUT method

	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

condition is always easily attainable by multiplying by −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 the 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, as a function of the deviation $x = a_{kj} - a_{pj}$ between the performances of A_k and A_p in respect to 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 larger than zero, closer to 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. The function type I ($p(x) = 1$ for each value of $x > 0$), called "usual criterion," is the simplest one and does not require any intervention of the DM. The function II ("quasi-criterion"), instead, requires that 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 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 $x > m$), called "criterion with linear preference," through the definition of the parameter m, allows the DM to express 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. Figure 2 shows these three types of preference functions. For other, more complex, function types, please refer to Brans and Vincke (1985).

With reference to the case study the method was applied seven times to investigate about the influence on the final result of all the involved parameters and choices. Table 12 briefly describes the peculiarities of each application, in which the same type of preference function (I, II, or III) 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.

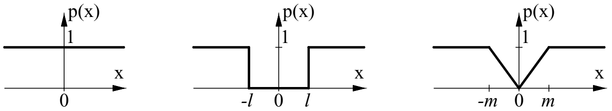

Fig. 2. Criteria of type I (*left*), type II (*middle*), and type III (*right*).

After alternatives A_k and A_p have been evaluated in respect to each criterion, it is possible to evaluate the so-called preference index $\pi(A_k, A_p)$ defined as follows:

$$\pi\left(A_k, A_p\right) = \sum_{j=1}^{m} w_j P_j\left(A_k, A_p\right) \tag{3}$$

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") $\Phi^+(A_k)$ of each alternative A_k in respect to the others has to be evaluated as in Equation (4) whereas its degree of "weakness" $\Phi^-(A_k)$ ("negative outranking flow") as in Equation (5).

$$\Phi^+\left(A_k\right) = \sum_{p=1}^{n} \pi\left(A_k, A_p\right) \tag{4}$$

$$\Phi^-\left(A_k\right) = \sum_{p=1}^{n} \pi\left(A_p, A_k\right) \tag{5}$$

The version of the method generally referred to as PROMETHEE I allows ranking the alternatives according to these rules:

Table 12
Applications of PROMETHEE

Application number	*Assumed preference function*	*Assumed parameter value*
1	I	–
2	II	$l = 10\%$
3	II	$l = 25\%$
4	II	$l = 50\%$
5	III	$m = 10\%$
6	III	$m = 25\%$
7	III	$m = 50\%$

- A_k is to be preferred to A_p if $\Phi^+(A_k) > \Phi^+(A_p)$ and $\Phi^-(A_k) < \Phi^-(A_p)$; also if $\Phi^+(A_k) > \Phi^+(A_p)$ and $\Phi^-(A_k) = \Phi^-(A_p)$ or if it results $\Phi^+(A_k) = \Phi^+(A_p)$ and $\Phi^-(A_k) < \Phi^-(A_p)$;
- A_k is indifferent to A_p if $\Phi^+(A_k) = \Phi^+(A_p)$ and $\Phi^-(A_k) = \Phi^-(A_p)$;
- A_k and A_p are incomparable otherwise.

By indicating with $A_k \to A_p$, the outranking of A_k to A_p, the results of PROMETHEE I method for the case study can be briefly reported as follows (the several values of Φ^+ and Φ^- for each alternative and each application done are not reported for the sake of brevity):

Application 1 (function type I): $A_1 \to A_3 \to A_2$; $A_1 \to A_4 \to A_2$; $A_1 \to A_5 \to A_2$; A_3, A_4, and A_5 noncomparable.

Application 2 (function type II, $l = 10\%$): $A_1 \to A_5 \to A_4 \to A_2$; $A_3 \to A_2$; A_1 and A_3, A_3 and A_4, A_3 and A_5 noncomparable.

Application 3 (function type II, $l = 25\%$): $A_1 \to A_4 \to A_2$; $A_5 \to A_4$; $A_3 \to A_2$; A_1 and A_3, A_3 and A_4, A_3 and A_5, A_1 and A_5 noncomparable.

Application 4 (function type II, $l = 50\%$): $A_1 \to A_4 \to A_2$; $A_5 \to A_2$; $A_3 \to A_2$; A_1 and A_3, A_3 and A_4, A_3 and A_5, A_1 and A_5, A_4 and A_5 noncomparable.

Application 5 (function type III, $m = 10\%$): $A_1 \to A_5 \to A_4 \to A_2$; $A_3 \to A_2$; A_1 and A_3, A_3 and A_4, A_3 and A_5 noncomparable.

Application 6 (function type III, $m = 25\%$): $A_1 \to A_5 \to A_4 \to A_2$; $A_3 \to A_2$; A_1 and A_3, A_3 and A_4, A_3 and A_5 noncomparable.

Application 7 (function type III, $m = 50\%$): $A_1 \to A_4 \to A_2$; $A_5 \to A_2$; $A_3 \to A_2$; A_1 and A_3, A_3 and A_4, A_3 and A_5, A_1 and A_5, A_4 and A_5 noncomparable.

Only the first application (carried out using the simplest preference function type) leads to select one solution (A_1) dominating all the others. No application leads, instead, to a complete ranking of the alternatives. The particular value chosen for the threshold parameters l (for function type II) and m (for function type III) has a clear influence on the results: 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 (due to the increasing number of noncomparable alternatives).

Very often the PROMETHEE I method only leads to a partial classification of the alternatives because generally two or more alternatives result in noncomparability. If one is interested to have a total classification of options, the use of a different version of the method, called PROMETHEE II, is needed. The latter defines a net outranking flow $\Phi(A_k)$ to each alternative as in Equation (6) and ranks the options assuming that A_k is to be preferred to A_p if $\Phi(A_k) > \Phi(A_p)$, and indifferent if $\Phi(A_k) = \Phi(A_p)$. In this way, the method always allows ranking the alternatives in a complete manner. Obviously, the preferred alternative is the one having the greatest value of $\Phi(A_k)$.

$$\Phi\,(A_k) = \Phi^+\,(A_k) - \Phi^-\,(A_k) \tag{6}$$

For the case study, the Φ values lead to the same final ranking for each of the seven applications done ($A_1 \to A_3 \to A_5 \to A_4 \to A_2$), not highlighting any significant influence of the particular chosen preference function and fixed parameters value.

5.5 VIKOR method

This method (*VlseKriterijumska Optimizacija I Kompromisno Resenje*, VIKOR, by Opricovic, 1998) ranks the alternatives $A_i (i = 1, 2, \ldots, n)$ according to the value of three scalar quantities (S_i, R_i, and Q_i) to be calculated for each option. For each criterion ($j = 1, 2, \ldots, m$), the best $a_j{}^*$ and worst $a_j{}^-$ performances among all the alternatives first have to be determined. Then S_i, R_i, and Q_i values can be assessed as in Equations (7) and (8). The meaning of S^*, S^-, R^*, and R^- is indicated in Equation (9):

$$S_i = \sum_{j=1}^{m} \frac{w_j(a_j^* - a_{ij})}{a_j^* - a_j^-}; \quad R_i = \max_j \left[\frac{w_j(a_j^* - a_{ij})}{a_j^* - a_j^-} \right] \tag{7}$$

$$Q_i = \upsilon \frac{S_i - S^*}{S^- - S^*} + (1 - \upsilon) \frac{R_i - R^*}{R^- - R^*} \tag{8}$$

$$\begin{aligned} S^* &= \min_i S_i; \qquad S^- = \max_i S_i; \\ R^* &= \min_i R_i; \qquad R^- = \max_i R_i \end{aligned} \tag{9}$$

The parameter υ is fixed by the decision maker in the [0, 1] interval giving a different weight of importance to each addend into the Q_i expression. Practically, if one assumes $\upsilon > 0.5$, he gives 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 exhibited by the alternatives in respect to 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 2, the S_i and R_i values in Table 13 are evaluated. In the same table, the S^*, S^-, R^*, and R^- values are also reported. Finally, the Q_i value is determined for each option, assuming the value 0.5 for υ.

Table 13

S_i, R_i, and Q_i values ($\upsilon = 0.5$) 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 VIKOR method ranks the alternatives according to the Q_i values. The preferred option (A') is that having the smallest Q_i value, but only if the following two acceptance criteria are both satisfied:

1. *Acceptable advantage*: It should be $Q(A'') - Q(A') \geq DQ$, where A'' is the alternative having the second best Q_i value and DQ is taken as equal to the ratio $1/(n-1)$ depending on the number n of alternatives.
2. *Acceptable stability in decision making*: Alternative A' should also be the best in terms of S_i value and/or R_i value.

If one of these conditions is not satisfied, it is not possible to directly select the preferred 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 $A', A'', \ldots, A^{(N)}$ 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 13 relative to the case study, 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 [0, 1] interval to investigate the actual influence of such a parameter on the results. For the application under exam the final ranking result is independent from the chosen υ. This is because the classifications that may be obtained by considering only the term $(S_i - S^*)/(S^- - S^*)$, accounting for the global satisfaction of criteria, and only the term $(R_i - R^*)/(R^- - R^*)$, accounting for the worst performance of each alternative in respect to the single criterion, are the same. Therefore, linearly combining the two terms through the parameter υ, the final ranking has to be necessarily the same, for any value of υ. Because it results (for $\upsilon = 0.5$):

$$Q(A_3) - Q(A_1) = 0.143 < 0.250 = \frac{1}{5-1} = DQ \quad (10)$$

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 close and it is not possible to distinguish the preferred one between the two. Therefore, even if the second criterion is satisfied (A_1 is the preferred 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 and A_3 as a group of compromise solutions. It has been verified that the particular value given to υ has no influence also for the final method response.

Conversely to the ELECTRE method, according to VIKOR method, to select only one alternative as the "winner," it may be useful to repeat its application to the subgroup of solutions obtained, eliminating the last ranked alternatives. With reference to the case study, the application done without considering the A_2 alternative leads again to the ranking $A_1 > A_3 > A_5 > A_4$ but both acceptability criteria results are satisfied, finally individuating A_1 as the preferred solution of the initial group.

6 RESULTS AND DISCUSSION

Table 14 summarizes all the above obtained information about the applicability of each examined MCDM method to the seismic retrofit decision problem. All the methods result suitable, even if sometimes requiring artifices (e.g., MAUT) except WSM and WPM methods, which are more appropriate for problems involving variables having homogeneous dimensions and criteria all of the same type (benefit or cost).

With reference to the case study, Table 14 also indicates, when available, the results each method leads to, in terms of ranking of alternatives. It may be useful analyzing the results also looking at the decision matrix (Table 2) and criteria weights (Table 1). Table 15 summarizes some information included in them reporting,

Table 14

Applicability (using an artifice*) of the examined MCDM methods 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

Table 15

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

Ranking	C_1 *Installation cost (0.073)*	C_2 *Maintenance cost (0.172)*	C_3 *Duration works (0.073)*	C_4 *Compatibility (0.280)*	C_5 *Labor specialization (0.026)*	C_6 *Foundations intervention (0.201)*	C_7 *SD risk (0.035)*	C_8 *DL risk (0.141)*
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.

for each criterion, the corresponding weight of importance and the ranking of the alternatives as it would result according to that criterion only. 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 14) lead to A_1 as the preferred retrofit option, with the exception of PROMETHEE I that only allows a partial ranking.

The following remarks can be made about each examined method.

The MAUT method, as said above, 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 performance 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 nonhomogeneous 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 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 noncomparable 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 types. 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. Although the vector normalization may generally lead to different normalized values depending on the particular unit of measure used for the original data, it is not the case of the decision problem under exam. Opricovic and Tzeng (2004) highlight such differences occurring when the two expressions f and ϕ of a same quantity using two different units of measure are related as $\phi = \alpha f + \beta$ (where α is larger than zero and β may assume any value). For β equal to zero (which represents the most common case for the decision problem under exam), the unit of measure has no influence on the normalized value.

After the final rankings 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.

It is worth noting that the comparison among the considered methods could be enriched performing a sensitivity analysis to assess the stability of the final result each method leads to. This analysis is generally addressed to determine what is the smallest change in current weights of criteria, which can alter the existing ranking of the alternatives. On the other hand, it aims to evaluate how critical the various performance measures of the alternatives are in the ranking of the alternatives (Triantaphyllou, 2002).

7 CONCLUSIONS

This study may be of help in the case of managing one or more existing buildings to be upgraded to resist seismic actions. In fact, the achieved structural performance is not the only criterion to be considered in choosing the preferred retrofit solution. There are instead several other technical, social, and economical aspects the practitioner has to deal with. MCDM methods clearly may help in the matter, although the large literature on the topic does not allow an easy determination of which procedure is the more appropriate. The presented study sheds some light on this issue comparing several well-known decision methods to a specific case study. After investigating the actual applicability and effectiveness of seven widely adopted MCDM methods, 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. (Note that, in principle, a decision-making method could be used to choose among the MCDM methods considered; nevertheless, it would lead to the *decision-making paradox* discussed by Triantaphyllou and Mann, 1989.)

Table 16 reports a brief comparison of the MCDM methods found to be applicable to the focused decision problem, aiming to highlight the main differences in terms of number of parameters to be fixed by the decision maker, the ease in setting this parameter, and the kind of results each method generally leads to.

The MAUT method, applied in its simple 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 (Mourits et al., 2006). 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 be 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

Table 16
Synthetic comparison of the considered MCDM methods under specific points of view

Method	*Number of parameters fixed by the DM**	*Ease in fixing parameters*	*Results****
TOPSIS	0	N/A	Complete ranking
ELECTRE	2	Moderate to low	Subset of preferred options
MAUT	0	N/A	Complete ranking
VIKOR	1	Good	Complete ranking or subset of options
PROMETHEE I	0 or 1**	Good, if needed	Partial ranking
PROMETHEE II	0 or 1**		Complete ranking
	Good, if needed		

*Except for those needed to define the decision matrix and criteria weights, common to all the methods.

**When the preference function types I, II, or III are used.

***It indicates the type of results generally the method leads to.

does not have these characteristics. 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 c and 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. These two methods result to be, among those investigated, the most suitable to the focused decision task, because of their capability to manage each kind of judgment criteria and variables, the clarity of their results, and the reduced difficulty to deal with parameters and choices they involve.

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