MCDM METHODS FOR THE IDENTIFICATION OF INTERVENTION STRATEGIES FOR SEISMIC RETROFITTING OF SCHOOL BUILDINGS

Angelo Anelli(1), Marco Vona(2), Sandra Santa-Cruz(3), Michelangelo Laterza(4), Nicola Tarque(5)

(1) PhD student, Pontifical Catholic University of Peru, angelo.anelli@pucp.edu.pe
(2) Assistant Professor, University of Basilicata, marco.vona@unibas.it
(3) Associate Professor, Pontifical Catholic University of Peru, ssantacruz@pucp.edu.pe
(4) Associate Professor, University of Basilicata, michelangelo.laterza@unibas.it
(5) Associate Professor, Pontifical Catholic University of Peru, sntarque@pucp.edu.pe

Abstract

Resilience of a city depends strongly on both the continual operation of the strategic buildings and the damage level of the structures. Unfortunately, in many cities of the world, these aspects represent weak points and limited resources reduce the possibilities to address the problem. Therefore, in these cases, it is necessary to propose optimal and massive interventions avoiding waste.

Prioritizations and selection of best retrofitting alternatives on a large territorial scale must consider technical, economic, and social criteria. The choice of criteria is one of the key issues especially for strategic buildings, such as schools and hospitals, which generally have high vulnerability and further problems related to the choice and the implementation of the retrofitting intervention. In this context, the Multi-Criteria Decision-Making (MCDM) methods can be used to provide a valuable support to deal with the intricate problem of identifying the solution of optimal intervention.

In this paper, we focus on definition of the optimal retrofitting alternative. Our case study is a school campus, with several buildings, designed and constructed in the ‘80s, according to the Italian seismic code applicable at the time. A wide experimental in situ and laboratory campaign was performed in order to know and understand their main structural elements.

Different retrofitting alternatives were considered and two MCDM methods were applied and compared in order to select the optimal solution. According to the current use of the buildings, the problem of disruption of occupancy has been a fundamental topic, and particular attention has been devoted to the safety conditions and operational phases in the construction site. The possibility of a next strength upgrade for incremental retrofitting was also assessed. These and other aspects have been pondered in order to promote procedures able to define optimal intervention strategies that can be easily extended to every city, so as to reduce the seismic risk of schools and increase the resilience of cities.

Keywords: City Resilience, School Buildings, Retrofitting Strategies selection, BIM models, MCDM methods.

1. Introduction

In accordance with some authors [1], the resilience of a city has been assumed as the ability of an urban system to absorb, adapt, and respond to adverse changes. In the context of disaster recovery, it depends strongly on both the continual operation of the strategic buildings and the damage level of the structures. In fact, schools, hospitals, police stations, local government buildings, namely strategic places in case of an emergency, such as an earthquake, play a central role in minimizing the inconvenience to the population. Nonetheless, their seismic safety is generally low. Furthermore, closed and inaccessible roads due to the damage level of the public and private buildings caused by earthquakes significantly increase the time to manage and recover from the emergency. Unfortunately, in many cities of the world, these aspects represent weak points and limited resources reduce the possibilities to address the problem. In these cities, optimal and massive interventions should be carried out in order to optimize the available economic resources.

The choice of criteria for the selection of intervention strategies for seismic retrofit of buildings is one of the key issues for the reduction of seismic risk on a large territorial scale [2] and for the increase of the cities resilience. This issue is certainly of greatest interest for schools and hospitals, which generally have a high vulnerability and further problems related to the choice and the implementation of the retrofit intervention.

The work objectives are to identify optimal and resilient intervention strategies for existing essential buildings through the application of Multi-Criteria Decision-Making (MCDM) methods and Building Information Modeling (BIM). In this manner, criteria that increase the capacity of the cities to adapt to new and adverse conditions could be considered. A case study developed in a previous work [3] was used to apply and compare the adopted MCDM methods. The results of this previous paper are useful for the legibility of the present work. In this study, the authors applied two MCDM methods and some connections with the cities resilience are described.

The structural complex under examination is an Italian scientific high school located in Sulmona. The school compound is composed by ten independent structures in reinforced concrete. They were designed and built during the ’80s in accordance to in force Italian Code. Four alternative retrofit interventions are designed and analyzed by MCDM methods, considering eight different judgement criteria.

In terms of resilience, the continuous operation of schools following a catastrophic event, such as a violent earthquake, allows the student population to restore normal conditions. For the community is also a sign of hope for the future. It means to maintain social cohesion in a community because schools are one of the most unifying elements of the families. They have many important and positive elements.

Therefore, in order to increase the resilience of cities, massive intervention strategies that allow a continuous use of school buildings and ensure adequate safety conditions during their implementation should be promoted. These interventions could be made in several steps due to limited economic resources of governments and the magnitude of the problem. Thus, in order to allow an incremental retrofit during the new service lives of the structures, in addition to ensure adequate levels of protection from damage, aspects related to the possibility of a next update of resistance should also be considered. In this way, flexible retrofit techniques can be promoted. They can increase the resilience of cities and reduce the seismic risk of schools.

2. Multi-criteria decision analysis

Multi-Criteria Decision-Making (MCDM) methods are commonly used in most scientific, economic, and industrial fields. These methods are applied when decision makers would like to establish a ranking of the alternatives in the presence of conflicting criteria. Some interesting applications have been carried out in order to select the seismic retrofitting strategy of single buildings [3], [4], [5] and compare different strategies of natural risks mitigation [6], [7].

In order to apply any MCDM method is necessary to define evaluation criteria, attribute their weights, and evaluate the alternatives of the decision problem according to the chosen judgment criteria.

MCDM methods allow the definition of a rational decision-making process. This process is not bound only to the expert assessments of the designer. In the decision-making process, which is based on economic, social and technical aspects, criteria and their weights should be assessed and weighted by the designer according to the positive feedback of the decision maker (that is the client) and users. If the decision-making process is affected by inconsistent assessment, the designer should redefine the various aspects and to reiterate the process in order to identify the optimal solution sought (Fig.1).

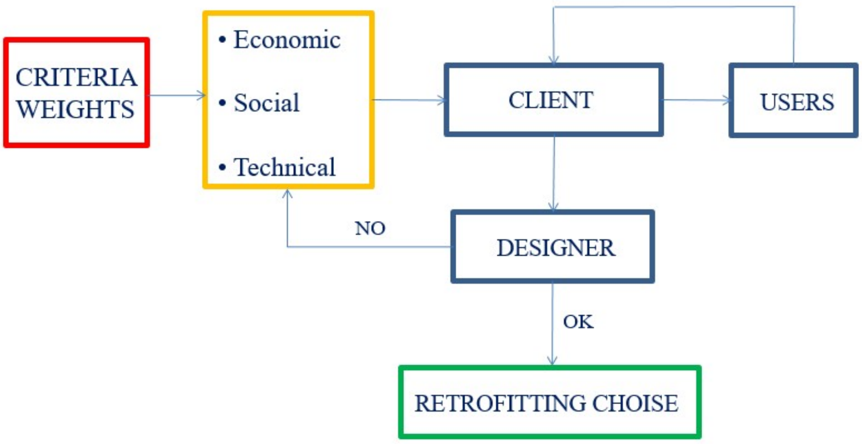


Fig. 1- Decision-making process

Among the numerous MCDM methods, the TOPSIS [8] and VIKOR [9] methods have been applied in an interesting case study.

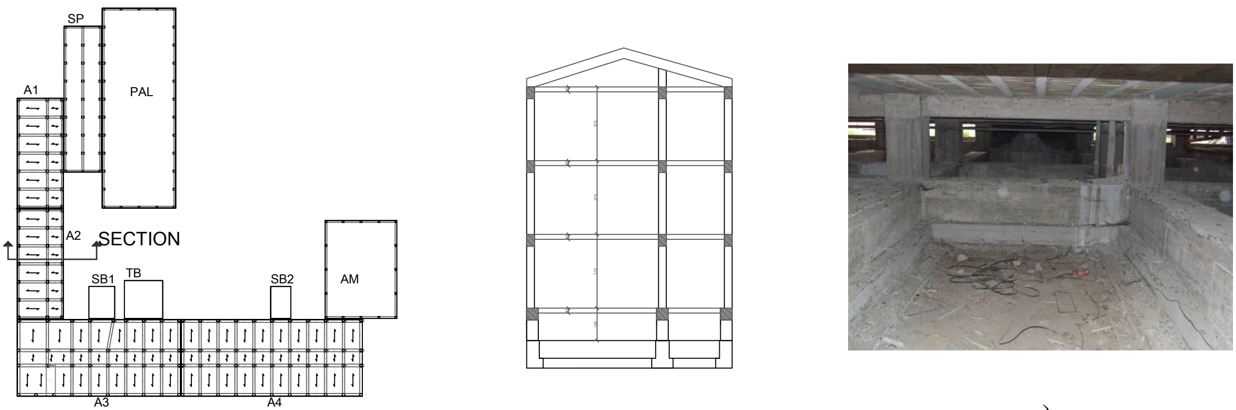
The TOPSIS method is based on the distance of the alternatives from the ideal solutions, namely the ideal solution and the negative ideal solution. They are defined by the best and worst conditions, respectively.

The VIKOR method determines the solution named compromise, based on the best and worst performance of the alternatives with respect to each criterion analyzed. According to this method, in order to establish a ranking of the alternatives, two conditions - acceptable advantage and acceptable stability in decision making - must both be respected. 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.

3. Description of the case study

The case examined is an Italian scientific high school located in Sulmona. The school compound is composed by ten independent structures in reinforced concrete: four structures for classrooms (A1, A2, A3, A4), one gym, two staircases, one boiler room, one assembly hall and one changing room (Fig.2.a). They were designed and built during the ’80s in accordance to the in force Italian Code (D.M. 27.5.1985).

The successive evaluations will refer to the most important structures in terms of volume and function: the structures for classrooms. They have four slabs, three of which are above ground plus the roof. The storey height is 3.75m for the above ground floors and 1.65m for the semi-underground floors (Fig.2.b). This height is measured starting from the extrados of the foundation beams, which can be inspected (Fig.2.c).



c)

b)

a)

Fig. 2- a) Plan of framing before retrofitting. b) Section of building A2. c) Foundation of buildings.

4. Vulnerability assessment

The vulnerability assessments have been carried out by linear dynamic analysis using q factor and considering seismic actions related to the life-safety limit state (probability of exceedance of 10% in 50 years, return period of 712 years), and the damage-limitation limit state (probability of exceedance of 63% in 50 years, return period of 75 years).

Using SAP2000 software [10], for each structure a 3D Finite Element model was defined and the vulnerability assessments were carried out.

The assessments have revealed an insufficient capacity of the structures regarding the seismic resistance required in the new Italian seismic code [11]. It is highlighted a high brittleness of the structural elements, especially of the short columns of the semi-underground floors. Thus, retrofitting is necessary.

5. Retrofitting description

Building retrofit design was conceived using the criteria of the recent Italian technical norm [11] and European codes [12] regarding the structural retrofit of RC buildings. Based on innovative and/or traditional techniques, four different intervention alternatives were designed:

a_1- Base Isolation system;

a_2- Carbon Fiber Reinforced Polymer (CFRP) wrapping;

a_3- Steel and RC jacket;

a_4- Energy dissipation bracing systems.

The retrofitting alternative a_1 involves the insertion of a base isolation system. This intervention increases the capacity of damping and significantly lengthens the vibration period of the structures in order to reduce drastically the seismic accelerations. Based on the arrangement of the various structures for classrooms, we have preferred to create two isolated regular blocks. The designed isolation system requires the use of elastomeric isolators integrated with sliding isolators. The verifications of the two isolated blocks have been carried out by linear dynamic analysis.

The intervention alternative a_2 consists of a retrofit solution with Carbon Fiber Reinforced Polymer commonly called CFRP. The intervention aims essentially to increase the ductility of the structures. The design of the intervention was carried out using non-linear static analysis.

The intervention alternative a_3 consists of steel and reinforced concrete jackets of various structural elements. The jacketing in reinforced concrete was performed on specific pillars in order to allow the decoupling of the vibration modes of structures. On the remaining structural elements with limited resistant and/or deformation capacity, a steel jacket was applied. In this case, the safety checks were also carried out through pushover analysis.

For each building, the intervention alternative a_4 involves the installation of energy dissipation bracing systems. These have been arranged in single or double diagonal and in inverted V in order to maintain the openings in the braced fields. The intervention produced an increase in strength and stiffness of the structures (remaining the ductility unchanged), a regularization of the vibration modes of the constructions, and a reduction of the energy input in the various structures through a damping increase. The dissipative devices have a non-linear behavior, dependent on the displacement and hysteretic type. The verifications of the intervention were done through non-linear static analysis using structural models containing the energy dissipation system.

6. Definition of the decision problem

Following the design of intervention alternatives, eight evaluation criteria were established. The various criteria analyze different themes usually neglected in the retrofitting strategies, such as the interruption of use, aspects related to the possibility of a next update of resistance, and the safety conditions in construction site operations.

The possibility of a next upgrade of resistance is highly related to the concept of resilience. Following disastrous earthquakes, technical regulations generally increase the seismic hazard of the devastated areas. Consequently, at post-disaster stages, even buildings that were safe might no longer be in conformity with the new regulations or most likely, they could present a poor structural condition due to occurred damage. In these contexts, intervention strategies that ensure a lower recovery time and an easy upgrade of the structural residual capacity, at least for essential buildings, should be considered. Through this criterion, the adaptability of the buildings in relation to adverse changes can be increased. In fact, in addition to assessing the ease of replacement and/or implementation of all or part of the intervention, it allows the estimation of the intervention characteristics with respect to any subsequent upgrade of resistance.

The previous criterion and the safety conditions in construction site operations are two of the essential and characteristic elements of the work. This last criterion considers the different aspects related to planning and safety in the construction site. These aspects are very important. In fact, the failure to assess these aspects in a preliminary phase involves delays and cost increases, as well as additional risks on the safety of operators and users. A systematic mechanism to interrupt and prevent injuries on construction sites should be developed. Thus, construction site operations and associated equipment were investigated. The main aim of the research was to investigate operations on construction sites exploring different options, their effectiveness, and their effect on safety. The factors influencing the occurrence of accidental situations were analyzed.

This research looked into the working processes, pondering the factors that have to be taken into consideration regarding placement and usage of equipment, and competent people required when operating equipment. The findings showed the main points to improve safety in construction site operations. These are: planning; equipment and person selection; continuous inspection and communication.

Integration between BIM and MCDM method showed high operational efficiency. It could be proposed as an effective tool for control and verification of activities with high complexity. In Fig.3 is reported the logical flow chart.

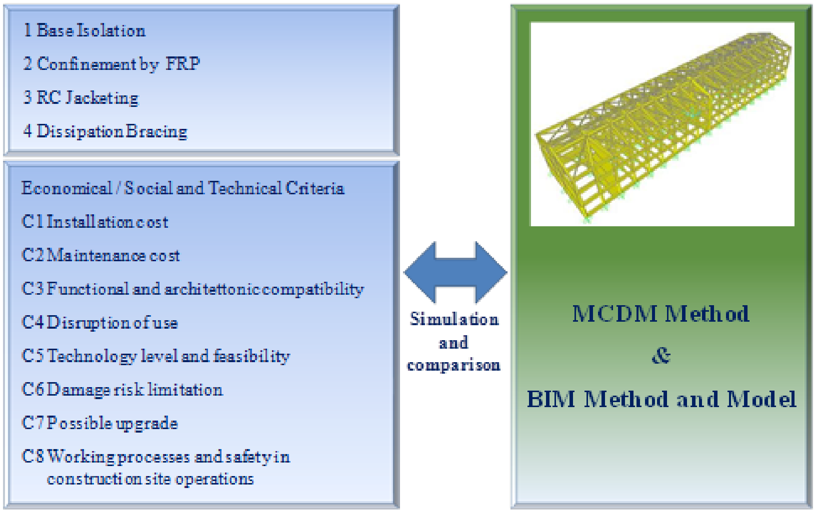


Fig. 3- The logical flow chart

After establishing the criteria, their weights were defined through the Analytic Hierarchy Process (AHP) of Saaty [13], [14], which provides:

i. The construction of the preference matrix (Eq. (1)) of the criteria weights through qualitative binary comparisons between the criteria, using the Saaty's scale shown in Table 1;

ii. The calculation of the principal eigenvalue of the preference matrix. The corresponding eigenvector is exactly the weights vector sought;

iii. Finally the consistency check of the matrix terms (the assigned values) in order to avoid any conflict between the expressed judgments.

$$C = c_{ij} = \begin{bmatrix} 1 & 4 & 1/3 & 2 & 1/2 & 1/4 & 5 & 3 \\ 1/4 & 1 & 1/7 & 1/3 & 1/6 & 1/8 & 2 & 1/2 \\ 3 & 7 & 1 & 4 & 2 & 1/2 & 8 & 5 \\ 1/2 & 3 & 1/4 & 1 & 1/3 & 1/5 & 4 & 2 \\ 2 & 6 & 1/2 & 3 & 1 & 1/3 & 7 & 4 \\ 4 & 8 & 2 & 5 & 3 & 1 & 9 & 6 \\ 1/5 & 1/2 & 1/8 & 1/4 & 1/7 & 1/9 & 1 & 1/3 \\ 1/3 & 2 & 1/5 & 1/2 & 1/4 & 1/6 & 3 & 1 \end{bmatrix} \quad (1)$$

Table 1- Saaty's scale

Intensity of Importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate judgements
Reciprocal (1/2, 1/3, …)	If criterion i compared to j gives one of the above, then j, when compared to i, gives its reciprocal

The criteria weight vector $\mathbf{W}^T = \{w_1,\ldots, w_8\}^T$ is shown in the following Eq. (2):

$$\mathbf{W}^T = \{0.103,0.030,0.234,0.069,0.160,0.335,0.022,0.047\}^T \quad (2)$$

Following the definition of the criteria and their weights, the intervention alternatives were evaluated according to the chosen judgment criteria, in order to build the decision matrix and apply the TOPSIS and VIKOR methods.

Using the new regional price list of the Abruzzo region (2013 edition), the installation cost of the four interventions have been calculated. They vary from 1,900,000 euro (for the base isolation) to 1,450,000 euro (for the steel and RC jackets of the structural elements). That is, they vary from 28.5 to 21.7 percent of the cost for demolition and reconstruction of the buildings, respectively.

Maintenance costs consider the cost of monitoring during the service life of the structures. Applying an appropriate annual revaluation rate, at the end of the new service life (50 years), these costs vary between about 77,000 euro (for the energy dissipation bracing systems) to about 38,500 euro (for the steel and reinforced concrete jackets of the structural elements).

In order to evaluate the terms to be inserted in the appropriate column of the decision matrix concerning the qualitative criteria - functional and architectural compatibility of the intervention, interruption of use, feasibility of the retrofitting strategy, damage limitation, and the next possible strength upgrade - it must transform qualitative judgments in terms of quantity, again using the Saaty's approach. For each of these criteria, a preference matrix was constructed through binary comparisons between alternatives according to the relevance with the examined criterion. Later, its principal eigenvector was determined and it was inserted in the appropriate column of the decision matrix after the consistency check.

Finally, the C_8 criterion analyzes the safety in construction site operations. For this criterion, the retrofitting alternatives were compared in terms of the risk level associated to them. The adopted methodology for the risk assessment considered the specific content of the Legislative Decree no. 81/08 and the UNI 10942:2001. In this work, a Building Information Model was partially defined in order to study the safety workplace evaluation, supporting in this way the decision-making process.

Based on the general list of risks provided by the UNI 10942:2001, the "*n*" risks present in each required activity for the realization of the single intervention were selected. After, the amount of risk $\{R_i\}$ associated with each required activity was calculated as shown in the following Eq. (3):

$$R_i = M \cdot P \quad (3)$$

Where M is the severity of injury of the person or the magnitude, and P is the probability that the risk will result in an accident (both factors can hire an integer between 1 and 4).

In order to compare the different choices, the risk level $\{R\}$ associated with each intervention alternative was calculated as shown in the following Eq. (4):

$$R = \sum_{i=1}^{n} R_i \quad (4)$$

The decision matrix is illustrated in the following Table 2.

Table 2- Decision Matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
a_1	1,900,000	69,954	0.565	0.134	0.073	0.657	0.648	674
a_2	1,520,000	57,242	0.262	0.310	0.073	0.046	0.085	280
a_3	1,450,000	38,346	0.118	0.495	0.594	0.094	0.043	223
a_4	1,550,000	77,023	0.055	0.061	0.259	0.203	0.224	325

7. Application of MCDM methods

After the definition of the decision matrix and the criteria weight vector, the selected MCDM methods were applied. The TOPSIS method provides:

i. The normalization of the decision matrix in order to homogenize the various terms (see Table 3);

Table 3- Normalized Decision Matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
a_1	0.588	0.561	0.888	0.222	0.111	0.945	0.936	0.813
a_2	0.471	0.459	0.412	0.515	0.111	0.066	0.123	0.338
a_3	0.449	0.307	0.185	0.822	0.905	0.135	0.062	0.269
a_4	0.480	0.617	0.086	0.101	0.395	0.292	0.324	0.392

ii. The weighing of the terms of the normalized decision matrix (see Table 4);

Table 4- Weighted Normalized Decision Matrix

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
a_1	0.061	0.017	0.208	0.015	0.018	0.316	0.021	0.038
a_2	0.048	0.014	0.096	0.036	0.018	0.022	0.003	0.016
a_3	0.046	0.009	0.043	0.057	0.145	0.045	0.001	0.013
a_4	0.049	0.019	0.020	0.007	0.063	0.098	0.007	0.018

iii. The identification of the ideal solution A^* and negative ideal solution A^- (see Table 5);

Table 5- Ideal solution A^* and negative-ideal solution A^-

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A^*	0.046	0.009	0.208	0.007	0.145	0.316	0.021	0.013
A^-	0.061	0.019	0.020	0.057	0.018	0.022	0.001	0.038

iv. Finally the determination of the relative distance C_{i^*} of the alternatives from the ideal solutions (see Table 6). The preferred option is the one having the maximum C_{i^*} value, which is the base isolation system. According to the sensitivity analysis of the results, this alternative is also sufficiently stable.

Table 6- Ranking of alternatives according to the TOPSIS method

	S_{i*}	S_{i-}	C_{i*}
a_1	0.131	0.352	0.729
a_3	0.322	0.135	0.295
a_4	0.300	0.104	0.257
a_2	0.341	0.083	0.196

According to the VIKOR method, the intervention alternatives were ranked based on the Q_i values. The preferred option is the one having the minimum Q_i value, which is the base isolation system (see Table 7). This alternative respects both acceptance conditions (acceptable advantage and acceptable stability in decision making). The Q_i value is determined for each option, assuming the value $\upsilon = 0.5$. In the same table, the S^*, S^-, R^*, and R^- values are also shown.

Table 7- Ranking of alternatives according to the VIKOR method ($\upsilon = 0.5$)

	S_i	R_i	Q_i
a_1	0.346	0.160	0.000
a_4	0.665	0.249	0.668
a_3	0.605	0.309	0.761
a_2	0.731	0.335	1.000

$S^* = 0{,}346$; $S^- = 0.731$; $R^* = 0.160$; $R^- = 0.335$.

Both applied methods lead to base isolation system (a_1) as the preferred retrofit option and the CFRP wrapping (a_2) as the worst alternative. While, the second and third place are reversed. Anyway, utilizing the VIKOR method the ranking may change. In fact, for $0\leq \upsilon <0.687$ the shown ranking (Table 7) does not change, but for $0.687\leq \upsilon \leq 1$, the rankings of the two methods are exactly the same ($a_1 > a_3 > a_4 > a_2$).

The investigated MCDM methods are easy to apply, but the VIKOR method is influenced by the double check of acceptability and the choice of the parameter υ. This parameter is fixed in the {0, 1} interval according to different weight of importance of each addend into the Q_i expression. For $\upsilon >0.5$, the decision maker gives more importance to the global performance of the alternative in respect to all the criteria. Instead, for $\upsilon <0.5$ the decision maker gives more weight to the magnitude of the worst performances exhibited by the alternatives in respect to each single criterion. Assuming $\upsilon =0.5$, the two aforementioned aspects are considered equally relevant.

8. Conclusions

Some technical norms, as for example the Italian code, prescribe a justified choice of the intervention type, without giving any information about it. The present work aims to show how in this field the MCDM methods and BIM models could be inserted. They allow you to define a rational and more detailed decision-making process in order to identify the optimum seismic retrofitting strategy for existing buildings.

The application of MCDM methods also permits to avoid that the choice is prejudiced by possible limited designer's skills and to achieve a solution that could be most acceptable to all involved parties. In this manner, it is possible to ensure an optimal utilization of resources and a continuous exchange of information that can also affect more territorial and decision-making levels. Moreover, these methods allow you to carry out a multidisciplinary preliminary analysis. Consequently, using appropriate criteria, it is possible to select intervention strategies for seismic retrofitting of buildings (in particular for the strategic buildings), that increase the cities resilience and reduce the seismic risk on large territorial scale.

9. Acknowledgements

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10. Copyrights

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