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University School for Advanced Studies IUSS, Pavia, Italy

ABSTRACT

The evaluation of retrofitting alternatives through multi-criteria decision making (MCDM) approaches allows an optimal selection based on a ranking system. This rank depends on evaluation parameters that assess particular aspects of the retrofitting options and influence the selection of the most advantageous alternative. Moreover, when integrating uncertainty of the input parameters into the procedure, the outcome may be altered and the rank order notably different with respect to a deterministic MCDM implementation. This paper examines an MCDM approach applied to four retrofit alternatives proposed for a case-study building, starting from a deterministic perspective. Subsequently, the MCDM method is extended to consider random variables, in order to compare and understand the influence of uncertainty of the input parameters in the selection of retrofit alternatives for the same building. To ensure that accurate and representative data was used in the stochastic implementation, an ad-hoc survey was developed to collect the views from relevant parties involved in the field of seismic retrofitting interventions, particularly those with an academic/research or practice/industry background. The outcomes of the study are believed to serve as useful guidelines and as a future reference for practitioners in the field of structural retrofitting, on how to select the most convenient retrofit alternative for an existing building.

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KEYWORDS

RC building; retrofit alternatives; evaluation parameters; MCDM; stochastic analysis

1. Introduction

When an existing building is vulnerable to earthquake hazard, the application of an adequate retrofitting intervention reduces its vulnerability by improving its seismic performance. This allows the building to withstand the expected seismic demands and also meet the requirements of local building codes. In general, there can be many retrofit interventions capable of reducing the building's seismic vulnerability by addressing the primary structural deficiencies identified during structural assessment. The various intervention options comprise a diverse range of techniques and building materials. For instance, ATC-40 (Applied Technology Council (ATC) 1996) provides a vast range of interventions, including traditional approaches, such as structural strengthening and stiffening, and more advanced techniques, such as base isolation, supplemental energy dissipation systems or mass reduction.

When several retrofitting alternatives are deemed feasible, the main issue becomes how to determine the most convenient one for an existing building. A general approach is to make a selection based solely on the structural performance, which might be estimated using either simplified or refined analyses. Past studies, such as the ones by Thermou and Elnashai (Thermou and Elnashai 2006) or Foo and

CONTACT Wilson Wladimir Carofilis Gallo wilson.carofilis@iusspavia.it University School for Advanced Studies IUSS, Palazzo del Broletto, Piazza della Vittoria, 15, 27100 Pavia PV, Italy

Davenport (Foo and Davenport 2003), adopted purely structural criteria to retrofit buildings by increasing their lateral capacity and stiffness. However, as highlighted by O'Reilly and Sullivan (O'Reilly and Sullivan 2018), strengthening and stiffening of a structural system can boost a building's lateral strength capacity but at the same time may considerably increase the expected annual losses (EAL), in monetary terms, as observed in the case of old reinforced concrete (RC) frame Italian buildings. More recently, Carofilis *et al.* (Carofilis et al. 2020) conducted a seismic risk analysis for three existing school building typologies and proposed several retrofit interventions for each building, which were comparatively evaluated using cost-benefit analysis. The procedure adopted in such a study aimed to assess the performance of the identified retrofit alternatives using EAL and collapse vulnerability as the decision metrics. The outcomes were further compared using cost-benefit analysis, implementing the approach described by Cardone *et al.* (Cardone, Gesualdi, and Perrone 2017), to determine whether the alternatives were feasible or not from a financial viewpoint. Nevertheless, while being focused on monetary losses and the safety of building occupants, which are also the two underlying criteria of the Italian seismic risk classification framework *Sismabonus* (Cosenza et al. 2018), the study by Carofilis *et al.* (Carofilis et al. 2020) did not address other important evaluation parameters, which are crucial for a more comprehensive selection of retrofit interventions. For example, the level of invasiveness, execution time, architectural impact, amongst other aspects, play a key role in the final selection of the most convenient seismic retrofit configuration, as highlighted by Calvi (Calvi 2013), Caterino *et al.* (Caterino et al. 2008), and Santarsiero *et al.* (Santarsiero et al. 2021).

These parameters, also known as decision variables (DVs), can be considered within different evaluation procedures to rank a set of retrofit options. Recently, Carofilis *et al.* (Carofilis, Gabbianelli, and Monteiro 2021) examined several of these evaluation methodologies, based on different criteria for the selection of retrofit options for a case-study RC school building. The study concluded that the results of the different methods are greatly influenced by the level of refinement and the number of criteria considered. The study also observed that the evaluation methodologies that considered criteria only related to the structural performance produced similar rankings in terms of retrofit options, whereas when only cost-related criteria were considered, the results changed significantly. Carofilis *et al.* (Carofilis, Gabbianelli, and Monteiro 2021) also highlighted that when other variables are integrated into the analysis (e.g. those of a social, aesthetic, or practical nature), the outcome will again change significantly, leading to a very different optimal choice being identified. This happened particularly when using the multi-criteria decision-making (MCDM) framework (Caterino et al. 2008), which allows the analyst to include multiple DVs and decide the relative importance of each DV.

MCDM is a decision-support process used in many fields of engineering to evaluate and compare a set of alternatives when many DVs are involved (Caterino et al. 2008). Typically, it is a deterministic procedure that requires users to specify the importance weights of each DV; however, it can be extended to account for stochastic DVs, as studied by Kolios *et al.* (Kolios et al. 2016), for example. A stochastic MCDM version, unlike the deterministic one, can thus account for the uncertainty in the DV weights by treating them as random variables, characterised by a certain probabilistic distribution.

Given the above, this study aims to evaluate both deterministic and stochastic implementation approaches of the MCDM framework, as well as determining the impact of DV uncertainty, in the identification of the optimal retrofit strategy of existing RC buildings in Italy. This will provide a comprehensive and useful perspective to practitioners, or decision-makers in general, in the field of structural retrofitting. For what concerns the stochastic approach, an ad-hoc questionnaire was designed and distributed to relevant parties involved in seismic retrofitting to quantify and evaluate the relative DV weights and their associated uncertainty within the Italian building retrofitting context.

2. Multi-Criteria Decision-Making Methods

MCDM frameworks evaluate different DVs using an analytical hierarchy process (AHP) (Saaty 1980) that ranks, typically in a deterministic fashion, a set of alternatives based on the characteristics/performance of the diverse options. On the other hand, a stochastic MCDM implementation can integrate the uncertainty of the DVs by considering them as random input variables. This stochastic modelling starts by adopting the deterministic approach and, through simulation, generates different scenarios where the alternatives are ranked. Unlike the deterministic approach, the stochastic one provides a probability of the rank observed for the different retrofitting strategies.

2.1. Deterministic MCDM

The deterministic MCDM method adopted in this study is based on that described in Caterino *et al.* (Caterino et al. 2008), who examined four retrofit alternatives for an existing RC residential building. Caterino *et al.* (Caterino et al. 2008) explored technical and social parameters known to influence the selection of retrofit alternatives. In other recent studies, Gentile and Galasso (Gentile and Galasso 2019; Gentile, Galasso, and Eeri 2020) evaluated an RC school building via the deterministic MCDM, adopting some of the same DVs previously used by Caterino *et al.* (Caterino et al. 2008) but assuming different relative importance, i.e. weights, of the variables. These evaluation criteria are integrated and listed in Table 1. To perform the MCDM analysis, the AHP introduced by Saaty (Saaty 1980) was used. In addition to the AHP, the "technique for order preference by similarity to ideal solution" (TOPSIS), defined by Hwang and Yoon (Hwang and Yoon 1981), was applied to rank the assessed options according to their relative closeness to an ideal alternative. This ideal alternative represents the option with the most convenient features, for example, best performance and lowest cost. Nevertheless, the closeness to an ideal solution depends on the weights given to each DV by the analyst, as well as to their specific values, as further explained in the following sections. Furthermore, these aspects are linked to the building's typology, the perspective of whoever is carrying out the retrofitting, the building owner's budget/needs, and the configuration of the retrofit interventions.

Given the large variability of the evaluation features, a sensitivity analysis of the relevance and impact of the difference DVs on the results of the MCDM methodology, as discussed in Section 2.1.2, becomes useful and is conducted later in this work.

2.1.1. Description of the Method

The MCDM process adopted by Caterino *et al.* (Caterino et al. 2008) and Gentile and Galasso (Gentile and Galasso 2019; Gentile, Galasso, and Eeri 2020) starts by applying the AHP, which assigns weights to each of the DVs. The weights or importance given to these variables are based on a scale of relative importance presented in Saaty (Saaty 1980). Once the weights are assigned to each DV a preference matrix *A* is generated. The preference matrix, *A*, is a square matrix of *n* rows and *n* columns, where n represents the number of DVs (i.e. C_1, C_2, . . ., C_i, . . ., C_n). Once the preference matrix *A* has been defined, the eigenvector can be obtained, Caterino *et al.* (Caterino et al. 2008) indicates the steps to

Table 1. Evaluation criteria to assess retrofitting options for buildings.

Group	Decision Variable	Reference Study(ies)
Economic/Social	Installation cost	(Caterino et al. 2008,Gentile and Galasso 2019, Gentile, Galasso, and Eeri 2020)
	Maintenance cost	(Caterino et al. 2008,Gentile and Galasso 2019, Gentile, Galasso, and Eeri 2020)
	Duration of works/disruption of use	(Caterino et al. 2008,Gentile and Galasso 2019, Gentile, Galasso, and Eeri 2020)
	Functional compatibility	(Caterino et al. 2008,Gentile and Galasso 2019, Gentile, Galasso, and Eeri 2020)
Technical	Skilled labour requirements/needed technology level	(Caterino et al. 2008,Gentile and Galasso 2019, Gentile, Galasso, and Eeri 2020)
	Significance of the needed intervention at foundations	(Caterino et al. 2008,Gentile and Galasso 2019, Gentile, Galasso, and Eeri 2020)
	Significant Damage risk	(Caterino et al. 2008)
	Damage Limitation risk	(Caterino et al. 2008)
	Loss (Intensity-based)	(Gentile and Galasso 2019, Gentile, Galasso, and Eeri 2020)

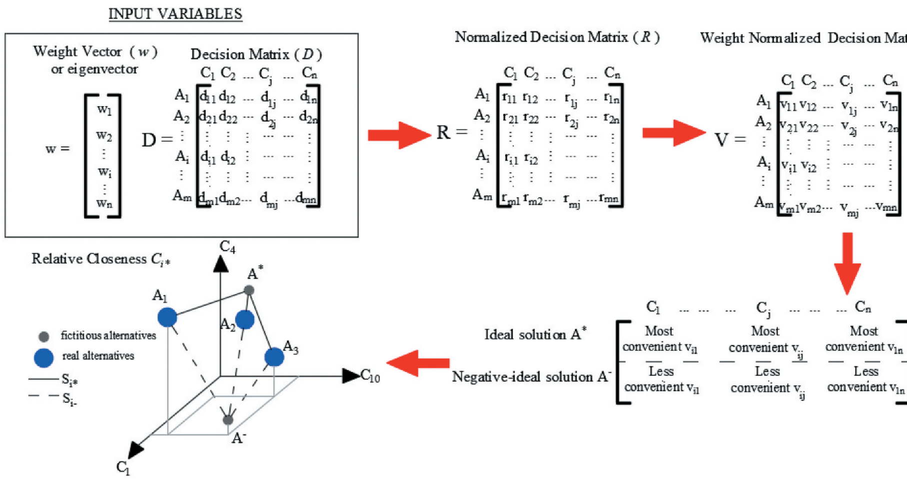

Figure 1. Procedure to carry out the deterministic MCDM.

determine the weight vector from a preference matrix. As shown in Fig. 1, this eigenvector is also known as the weight vector *w*, representing the relative importance of each DV, hence the DV with the highest relative importance will have a larger impact on the ranking of the retrofit alternatives.

After the weight vector *w* is determined, the decision matrix *D* can be assembled; these two variables represent the input variables for the MCDM as illustrated in Fig. 1. The decision matrix *D* contains the values of all *m* retrofit alternatives with respect to the *n* evaluation aspects. These are indexed as d_{ij} in Fig. 1, where *i* corresponds to a retrofit alternative and *j* to a DV. For example, d_{ij} could refer to a repair cost in € or to a repair time in days, highlighting that the DVs might include different units. Consequently, the matrix *D* needs to be normalised using Equation 3, which results in the normalised decision matrix *R*. To consider the relative importance of the evaluation criteria, the component of each eigenvector *w* is multiplied by the elements of each column of the matrix *R* (e.g. $v_{j1} = r_{j1}{}^{*}w_1$, component w_1 multiplies all elements in column r_{j1}), resulting in the weight-normalised decision matrix *V*.

$$r_{ij} = \frac{d_{ij}}{\sqrt{\sum_{k=1}^{n} d_{kj}^2}} \tag{3}$$

From the weight normalised decision matrix *V*, the most-ideal (A^*) and least-ideal (A^-) solutions are determined, corresponding to the highest and lowest values according to the DV (Fig. 1). These solutions are intrinsically related to the criteria used for the DVs. For example, in terms of cost, A^* is defined as the lowest cost and A^- as the highest one. On the other hand, in the case of lateral strength, A^* is picked as the highest lateral strength and A^- as the lowest one.

Finally, the distances to the most-ideal and least-ideal solutions (S_{i*} and S_i) are calculated through Equation 4. Figure 1 illustrates the meaning of these distances, which represent the intervals of the set of retrofit options with respect to the evaluation parameters. The values of S_{i*} and S_{i-} are used to determine the relative closeness, C_{i*}, using Equation 5. The relative closeness represents the distance of a particular retrofit option to the ideal retrofit solution and the retrofit option with the highest C_{i*} is selected as the most effective option for the set of DVs considered.

$$S_{i*} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_{j*}\right)^2}; \quad S_{i-} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_{j-}\right)^2} \text{ (Distances } S_{i*} \text{ and } S_{i-}) \tag{4}$$

$$C_{i*} = \frac{S_{i-}}{S_{i*} + S_{i-}} \text{(Relative closeness)} \tag{5}$$

2.1.2. Sensitivity Analysis

Given the sensitivity of the method to the selected DVs and their corresponding weights, as well as to the uncertainty in these values, a parametric analysis is useful to better understand the advantages and shortcomings when using MCDM. Caterino *et al.* (Caterino et al. 2008), for instance, conducted a sensitivity analysis to assess the stability of the optimal solution to changes in the values of the weight vector. Intervals for each DV, referring to both the weight vector and the decision matrix, were estimated and they indicated how much the relative weight of a DV can be modified without affecting the rank of the set of alternatives. Variables to which no intervals were assigned were considered robust to changes, i.e. arbitrary changes to their weight did not affect the obtained ranking. The sensitivity analysis considered the minimum absolute change causing the variation of the best solution, estimated through the absolute-top (AT), Equation 6. Additionally, the analysis relied on the percent-top (PT), Equation 7, which was appropriate to survey the best solution changes. The sensitivity of the MCDM method to each DV was evaluated using the reciprocal of PT and it was frequently observed that the most influential DV was the one with the highest relative weight (Caterino et al. 2008).

$$AT = min(abs(interval - w_i)) \tag{6}$$

$$PT = \frac{AT * 100}{w_i} \tag{7}$$

Moreover, it has also been observed that a large number of DVs (more than seven) increases the complexity of the analysis. This means that assigning values to the preference matrix may need several iterations to obtain a consistency index within the defined limits. Additionally, when the number of retrofit alternatives is lower or equal to three, the analysis reduces in its complexity. As such, three can be considered as the minimum number of retrofit alternatives to consider the MCDM method applicable. Otherwise, to avoid the evaluation of several DVs, the selection of the ideal solution could rely only on one or two features (i.e. cost-benefit analysis and structural performance).

2.2. Stochastic MCDM

2.2.1. Overview of the Stochastic Approach

MDCM with stochastic inputs turns the deterministic approach into a stochastic version by incorporating the uncertainty of the input variables (i.e. weight vector w and decision matrix D). This methodology, used by Kolios *et al.* (Kolios et al. 2016; Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014) in a study of offshore wind turbines, can be extended to the MCDM assessment of retrofit alternatives for buildings as it also uses the TOPSIS and AHP implemented in Caterino *et al.* (Caterino et al. 2008).

The methodology follows the process described by the flowchart in Fig. 2, which requires the mean and standard deviations of the weight vector w and decision matrix D defined by a statistical distribution. As expressed by Kolios *et al.* (Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014), Monte Carlo simulation is particularly useful to represent the random nature of stochastic variables. This simulation allows one to perform numerous iterations of analysis in order to quantify results. As mentioned previously, the decision matrix contains the specific values of each DV (i.e. costs, downtime, losses, etc.) associated with each alternative. In the study of Kolios *et al.* (Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014), the input stochastic variables were statistically characterised from the best fit of the data collected for each DV through a survey that gathered the opinion of professionals in the field of offshore wind turbines.

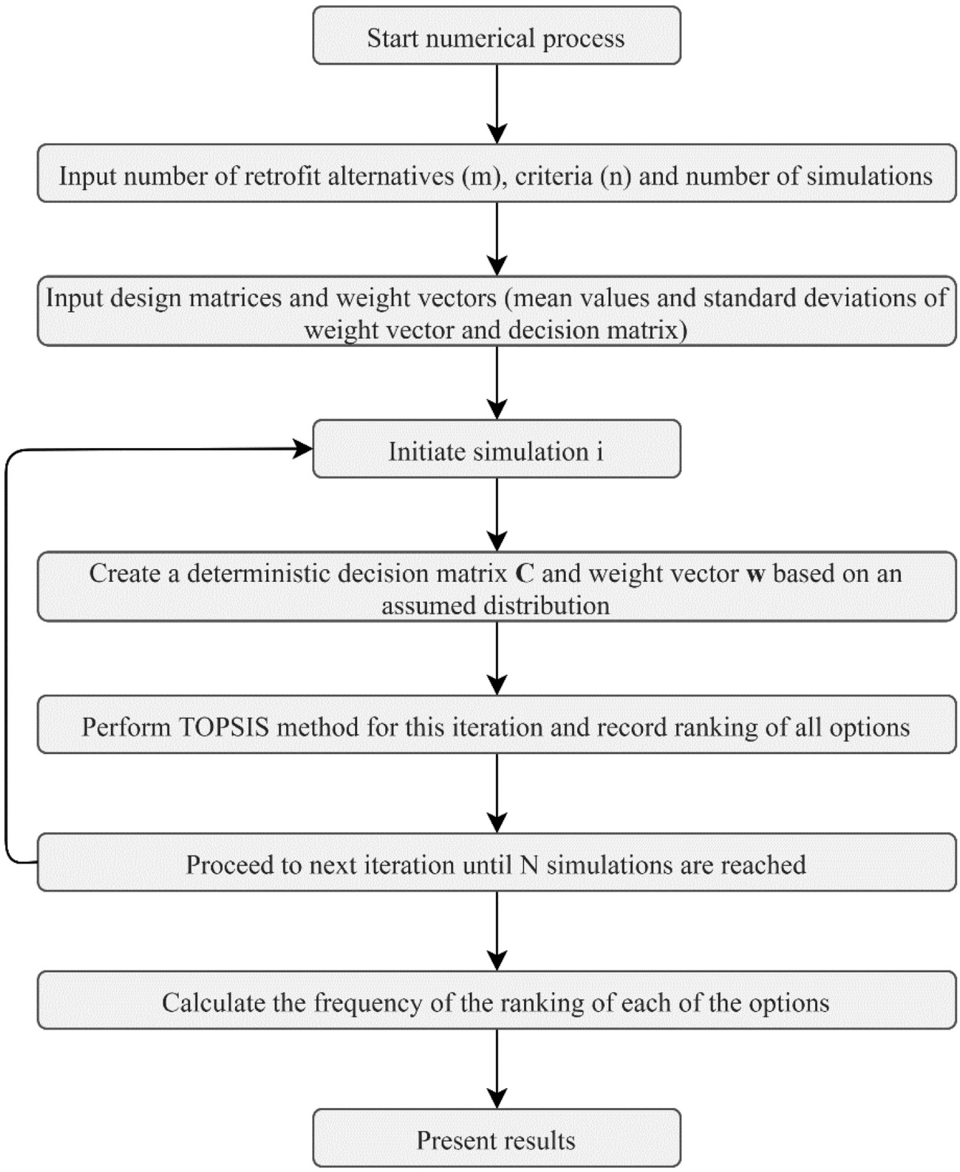

Figure 2. Methodology for conducting the stochastic MCDM (Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014).

For each simulation of the procedure described in Fig. 2, a deterministic MCDM analysis (Fig. 1) is carried out, generating a weight vector w and decision matrix D at each iteration according to the probability distribution function assumed for these input variables. This Monte Carlo simulation is repeated N times, where N accounts for the number of iterations (1000 or more iterations produces stable results according to Kolios *et al.* (Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014)). For each iteration, the ranking of the alternatives is stored and, then, for all the retrofit alternatives, the probability of each ranking position is determined. The goal of this simulation is to obtain the most probable ideal and non-ideal alternatives; in other words, the probability of being ranked as the first or best option by the MCDM method.

By adopting the methodology of Fig. 2 in the evaluation of retrofit strategies for buildings, the MCDM analysis does not result in a simple deterministic ranking of the alternatives but provides the probability of each retrofit strategy to rank first. Consequently, the strategy with the highest probability of ranking first, when all sources of uncertainty are considered, is recognised as the most suitable intervention from the set of retrofitting options. Although this procedure has been applied in an engineering context, the assumptions and considerations made by Kolios *et al.* (Kolios et al. 2016; Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014) still need to be revised and evaluated within the context of seismic retrofitting of buildings. For instance, Kolios *et al.* (Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014) assumed that the weight vector w and decision matrix D were normally distributed variables, which simplifies the analysis. Normal distributions have been assumed to represent engineering problems in past studies, such as the ones by Singhal and Kiremidjian (Singhal and Kiremidjian 1996) and Kappos *et al.* (Kappos, Chryssanthopoulos, and Dymiotis 1999). However, other possible variable distributions, or combinations, should be examined.

Furthermore, a parametric analysis was conducted (Kolios et al. 2016; Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014) to evaluate the convergence of the results as a function of the sampling size. A large number of simulations (10,000 or 100,000 iterations, formerly selected for optimum simulation resolution (Kolios et al. 2016; Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014)) proved to be consistent for the ten different alternatives and ten evaluation criteria in the study of Kolios *et al.* (Kolios et al. 2016; Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014). Nevertheless, a lower number of iterations (e.g. 1,000 or 5,000) would be expected to be adequate for consistent results in the case of fewer retrofit alternatives and/or DVs.

Moreover, the decision matrix D and weight vector w used in the studies of Kolios *et al.* (Kolios et al. 2016; Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014) were defined using a scale from 1 to 9, rather than based on direct price tags or direct quantifiers of performance. Consequently, no direct values for the DVs of each alternative were provided. However, for the analysis conducted in this study, real values were adopted in the decision matrix D (i.e. costs are represented by realistic values in Euros; retrofit duration is represented by time in days, etc.) and the uncertainty associated with these values is addressed in the next section, as well as in Section 4.

2.2.2. Characterisation of Uncertainty

When no input stochastic variables are provided (i.e. mean or standard deviations), the stochastic approach can still be implemented starting from a deterministic weight vector w and decision matrix D. In this study the values of the weight vector and the decision matrix were assumed to be normally distributed random variables with a mean equal to their deterministic value. The coefficient of variation for all the variables was assumed to be 0.25. The results of this simplifying assumption will be examined in Section 4.3 when compared to the results obtained from a detailed survey. In addition to the assumed random variable distributions, it was also assumed that all the DVs are independent random variables to simplify the calculation procedure in this study. It is acknowledged that some level of correlation between variables is possible, given that all of the DV values are determined based on the type and amount of material used. While this study assumes that such a correlation level between variables will have little effect on the overall result of the assessment, future studies could investigate the validity of this assumption.

3. Application of MCDM to a Case-Study Building

The case-study building considered for this paper is an existing RC school building of two storeys and one underground portion (stair-case section) as illustrated in Fig. 3. It is located in Isola del Gran Sasso, Italy (Project DPC-ReLUIS 2020-2021). Given the decade of construction of the building (1960–1970), the numerical model was developed, with the software OpenSees (McKenna, Scott, and Fenves 2010), following the recommendations by O'Reilly and Sullivan (O'Reilly and Sullivan 2019) for simulating the structural behaviour of older RC frames in Italy. The flexural elements (i.e. beams and columns) were

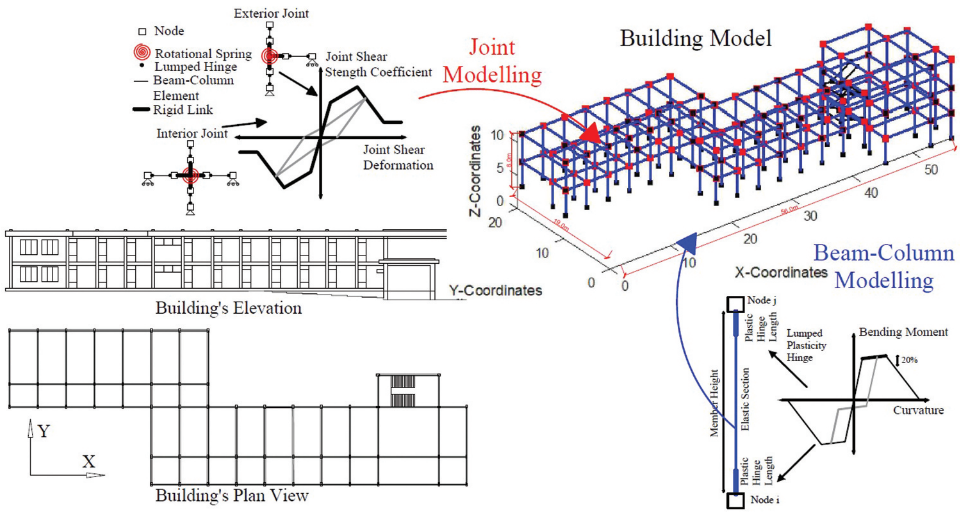

Figure 3. Configuration and modelling of the RC case study school building.

assumed as force-based beam-column elements with a modified Radau plastic hinge integration scheme, as suggested by Scott and Fenves (Scott and Fenves 2006), with lumped plasticity. Furthermore, the potential shear failure of the beam-column joints was modelled using a zero-length rotational spring at their centreline to capture their nonlinear behaviour. The shear behaviour of flexural elements was assumed to be elastic (i.e. any shear failure in the beams or column was determined during post-processing analysis by comparing the shear forces of the flexural elements to their maximum shear capacity). The building model also incorporates a rigid floor slab and considers second-order geometry effects (P-Δ). Regarding damping, a 5% tangent-stiffness-proportional Rayleigh damping model for the periods of the fundamental modes was adopted. The gravity loads acting on the building (i.e. dead and live loads) were defined according to the standards available at the time of construction (O'Reilly and Sullivan (O'Reilly and Sullivan 2019), NTC 2018 (Norme Tecniche Per Le Costruzioni (NTC) 2018), and ReLUIS Project (Project DPC-ReLUIS 2020-2021)).

3.1. Description of Retrofitting Strategies

Carofilis *et al.* (Carofilis, Gabbianelli, and Monteiro 2021) conducted a detailed performance assessment for this case-study school building and highlighted the poor overall seismic performance. Consequently, different seismic retrofitting strategies were proposed to not only boost the building's structural capacity, but also to meet the code-defined limit state requirements of NTC 2018 (Norme Tecniche Per Le Costruzioni (NTC) 2018). Nevertheless, when this cannot be achieved (e.g. due to excessive cost or material requirements) the maximum improvement that can be realistically reached is accepted and evaluated even if the performance is technically less than required by the code (Norme Tecniche Per Le Costruzioni (NTC) 2018). All four retrofitting strategies, illustrated in Fig. 4, meet the drift requirements of NTC 2018 (Norme Tecniche Per Le Costruzioni (NTC) 2018), but present different overall performance as illustrated by Fig. 5. The strategy A1 involves carbon fibre reinforced polymer (CFRP) wrapping of columns along with CFRP bars, as well as CFRP strips placed on beam-column joints. Strategy A2 implements exterior cross-steel braces in some strategic locations of the building. Strategy A3 combines the two previous interventions (i.e. CFRP and steel braces) and, lastly, strategy A4 combines CFRP and viscous dampers placed strategically in the building. Further details of the original and retrofitted configurations, as well as their design, can be found in Carofilis *et al.* (Carofilis, Gabbianelli, and Monteiro 2021).

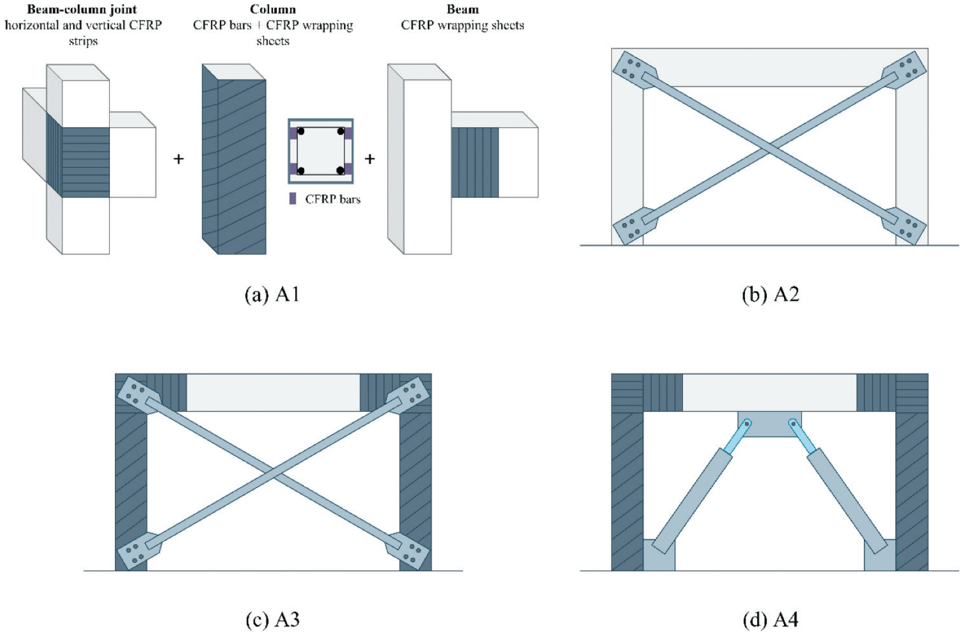

Figure 4. Retrofit interventions proposed for the case study school building, adapted from (Carofilis, Gabbianelli, and Monteiro 2021).

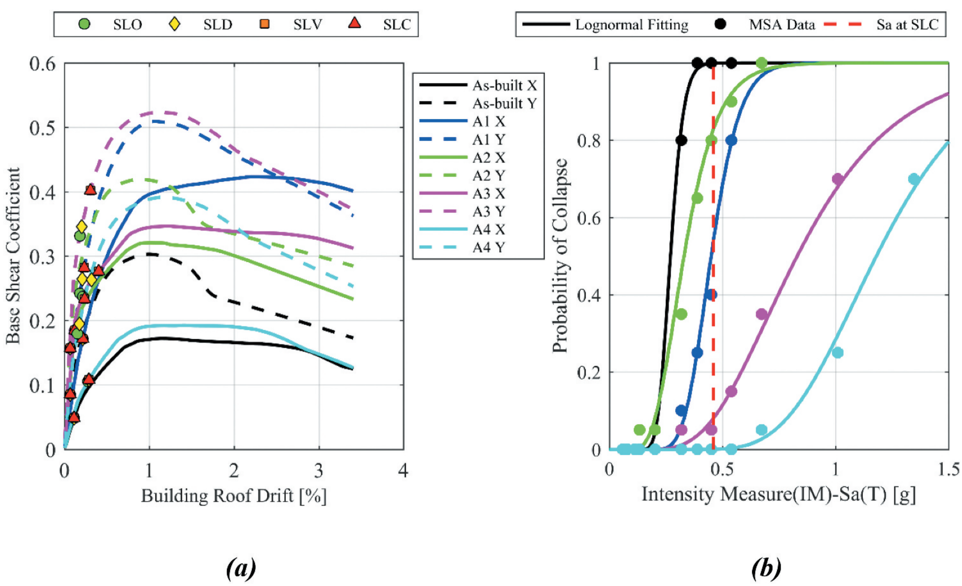

Figure 5. Structural response using the different retrofit strategies: (a) lateral strength and (b) collapse fragility functions, adapted from (Carofilis, Gabbianelli, and Monteiro 2021).

All the four strategies significantly improved the structural performance of the school building for a range of engineering demand parameters (e.g. drift profile and maximum peak floor acceleration), as well as the building's lateral capacity, as illustrated in Fig. 5a. However, as illustrated in Fig. 5b, only two strategies, A3 and A4, substantially reduced the collapse vulnerability of the school building. Indeed, from the structural performance assessment and refined analyses (i.e. collapse vulnerability and loss estimation), A4 was recognised as the most satisfactory retrofit strategy. This alternative complies with the Italian code requirements (NTC 2018 (Norme Tecniche Per Le Costruzioni (NTC) 2018)) for the ultimate and serviceability limit states. Additionally, it improved the overall performance of the school building by reducing its collapse vulnerability and expected losses. In terms of overall seismic performance, this strategy is followed by A3, the second-best improvement in all of the aforementioned aspects. Although A2 and A1 exhibited a better performance in comparison to the as-built configuration, they could not increase the safety against collapse since their collapse margin ratio (i.e. the ratio between the median collapse intensity and the intensity at the collapse prevention limit state) is lower than unity (FEMA P695 2009). Further analyses and details related to the seismic performance and loss estimation of the different retrofitted configurations can be found in Carofilis *et al.* (Carofilis, Gabbianelli, and Monteiro 2021).

3.2. Assessment of Retrofit Strategies Using Deterministic MCDM

The deterministic MCDM methodology described in Section 2.1.1 was applied to the case-study building using some of the evaluation parameters reported in Table 1, where the preference matrix A used to generate the weight vectors was based on the proposing authors' judgment (Caterino et al. 2008; Gentile and Galasso 2019). For example, Caterino *et al.* (Caterino et al. 2008) assessed a residential building and thereby their judgment was expressed by the owner of the building. On the other hand, Gentile and Galasso (Gentile and Galasso 2019) investigated a school building and their judgment contemplated a government agency as the decision maker. Even though the case-study addressed herein refers to a school building, the criteria adopted by Caterino *et al.* (Caterino et al. 2008), which refer to a residential building, were also used to compare two different occupancy classes (residential and school buildings) and to verify the influence of the weight vector defined from different perspectives (i.e. building occupancy types). Moreover, DV C_3 "Duration of works/disruption of use was considered as the time needed to undergo and complete the retrofitting intervention, assuming that this will cause disruption in the use of the building (similar to the assumption made by Caterino *et al.* (Caterino et al. 2008)). However, it is recognized that "duration of work" and "disruption of use" are not necessarily correlated completely, especially when a particular retrofitting option does not disrupt the use of the building, as in the case of external retrofitting interventions, such as the ones addressed by Labò *et al.* (Labò et al. 2020) and Manfredi *et al.* (Manfredi et al. 2021). Additionally, for DVs C_7 and C_8, the expected loss ratios corresponding to the damage limitation and life safety limit states were adopted in lieu of the probability that the PGA of ground motions at the site exceeds the PGA capacity at each limit state in a 50 year period, as used by Caterino *et al.* (Caterino et al. 2008). The rationale for this change is that the detailed non-linear time history analyses and loss estimates are expected to provide a much better indication of the actual seismic risk and damage the case-study structures face, as opposed to the ratio of intensities (O'Reilly and Calvi 2020). The DVs adopted to address residential building criteria comprise from C_1 until C_8 (Table 1), while for the school building case the range of variables include from C_1 to C_7. For this case C_7 refers to loss intensity-based according to Table 1, which is equivalent to the value given to $C7$ for the residential building criteria (expected loss ratio at life-safety level). The decision matrix D and weight vector w for each case are presented in Table 2, which relate to the evaluation parameters reported in Table 1.

The different retrofit strategies are therefore ranked as reported in Table 3 for each building occupancy type, from left to right, i.e. from the highest to the lowest relative closeness (C_{i*}), as most ideal to less ideal solution. Strategy A1 is recognised as the most convenient solution when residential building occupancy is considered, whereas strategy A4 is the most advantageous in the case of school buildings. Furthermore, it is also worth noting that strategy A1 went from being ranked as the best solution with residential building criteria to the least favourable alternative when considering school building criteria. This confirms and highlights the importance of the input weighting and criteria when using MCDM methods to identify the most favourable solution for a given situation.

Table 2. Decision matrix D and weight vector w, adopting evaluation parameters of Table 1.

	Decision Matrix *D*							
	C_1 [€]	C_2 [€]	C_3 [days]	C_4	C_5	C_6	C_7	C_8
Alternatives	Installation cost	Maintenance cost	Duration of works/ disruption of use	Functional compatibility	Skilled labour requirements/ needed technology level	Intervention on Foundations	Significant Damage risk	Damage Limitation risk
A1	1,689,204.1	1,252,917.1	49	0.66	0.42	2.70	1.00	0.04
A2	7,583.52	17,442.10	8	0.12	0.12	14.8	1.00	0.08
A3	826,875.2	1,421,941.7	41	0.17	0.05	14.8	0.46	0.07
A4	1,034,701.	660,686.3	39	0.05	0.42	1.13	0.23	0.01
	Weight Vector *w*							
Residential Building Criteria	0.071	0.179	0.074	0.275	0.026	0.203	0.034	0.139
School Building Criteria	0.307	0.032	0.032	0.108	0.035	0.179	0.307	-

Table 3. Retrofit strategy ranking for the case-study building.

Building Occupancy Class	Rank order	Relative closeness
Residential Building criteria	A1- A4 - A2 - A3	0.66 - 0.41 - 0.35 - 0.17
School Building criteria	A4 - A2 - A3 - A1	0.55 - 0.53 - 0.47 - 0.33

In the case of the residential building occupancy type, the most influential parameters were assumed as the functional compatibility (C_4 = 0.275), intervention on the foundations (C_6 = 0.203) and maintenance cost (C_2 = 0.179). Consequently, the strategy having the most favourable values (i.e. highest functional compatibility, lowest intervention at foundation and maintenance cost) may be selected as the most suitable retrofit alternative. Although alternative A1 does not account for the lowest maintenance cost and intervention at the foundation, its considerably larger functional compatibility (0.66) favours this retrofit strategy over the other ones. On the other hand, in the case of school building occupancy type, the highest-weight variables are the total retrofit cost (C_1 = 0.307), loss intensity-based (C_7 = 0.307), and intervention on the foundation (C_6 = 0.179). Strategy A4 resulted as the most advantageous one, although its installation cost is not the lowest. Nevertheless, the low intensity-based loss and intervention on the foundations (0.23 and 1.13, respectively) very likely placed this strategy in the first place of the ranking.

In addition, the results of the sensitivity analysis described in Section 2.1.2, using the evaluation parameters listed in Table 2, are reported in Table 4 for both building criteria. From Table 4, it can be seen that the methodology was most sensitive to DV C_6 when adopting residential building criteria, meaning that changes to the weight of this DV would alter the ranking for the retrofit options considerably

Based on the analyses carried out in this study, it was determined that there is a fair match between the sensitivity analysis outcome and the DVs with the largest relative importance. This pattern is observed when the sum of all the values of the weight normalised decision matrix V (Fig. 1) is approximately equal to half of the number of retrofit strategies, which would be 2 for the present study, when dealing with 4 for retrofitting interventions.

Moreover, the methodology was more sensitive to the variable C_1 (installation cost), as indicated by Table 4 for a school building criteria. The DVs C_1 and C_7 are the ones with the highest weights, however, C_1 was recognised as the DV influencing the methodology the most, followed by C_7. This correlation between the most influential DV and the one with the highest relative weight had also been observed in the study by Caterino *et al.* (Caterino et al. 2008), however, this did not hold when the residential building criterion was used, possibly because it was applied to a school building. The outputs of this sensitivity analysis are particularly useful to identify the DVs for which a more accurate characterisation is important, given their impact in the ranking.

The sensitivity analysis can also be used to scrutinise the deterministic MCDM ranking and verify the optimal solution. From an analysis of the intervals (Fig. 6) it was determined that, out of the 30 observed intervals for the residential building criteria, A1 ranked first 18 times, A2 just 7 times, A3 once and A4 four times. Similarly, the intervals for the school building criteria

Table 4. Absolute-Top (AT), Percentage-Top (PT) changes, and sensitivity of criteria weights applied to the case-study building.

	Residential Building criteria, (Caterino et al. 2008)				School Building criteria, (Gentile and Galasso 2019)			
DV	Weights	AT	PT (%)	Sensitivity (1/PT)	Weights	AT	PT (%)	Sensitivity (1/PT)
C_1	0.071	0.084	118.31	0.008	0.307	0.013	4.23	0.236
C_2	0.179	0.071	39.66	0.025	0.032	0.103	321.88	0.003
C_3	0.074	0.121	163.51	0.006	0.032	0.088	275.00	0.004
C_4	0.275	0.145	52.73	0.019	0.108	0.057	52.78	0.019
C_5	0.026	0.149	573.08	0.002	0.035	0.065	185.71	0.005
C_6	0.203	0.058	28.57	0.035	0.179	0.024	13.41	0.075
C_7	0.034	0.291	855.88	0.001	0.307	0.022	7.17	0.140
C_8	0.139	0.486	349.64	0.003			-	

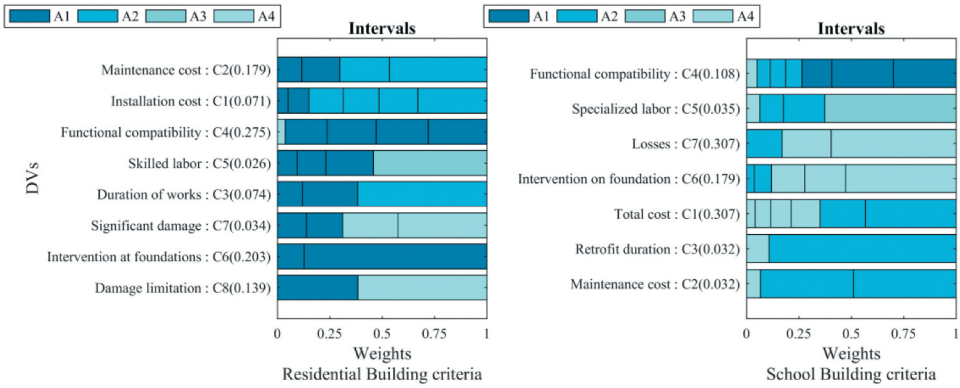

Figure 6. Intervals observed for the sensitivity analysis indicating the alternative ranking first for those intervals.

indicate that, out of 30 observed intervals, A4 ranks first 12 times, A2 12 times as well, A1 three times and A3 just once. This analysis confirms the ranking, given that the alternatives with the higher frequency of ranking first, from the generated intervals, had also ranked first in the deterministic approach (Table 3).

3.3. Assessment of Retrofit Strategies Using Stochastic MCDM

A stochastic version of MCDM was implemented, as explained in Section 2.2.2, considering the mean input DVs and weights, and corresponding standard deviations, listed in Table 5. As explained beforehand, the mean of the input variables was assumed to be the deterministic DVs reported in Table 2.

Following the procedure previously outlined in Fig. 2, the probability of being ranked as the ideal strategy is illustrated in Fig. 7 for the two considered building occupancy types. When the residential building criterion was used, the strategy A1 (i.e. implementation of CFRP) had the highest probability over the other strategies of being ranked as the most convenient. Indeed, its probability (P[1] = 0.96) is very high in comparison to the other strategies and the ranking sequence of the strategies is as follows: A1-A4-A2-A3. On the other hand, for school buildings, the strategy A4 (i.e. application of CFRP and viscous dampers) resulted as the most probable strategy to be ranked in the first place, followed by strategy A2 (i.e. implementation of exterior cross-steel braces). The ranking sequence for this case is A4-A2-A1-A3. As can be observed, the assumed uncertainty had no effect on the alternatives' ranking, which may be related to the same coefficient of variation (25%) that was adopted for all DVs.

Table 5. Standard deviation input variables applied to the case-study building.

Decision Matrix D								
Standard deviation	C_1 [€]	C_2 [€]	C_3 [days]	C_4	C_5	C_6	C_7	C_8
A1	422,301.0	313,229.3	12.3	0.165	0.104	0.68	0.00	0.010
A2	1,895.9	4,360.5	2.0	0.030	0.030	3.70	0.00	0.020
A3	206,718.8	355,485.4	10.25	0.042	0.013	3.70	0.12	0.018
A4	258,675.3	165,171.6	9.8	0.013	0.104	0.28	0.06	0.003
Standard Deviation for Weight Vector w								
Residential Building Criteria	0.018	0.045	0.019	0.069	0.007	0.051	0.009	0.035
School Building Criteria	0.077	0.008	0.008	0.027	0.009	0.045	0.077	-

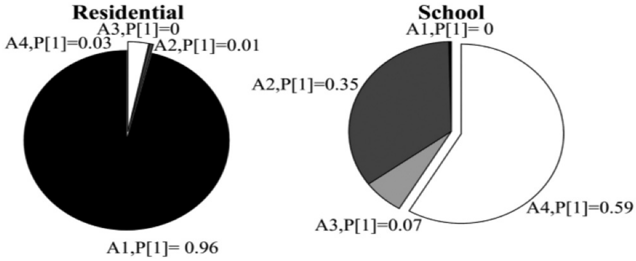

Figure 7. Ranking of retrofit strategies for the case-study building.

4. Stochastic MCDM Using Input from Ad-hoc Data Collection Survey on RC Buildings Retrofitting

The expert judgment of different professional groups involved in the field of structural engineering – academics, researchers and practitioners – was consulted, using an ad-hoc developed survey, to reimplement the stochastic version of MCDM with more realistic and accurate estimates of the variability of the DVs. In this respect, the source of the collected data influences the quality of the results and thereby the statistical uncertainty, as highlighted by Kolios *et al.* (Kolios et al. 2016), referring in particular to selecting a proper number of participants, as well as diverse expertise types and levels.

4.1. Scope and Development of the Survey

With the aforementioned objective in mind, a survey, in which 24 responses were obtained, was carried out to collect the views/opinion of professionals with general experience in the field of retrofitting interventions on the importance of the decision variables, as well as to qualitatively estimate the performance of each retrofit alternative. The profile of the practitioner involved in the survey is someone with general experience in the field of retrofitting interventions. Additional sections, considered to be fundamental features that directly relate the respondents to the field of retrofitting of buildings, were included in the survey. These features included: the person/entity responsible for conducting the retrofitting intervention, years of experience of the respondents (as a proxy to the level of expertise) and their professional involvement (i.e. either academia or industry). In particular, Kolios *et al.* (Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014) concluded, for what concerns the last two features, that the level of expertise of the respondents may affect the rank probability of the alternatives. Moreover, respondents were asked to express the importance of each variable with respect to who they believe is responsible for carrying out the retrofit intervention in residential and school buildings. Regarding the main core of the survey (i.e. ranking of the DVs and estimation of the performance of the retrofit alternatives), the respondents were asked to score, on a scale from zero to nine (zero would mean an irrelevant DV), the DVs and retrofit options defined for the case-study building under the two occupancy classes, as illustrated in Table 6.

Even though the decision matrix of the retrofit strategies was not quantitatively measured (i.e. exact quantities for cost, displacements, forces, etc.), the scores (0–9) were used by the respondents to evaluate the performance of each retrofit alternative with respect to each DV (as presented in Table 7) and also serves as a manner of comparison with respect to Section 3.3.

The survey questionnaires included the eight DVs studied by Caterino *et al.* (Caterino et al. 2008) and two additional ones: design knowledge and life-cycle environmental impact, which were considered to be relevant for the choice of a retrofitting strategy and for future analyses, especially to explore the integration/compatibility between seismic and energy retrofitting. Although this aspect

Table 6. Evaluation criteria considering how important/influential the DVs are in the selection of optimal retrofitting solutions.

Evaluation Criteria	Scores	Scores
1. Installation cost of retrofit strategy 2. Maintenance cost of retrofit strategy 3. Duration of works of retrofit strategy 4. Architectural impact of retrofit strategy 5. Need for skilled/specialised work for execution of retrofit strategy 6. Need for intervention at foundations following the retrofit strategy 7. Economic losses due to low intensity earthquakes 8. Economic losses due to medium-high intensity earthquakes 9. Technical knowledge for design of retrofit strategy 10. Environmental impact of retrofit strategy	Evaluation criteria for RESIDENTIAL buildings (Please score from 0 to 9).	Evaluation criteria for SCHOOL buildings (Please score from 0 to 9).

Table 7. Input variables for residential buildings from the survey. Values of the standard deviation in parenthesis.

	Mean Decision Matrix *D* (Standard Deviation Decision Matrix D)							
For both buildings criteria	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A1	5.32 (1.55)	4.35 (1.81)	5.29 (1.79)	3.41 (1.62)	6.27 (1.88)	3.29 (2.76)	5.00 (2.10)	5.10 (1.67)
A2	4.86 (1.98)	4.65 (1.84)	5.57 (1.54)	7.00 (1.90)	5.36 (1.99)	5.90 (2.32)	4.00 (1.76)	5.05 (1.80)
A3	6.41 (1.18)	5.75 (1.62)	6.57 (1.21)	6.86 (1.88)	6.59 (1.71)	5.95 (1.89)	3.81 (1.89)	4.76 (2.00)
A4	7.59 (1.50)	6.35 (2.25)	6.65 (1.46)	6.18 (2.28)	7.55 (1.53)	4.86 (2.43)	3.76 (2.34)	4.00 (2.21)
	Mean Weight Vector *w* (Standard Deviation Weight Vector w)							
ResidentialBuilding Criteria	0.141 (0.027)	0.136 (0.033)	0.127 (0.037)	0.116 (0.049)	0.107 (0.041)	0.124 (0.050)	0.123 (0.049)	0.127 (0.036)
School Building Criteria	0.154 (0.037)	0.159 (0.034)	0.139 (0.047)	0.121 (0.056)	0.125 (0.050)	0.147 (0.056)	0.154 (0.051)	-

was not explored in this study, it is certainly important from an environmental sustainability perspective and should thus be properly explored in future research. The design knowledge would reflect the complexity in the analysis and design of the retrofit option, as well as whether special knowledge is required at the moment of implementation on site. The life-cycle environmental impact was considered a key parameter in decision making, as environmental performance and sustainability have become a major focus of transnational policy in recent years (Directive 2010/31/EU 2010; European Commission 2011). The inclusion of environmental performance as a DV also allows future studies to provide a more holistic assessment of the retrofit alternatives, considering aspects from all three of the pillars of sustainability (social, economic, and environmental) (Gencturk, Hossain, and Lahourpour 2016; Menna et al. 2013). Moreover, and while not directly addressed in this study, the views of professionals related to the energy efficiency of buildings is another parameter that could be considered. Even though this was not addressed in this study, these parameters should be evaluated in future studies as recently proposed by Prota *et al.* (Prota et al. 2020).

4.2. Survey Results

The relative importance of the evaluation criteria (weight vector) for each building occupancy type, taken as the normalised mean of the provided scores, is illustrated in Fig. 8.

In the case of residential buildings, the respondents agreed that installation cost and maintenance are critical aspects to consider for retrofit options and that these aspects can greatly influence the selection of a strategy. On the other hand, architectural impact and need for skilled workers were considered as the least essential criteria. This DV prioritisation contrasts with the one assumed by Caterino *et al.* (Caterino et al. 2008), in which architectural impact was taken as the most important *DV*. It could thus be argued that not only engineers should have been included in the survey but also other professionals, such as architects, project managers, contractors or even the clients themselves. Similarly, when possible, the involvement of building administrators is also desirable, to include views regarding supervision and management of buildings. However, in the context in which the survey was conducted (the selection of retrofit options for Italian buildings) it is the structural engineer who is primarily responsible for proposing the final design alternative and is therefore likely to be the one assuming weights for the DVs, even if they are related to other fields, such as architectural impact. It is worth noting that in different contexts, for example, where a close collaborative relationship exists between the architect and structural engineer, a compromise between the different parties may result in a different set of values for the weight vector. With this in mind, the values obtained from the survey are directly applicable to the structure in this case study and the broader context of retrofit of pre-1970s Italian RC structures, but care should be taken when using these weight vectors in other contexts as they may not reflect the design priorities or expectations of the local design teams.

A summary comparison between the weight vector obtained from the survey and the ones assumed in the study by Caterino *et al.* (Caterino et al. 2008) is presented in Fig. 9, for residential buildings. The differences in this case are due to the fact that only the eight evaluation parameters from Table 8 were considered and normalised by dividing the mean value of each DV by the sum of the means of these eight DVs. Overall, the weight distribution of each DV obtained from the survey is more uniform than the ones assumed in past studies (Caterino et al. 2008). A possible reason for this is the way each weight vector was obtained; the weight vector from the survey was determined directly from the normalisation of the mean scores provided by the respondents, while the other studies used a weight vector based on the authors' own judgment.

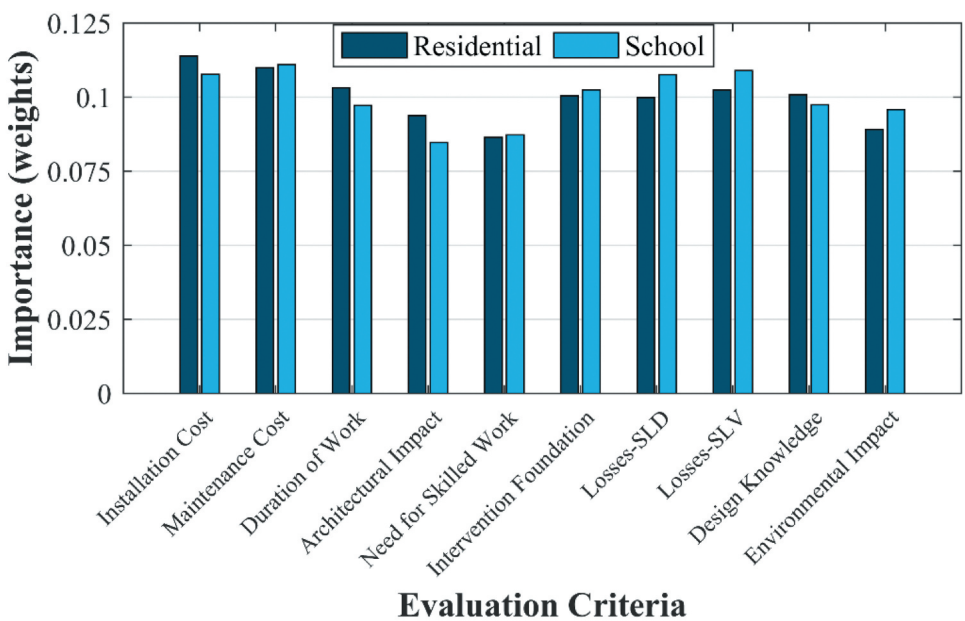

Figure 8. Relative importance (weight vector) of decision variables from the survey.

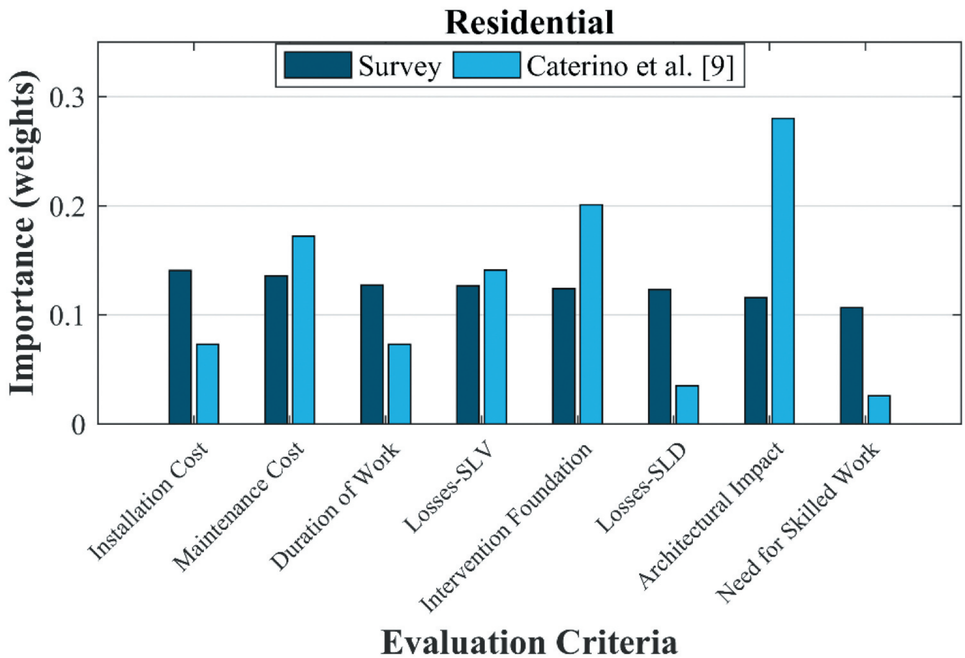

Figure 9. Comparison of weight vector for a residential building.

Table 8. Evaluation criteria with respect to the different retrofit strategies.

Retrofit Alternatives	Evaluation Criteria
A1. CFRP. A2. Exterior steel cross-bracing. A3. CFRP + steel braces. A4. CFRP + viscous dampers.	(1) Installation cost of retrofit strategy, please score from 0 to 9. (This same format was used for all 10 DVs reported in Table 8)

In particular, the respondents considered cost-related variables as a decisive aspect for the retrofit of residential buildings, whereas the study by Caterino *et al.* (Caterino et al. 2008) assumed architectural impact as an essential element for this building type. This difference may depend on the context in which the survey was conducted (the selection of retrofit options for Italian buildings); the survey gathered the opinion of professionals that look at the problem from the perspective of the engineer responsible for selecting the final design alternative. This may lead to the cost-related variables having a bigger impact on the final decision of a retrofit option according to most of the experiences of the respondents.

In the case of the school building use, Fig. 10 compares the weight vector of the survey with respect to Gentile and Galasso (Gentile and Galasso 2019). For this reason, only the seven DVs used by Gentile and Galasso (Table 1) were normalised and illustrated in Fig. 10. The importance of the DVs follows a more similar trend in both studies, with respect to residential buildings, even though the weights are different and were based on the engineering judgment of the authors, for the case of Gentile and Galasso (Gentile and Galasso 2019). Both sources consider installation cost and losses as the most critical evaluation parameter in school buildings. In addition to these, the survey respondents also gave high importance to maintenance costs, which was, however, considered of low importance by Gentile and Galasso (Gentile and Galasso 2019). On the other hand, the need for skilled labour was recognised as the least influential aspect according to the survey.

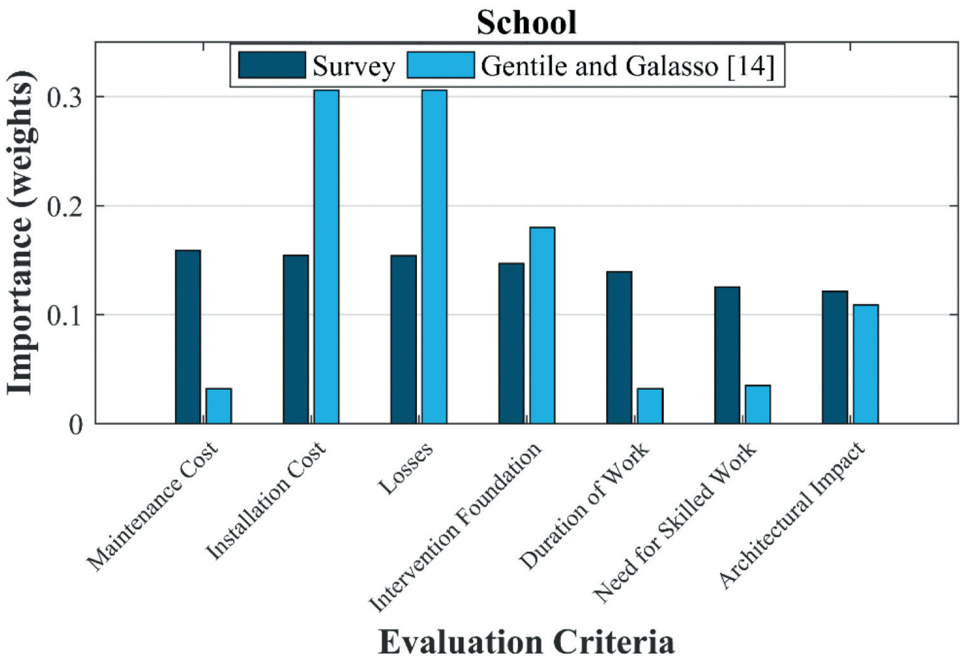

Figure 10. Comparison of weight vector for a school building.

Moreover, the internal consistency of the collected data was verified through Cronbach's alpha (Cronbach 1951), demonstrating that, for the different criteria scenarios/analyses, the resulting reliability coefficients were higher than 0.7 (a reliability coefficient of 0.7 or higher is considered acceptable (Cronbach 1951)).

The survey gathered data from participants with diverse levels of experience, professional involvement and education. The distribution of the years of experience of the respondents is illustrated in Fig. 11 left. It is observed that most of the respondents (46%) had between 2 and 5 years of experience in the field of retrofitting. Respondents with 6–10 years of experience or 0–1 year of experience represent both 17% whereas 21% of the participants had more than 10 years of experience. Therefore, for simplification and as a means of comparison, the participants' years of experience are grouped in three important categories: more than 6 years of experience (38%), 2–5 years of experience (46%) and less than 2 years of experience (16%). Accordingly, the ratio between more experienced to less-experienced respondents is 3:5, considering a 6-year experience threshold. Furthermore, most of the respondents are involved either in academia or research (67%) and 17% of the participants reported being involved in the engineering industry (another 17% did not specify their professional involvement, i.e. whether they are involved in the Engineering industry, Academia/research, or both).

Figure 12 illustrates the comparison of the weight vector for residential buildings occupancy, disaggregated by the responders' years of experience. Participants with more than six years of experience consider cost-related variables to be the most important aspects to assess for retrofit strategies. This may be because they have worked with installation costs for a considerable time and realised that monetary issues are key when selecting a retrofit intervention. Cost-related variables may include installation cost, maintenance and duration of work.

Similarly, this group considers economic losses as another influential parameter, particularly with respect to the less experienced groups. Less experienced participants also agree that cost-related variables should be the most critical aspects to assess. Additionally, this group thinks that the need for skilled workers is as important as cost-related variables. In contrast, the need for skilled workers is the least influential DV according to more experienced participants and to all groups, on average.

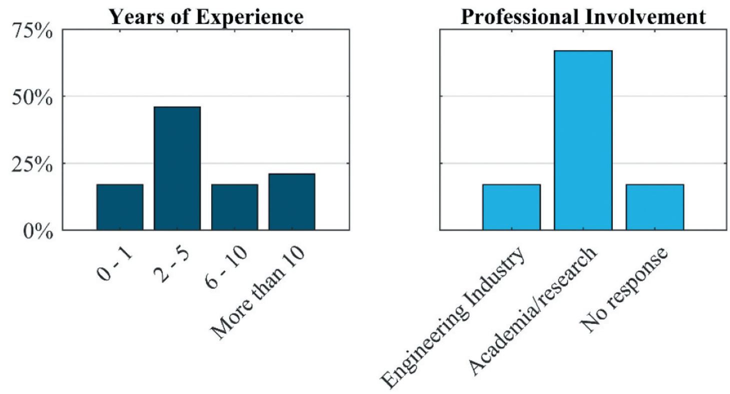

Figure 11. Years of experience of the respondents in the field of retrofitting and professional involvement.

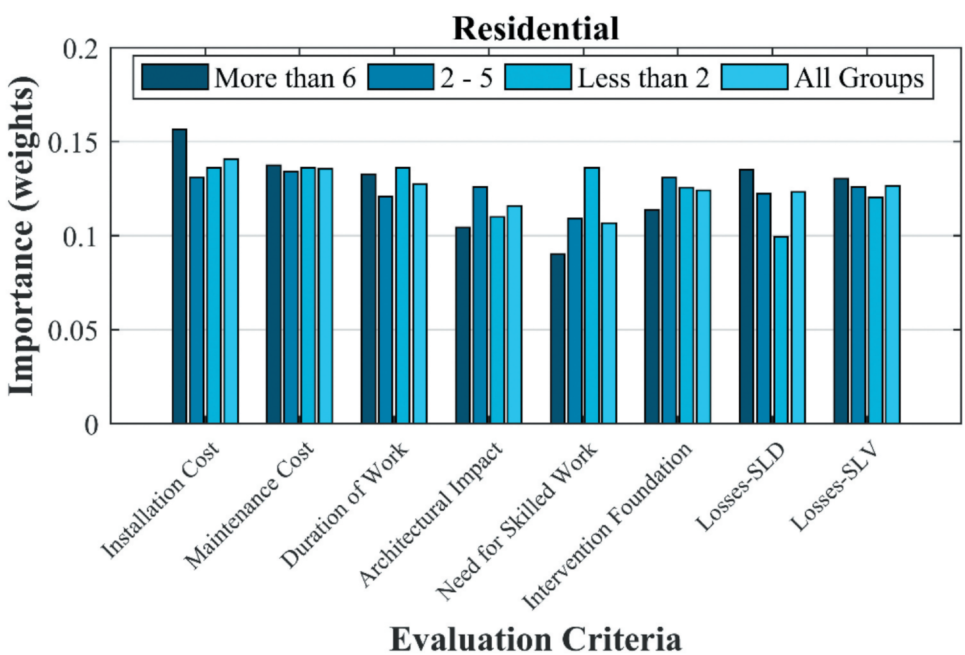

Figure 12. Weights for residential buildings according to respondents' year of experience.

Moreover, in the case of school building occupancy (Fig. 13) more experienced participants consider again the monetary variables (i.e. installation cost, maintenance, and economic losses) as the most critical aspects for selecting retrofitting interventions. On the other hand, architectural impact and need for skilled workers are recognised as the least influential DVs, which is a clear consequence of the change in the building occupancy type. Unlike more experienced participants, less experienced ones consider that the need for skilled labour is, in turn, an important aspect, whereas the architectural impact is the least important DV based on the weights presented in Fig. 13.

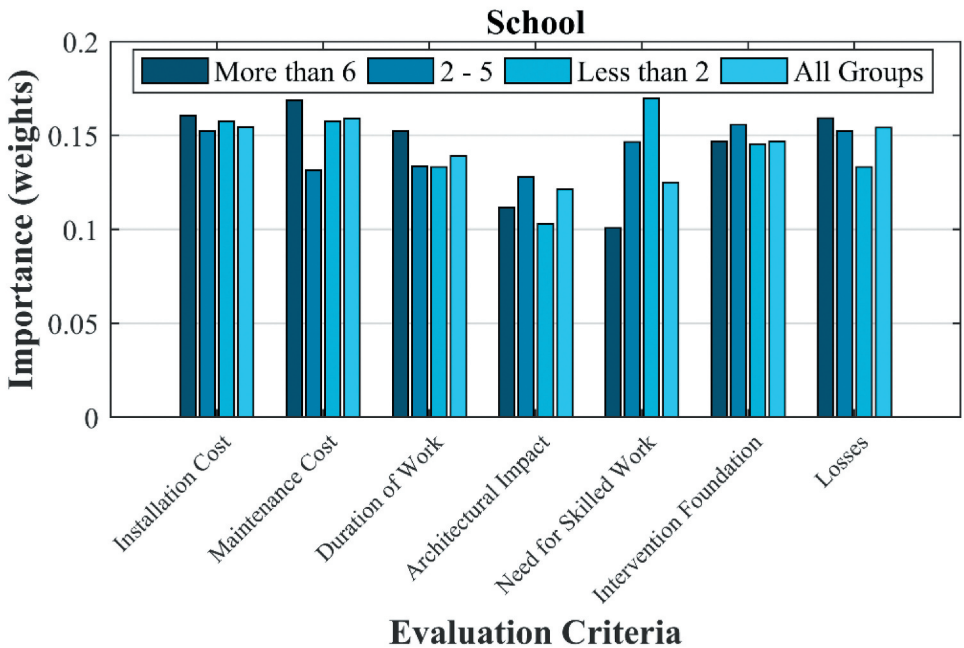

Figure 13. Weights for school buildings according to respondents' year of experience.

4.3. Stochastic MCDM Using Survey Outputs

The data gathered from the survey questionnaires was post-processed and resulted in the input variables reported in Table 7 (considering the first eight DVs for the residential, and first seven DVs for school building criteria). For simplicity, the weight vector was normalised. These input variables were used to perform a stochastic version of MCDM, as outlined in Section 3.3, using 1000 simulations, which was found sufficient to reach a stable set of results via the observed probability pattern. In the study of Kolios *et al.* (Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014)), considering 100 to 1000 simulations resulted in significant variation of the outcomes. However, that study examined ten evaluation parameters and alternatives thus a larger number of simulations was needed. Since a lower number of aspects are examined in this study and, especially, just four alternatives are considered, a lower number of simulations was sufficient.

The survey-based decision matrix is not fully quantitative, i.e. composed of real values describing the retrofit alternatives, but rather qualitative, i.e. uses the relative scores from 0 to 9. Nevertheless, the results of the stochastic implementation of MCDM using this qualitative matrix, in a similar fashion to what carried out by Kolios *et al.* (Kolios, Rodriguez Tsouroukdissian, and Salonitis 2014), can be used to highlight the importance of considering real values and how using survey results for the decision matrix leads to a diverse alternative prioritisation. The analysis was carried out assuming different distributions to statistically characterise the variables, namely normal, lognormal, uniform and Gumbel, given that any of them may represent the data and help to better understand the influence of the distributions in the stochastic procedure. As observed in Fig. 14, the strategy with CFRP, A1, has a higher probability of being ranked as the first option for both building classes and all variable distributions. On the other hand, A3 (CFRP and steel braces) is found to be the least desirable alternative. The values assigned to A1 in the decision matrix (reported in Table 7) are the most convenient with respect to the other alternatives (all the DVs in the survey are considered positive, which means that the most desirable situations are the ones corresponding to the lowest values). Indeed, A1 has four desirable characteristics (i.e. the lowest values highlighted in bold in Table 7) and

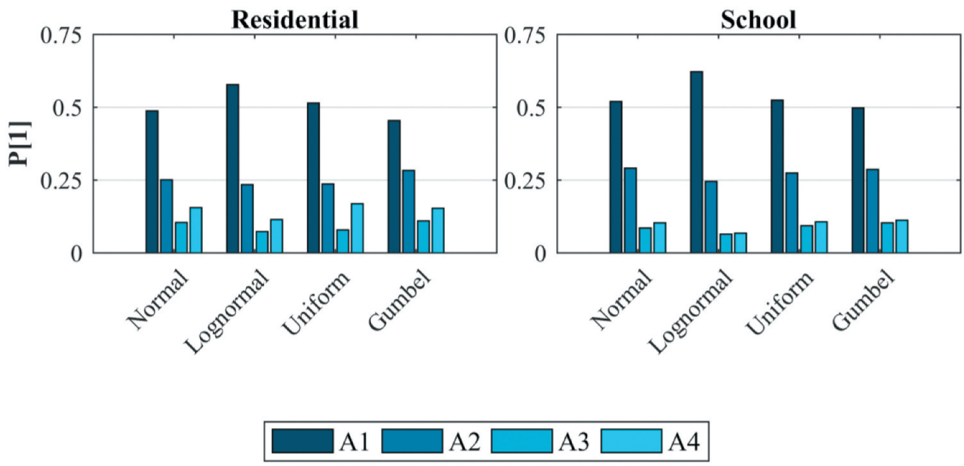

Figure 14. Probability of the alternatives of being ranked as the most convenient strategy, using data only from the survey.

is, therefore, ranked as an ideal strategy for a significant number of simulations. The most likely complete ranking is A1-A2-A4-A3, regardless of the distribution adopted and the building's occupancy type.

Finally, for completeness, the stochastic version of MCDM was also repeated for all four variable distributions considering the weights presented in Table 7 (i.e. from the survey) and the quantitative decision matrix from Tables 2 and 5 (i.e. uncertainty characterisation). The goal is to combine the exact values for the DVs with the weights obtained through the survey, which can be seen as the most subjective MCDM parameters. The probability, for the different strategies, of being ranked in the first place is illustrated in Fig. 15. The first conclusion is that, again, the distribution assigned to the DVs has no influence in the ranking but only in the absolute probability values. When the residential building criteria are used, the strategy A2 is now seen as the most convenient. Likewise for the case of school buildings, the strategy A2 has a higher probability of being ranked as first.

A comparison of the different adopted deterministic and stochastic MCDM approaches, and corresponding rankings, combining the different data sources (literature, uncertainty characterisation, and survey-based) is presented in Table 9. The different rankings have a number of common points, regardless of the approach implemented. It is noticed that the uncertainty does not have a major impact on the rank classification. However, it may have a greater influence in the definition of the weight vector, rather than the decision matrix, especially when the weight of the DVs is concentrated on certain variables. In fact, uniformly distributed weights among all the evaluation parameters may reduce the effect of the uncertainty on the outcome. This can be seen when comparing the deterministic and stochastic approaches using the weights proposed in the literature (Section 3.2) for residential buildings, and when using weights from the survey for both building occupancy criteria in Table 9.

Furthermore, for the deterministic and stochastic outcomes presented in Section 3.2 and 3.3, it is noteworthy that the weights derived from the survey changed the rank pattern in both building occupancy classes. Strategy A2 is ranked as the most convenient alternative for these buildings since the weight vectors are uniformly distributed and have similar values (Fig. 9).

5. Discussion

The examination of the deterministic and stochastic approaches to rank the four selected retrofitting alternatives and the considerations regarding their implementation raise a number of aspects that are worth discussing:

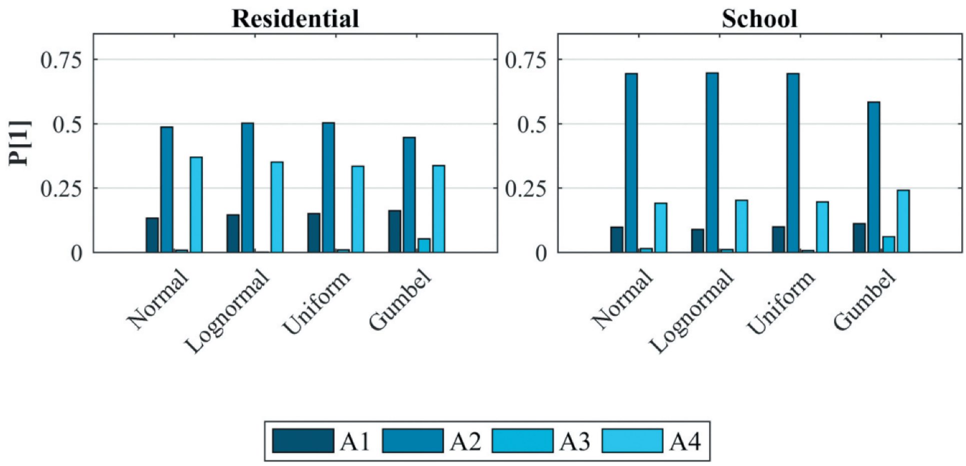

Figure 15. Probability of being ranked as the first option, using the quantitative decision matrix and weight vector from the survey.

Table 9. Comparison of rank classification between deterministic and stochastic outcomes.

Building Occupancy Class	Deterministic (weights from literature – Section 3.2)	Stochastic (weights from literature and assumed uncertainty – Section 3.3)	Deterministic (weights from survey)	Stochastic (weights and corresponding uncertainty from survey and DV uncertainty from Section 3.3)
Residential Building criteria	A1-A4-A2-A3	A1-A4-A2-A3	A2-A4-A1-A3	A2-A4-A1-A3
School Building criteria	A4-A2-A3-A1	A4-A2-A3-A1	A2-A4-A1-A3	A2-A4-A1-A3

- The deterministic MCDM described in Section 2.1.1 can be easily implemented in a spreadsheet or any programming software. At a first glance, the steps involved may appear complex, but the procedure is simple and straightforward. In view of this, a practising engineer could easily follow the steps and adopt not only the evaluation parameters but also the weights explored in this study or others (e.g. Caterino *et al.* (Caterino et al. 2008) and Gentile and Galasso (Gentile and Galasso 2019)). Otherwise, they may carry out a pairwise comparison of the evaluation parameters that they consider decisive for the selection of a retrofit intervention.
- The choice of the evaluation parameters is made based on diverse aspects, such as engineering criteria, the building's occupancy type, as well as the perspective of who is in charge of carrying out the retrofitting or even the building owner's budget and specific needs. Therefore, the evaluation parameters must be carefully selected keeping in mind the aforementioned aspects or the context that best fits the needs of the engineer behind the intervention. As such, there were 10 aspects that were selected and considered to represent the main criteria influencing the final decision of a retrofit intervention. They include a wide range of elements, such as cost, performance, duration of works, intervention at the foundations, economic losses, design of the intervention, and environmental impact of the retrofit interventions. For the case study building, the decision variables 'duration of works' and 'disruption of use' were combined in one single variable. However, this might not apply to some cases where the disruption of use causes people to leave a residential building while works are carried out, leading to an additional cost. Future analyses or improvements of the framework could take this aspect in consideration. Nevertheless, the MCDM method is flexible to accommodate other or different parameters that

can be decided on a case-by-case basis. In particular for this study, the incorporation of the environmental impact adds value to the framework of sustainability that has recently gained importance in all aspects of engineering. Consequently, the variables examined in this study comprise practical evaluation parameters that are believed to be used as reference (or at least some of them) to conduct similar analyses.

- Regarding the characterisation of uncertainty examined in Section 2.2.2, it may be argued that not all the DVs follow a normal distribution, however, most of the random variables in nature can be assumed to follow a normal distribution, therefore, this assumption was considered acceptable for the purposes of this study. Furthermore, the survey included civil engineers with experience in retrofitting existing buildings, either dealing with conceptual or detailed designs, costs, direct execution of interventions at the site, among other related factors. Therefore, under the usual context surrounding existing buildings (i.e. that the engineer is generally responsible for the final design alternative), this group was considered representative for collecting useful information. However, it might be argued that the survey should not only include the feedback from engineers but also other professionals that may be directly or indirectly involved in retrofit interventions (e.g. architects, project managers, contractors and even the clients themselves). In this sense, again, the framework presented here is easily adaptable to the use of different weights, coming from a different or wider survey, or any other judgment. The idea behind the survey conducted herein was to be as representative as possible of the engineering practice context.
- Overall, there is a fair agreement between the deterministic and stochastic MCDM approaches, with respect to the most convenient and less convenient retrofit strategies. On the one hand, in the deterministic approach, adopting weights of previous authors resulted in A1 as the most favourable strategy and A3 as the least. On the other hand, A2 is selected as the ideal solution when the weights of the survey are implemented. The weights developed from the survey are more uniformly distributed, unlike the weights provided by previous authors which are concentrated on certain variables. This greatly influences the selection when the deterministic MCDM is performed. After all, this approach ranks the alternatives based on the closeness to the ideal solution. Therefore, if there is a variable with a concentrated weight, the strategy containing the most convenient aspect of this variable would stand over the other options and be selected as the most advantageous strategy. Furthermore, in the stochastic MCDM several deterministic scenarios are generated and the results are presented in terms of probabilities. This allows other variables to impact the selection hence for other alternatives to have a larger closeness to the ideal solution.
- Finally, even though the last two evaluation parameters of the survey (i.e. design knowledge of the intervention and environmental impact) were not examined, the basis for considering these variables has been raised in this study. Indeed, once the quantities of these variables are defined, the MCDM procedure can be integrated to account for their influence.

6. Summary and Conclusions

This paper discussed the evaluation of four retrofit strategies for a case-study RC school building. Different decision variables (DVs) were assessed regarding the set of alternatives to select the most convenient option through a multi-criteria decision-making (MCDM) framework, applied in both deterministic and stochastic ways. For the implementation of the latter, the uncertainty was assumed through a coefficient of variation, as well as through a surveying process. Such a survey was distributed mostly to engineering professionals involved in the field of retrofitting of existing buildings to collect information about the selected evaluation parameters. The main conclusions that can be drawn from this study are as follows:

- Within the MCDM framework, an evaluation parameter with a relatively high importance has a substantial impact on the ranking of the retrofit alternatives, when the value of a retrofit strategy related to this parameter is also substantial with respect to the other strategies.
- A sensitivity analysis carried out for the deterministic MCDM approach is another way to verify that the alternative selected as the most convenient is the one with the highest frequency of being ranked as first in all the generated weight intervals. Furthermore, this analysis can be equally useful to determine what variables have a considerable impact on the outcome of the method and those that do not (robust variables). Therefore, it indicates which parameters in the weight vector and decision matrix need to be carefully defined or be as accurate as possible. It was shown that slight changes in the values of the most influential DVs can alter the ranking of the interventions drastically.
- The ranking of the four strategies did not change with the introduction of the uncertainty in the weight vector and decision matrix. However, using different weight vectors resulted in diverse ranking patterns. On the one hand, when using weights from previous studies, the strategy consisting of only carbon fiber reinforced polymer (CFRP) came up as the most ideal solution for residential building criteria, whereas the intervention with CFRP and viscous dampers was ranked as the first option for school buildings. On the other hand, the retrofit strategy composed of exterior steel braces was selected as the ideal one according to the weights obtained from the survey. It is noteworthy that the uncertainty effect is neglected by the MCDM analysis when there is a decision variable with a clearly higher weight with respect to the other variables or when the weights are uniformly distributed (as happened with the surveyed ones). This leads to the same ranking for both deterministic and stochastic MCDM analyses.
- From the survey questionnaires, it was found that, regardless of the building occupancy type, the aspects to consider evaluating a retrofit option should focus on cost-related variables, particularly considering the views of the more experienced participants. On the other hand, architectural impact and need for skilled labour are considered as the least influential parameters. This variable prioritisation is different from the ones defined by past studies in the field. Additionally, the weights obtained from the survey are not concentrated on certain variables since the evaluation parameters were assigned according to a 0–9 scale and not through a pairwise comparison as previously done in other MCDM studies.
- The decision matrix for the retrofit strategies defined using the survey, according to the 0–9 scale, could not describe exactly the real performance or characteristics of the retrofit strategies (i.e. structural response, cost, loss estimates, etc.). Consequently, when reconducting the MCDM analysis considering the data from the survey for both weight vector and decision matrix, the optimal retrofit strategy changed, becoming the use of CFRP, regardless of the building occupancy type.

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ORCID

Giammaria Gabbianelli http://orcid.org/0000-0003-0657-9538
Gerard O'Reilly http://orcid.org/0000-0001-5497-030X
Ricardo Monteiro http://orcid.org/0000-0002-2505-2996

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