

# MULTI-CRITERIA APPROACHES FOR EARTHQUAKE RETROFIT STRATEGIES AT REGIONAL SCALE

Sonia Giovinazzi & Stefano Pampanin

*University of Canterbury, New Zealand*

## **ABSTRACT:**

Recent developments of viable and low-cost seismic retrofit solutions within a performance-based approach, suggest the possibility to implement “standardized” solutions at a regional scale. However, different and complex criteria should be considered in order to define the most effective retrofit strategy able to minimize the overall risk. First of all, the feasibility of the intervention should be investigated accounting for the actual limits of the available resources, e.g. financial, physical or human, which could represent a critical constraint for a large scale intervention. Secondly, it should be taken into account that the benefits and costs associated with seismic risk mitigation strategies might have different impacts into the local and regional economy, while affecting a wider variety of stakeholders, if not a substantial portion of the society as a whole. In this contribution, a multi-criteria approach is proposed as a valuable tool to select an effective retrofit strategy while accounting for both monetary and non-monetary-based criteria. The effectiveness of alternative retrofit options is assessed on a case study area using a multi-criteria approach and compared with the results from a more standard cost-benefit approach.

## **1 INTRODUCTION**

Recent catastrophic seismic events (e.g. Turkey 1999, 2003 and Taiwan 1999) have highlighted the need for the development of advanced but reliable retrofit solutions for under-designed structures. Latest developments and numerical/experimental validation of viable and low-cost retrofit solutions for pre-1970 buildings within a multi-level retrofit strategy approach, suggest the possible implementation of “standardized” solutions at a urban or territorial scale. Nevertheless, the decision to set a large scale retrofit strategy is still neither straightforward nor obvious. In addition to the technical aspects, e.g. improvement in the seismic performance of the retrofitted building with direct consequences on reduction of damage and casualties, issues associated to costs, practical implementation and social effects have to be accounted for.

By referring to two vulnerability methods, implemented within the Risk-EU project (2004) and based on an observational and a mechanical approach (Lagomarsino and Giovinazzi 2006), further refinements have been proposed by the authors (Giovinazzi et al. 2006) to better represent the seismic response of pre-1970 R.C. buildings, following recent results from numerical and experimental investigations. Using these refined vulnerability and capacity curves, the efficiency of targeting partial or total retrofit interventions, i.e. aiming at different target performance levels, as part of a territorial scale retrofit strategy (via the adoption of standardized multi-level retrofit strategies) have been investigated by means of seismic risk mitigation analyses on a case study region. A cost-benefit analysis approach, assuming a discount rate of 4%, has been carried out to evaluate the efficiency of alternative performance-based retrofit strategies. As a main result of this investigation, it has been shown that a partial retrofit approach (i.e. achievement of lower performance level while preventing the structural collapse), targeting a selected typology of buildings within a given region (localized intervention) appear to be a more attractive and efficient proposal (Giovinazzi and Pampanin 2007).

Moreover, in the same contribution, the intrinsic limitations of applying a rough but more traditional

cost-benefit analysis for assessing and prioritising the seismic retrofit at a territorial scale have been demonstrated. Cost-benefit analyses, balancing the structural requirements and associated benefits versus the costs, can be successfully implemented to support decision-makers when dealing with seismic retrofit of single structures. However, difficulties for the implementation of such analyses may arise when dealing with an intervention at urban or territorial scale, due to: 1) the fact that a unique solution can hardly satisfy at the same time multiple criteria which combine technical and social aspects; 2) the difficulties in reliably quantifying social and societal criteria.

In this paper, after a brief introduction to the basic concept of Multi-Criteria Decision Analysis, MCDA, the feasibility of adopting a multi-criteria approach is investigated and proposed as valuable tools to account for both monetary and non-monetary aspects when planning the implementation of retrofit strategies at territorial scale for the mitigation of the seismic risk. The enhanced capability of a multi-criteria approach in identifying the most suitable seismic mitigation strategy, based on strengthening/retrofit, will be discussed and compared to a more standard cost-benefit analysis. A practical example will be provided via the implementation of both a GIS-based cost-benefit analysis and of a MCDA to a case study region in Western Liguria Region, Italy.

## 2 COST-BENEFIT ANALYSIS FOR THE EVALUATION OF SEISMIC RETROFIT STRATEGIES AT A TERRITORIAL SCALE

### 2.1 Performance-based retrofit strategies: partial and total retrofit interventions

According to the concept of multi-level performance-based retrofit strategy, recently proposed in literature (Pampanin and Christopoulos, 2003) for pre-1970 frame systems, a partial retrofit, PR, aiming to achieve an intermediate performance objective, could be targeted if a full upgrade, or total retrofit, TR, is not achievable or is impractical from a cost and invasiveness viewpoint.

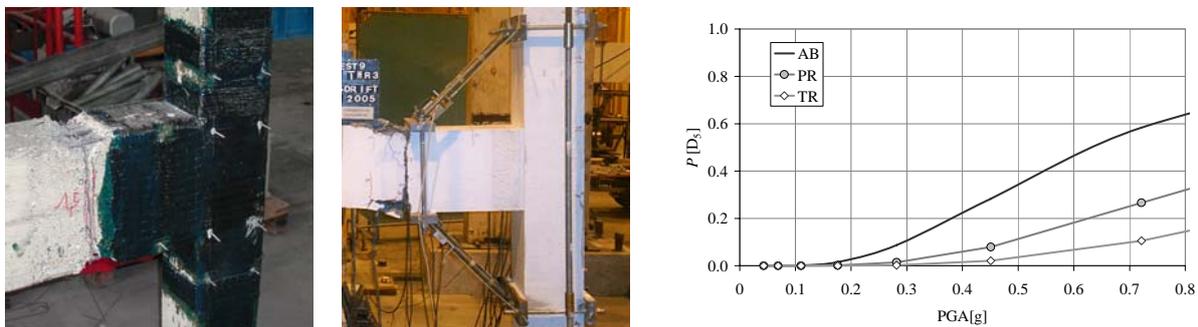


Figure 1. Alternative retrofit solutions: a) FRP (Pampanin et al. 2007); b) Metallic Haunch (Pampanin et al. 2006); c) Fragility curves representing the effects of multi-level performance-based retrofit strategies (AB=As Built, PR=Partial Retrofit, TR=Total Retrofit).

A multi-level performance-based retrofit strategy can be implemented with reference to alternative retrofit techniques (e.g FRP as in Fig.1a or metallic haunch as in Fig.1b). In particular, two levels of upgrading plus a “do nothing” option are considered in this contribution: 0) No Action–As Built condition (AB); 1) Partial Retrofit (PR); 2) Total Retrofit (TR). The effects and efficiency of alternative retrofit strategies can be appreciated by comparing fragility curves describing the probability of reaching or exceeding pre-defined levels of damage (Fig. 1c).

It could thus be suggested that, based on the results of damage scenario analyses pre- and post-retrofitting, a quick implementation in critical sub-areas or regions of “partial” retrofit strategies could be favoured, in order to drastically reduce to a manageable level the consequences of the seismic event. A practical example will be given with the case study described in the following sections.

### 2.2 Investigating the benefits and costs of alternative retrofit strategies for a study case

The efficiency of targeting a partial or total retrofit intervention as part of a territorial scale retrofit

strategy, via the adoption of standardized multi-level retrofit strategies, have been investigated and confirmed in a previous contribution (Giovinazzi and Pampanin 2007). A virtual implementation of retrofit strategies and mitigation analyses, basically consisting on a cost-benefit analysis, have been carried out on a case study region identified with Western Liguria, Italy (Fig. 2a). A summary will be given herein, prior to introducing the proposed multi-criteria approach.

The building vulnerability and the expected consequences of an earthquake in this area have been examined as part of an Italian National research project for the definition of Earthquake scenario and strategies for the preservation of historic centres funded by the INGV-GNDT (2004). The inventorying of the buildings stock, including number and characteristics, has been carried out by processing census statistical data (Fig. 2b and 2c). The total number of current buildings in the selected region is 49,372, with RC and URM typologies representing the 36% and 64% of the total, respectively. In spite of the higher number of URM buildings, the majority of population lives in RC buildings (60% out of the total 211,349 inhabitants living in RC buildings), mostly designed prior to 1971 (56%). Focusing on the characteristics of pre-'71 buildings, the majority are low-rise buildings (59% 1÷2 floors, 33% 3÷5 floors, only 9% >5 floors) and a not negligible part is prone to soft-storey mechanisms (18%) having infills present only in the upper storeys. The highest concentration of pre-'71 buildings is in the costal area where soil amplification effects can be expected.

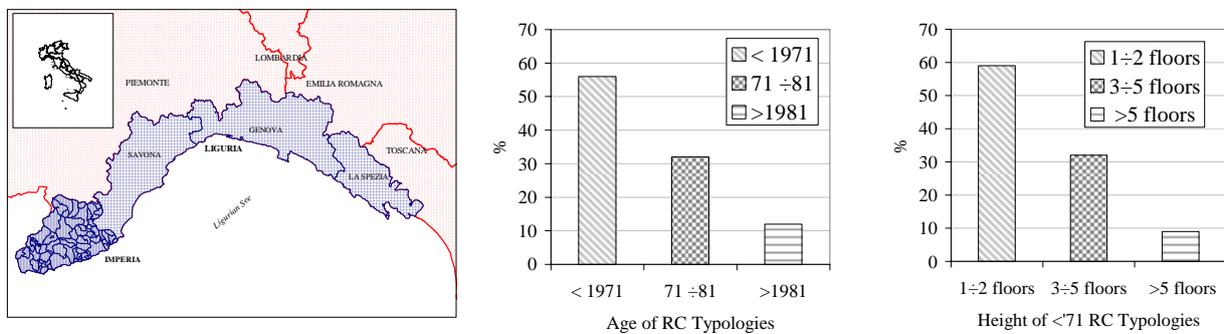


Figure 2. Western Liguria, Italy and characteristics of the buildings stock: a) study area (Imperia County); b) classes of age for RC typologies, c) classes of height for >'71 - RC typologies.

A capacity spectrum-based developed for European building typologies and calibrated on the basis of a macroseismic vulnerability method and observed damage data (Lagomarsino and Giovinazzi 2006) within the Risk-EU project (2004) has been adopted for the representation of the seismic behaviour of pre-1971 RC buildings. Partial (PR) and total (TR) retrofit intervention have been represented within the same capacity spectrum-based vulnerability method by properly specifying the upgrading factors for the capacity-curves (Giovinazzi et al. 2006), based on results from recent numerical and experimental investigations. In the deterministic damage scenario analysis, the maximum historical event in the region has been assumed, corresponding to the Western Liguria Feb 23, 1887 earthquake (M=6.3) which caused over 509 victims, severe destruction in costal towns and villages (Fig. 3a). The expected consequences to buildings and people (Fig. 3b,c) and the relative costs have been evaluated for alternative retrofit strategies.

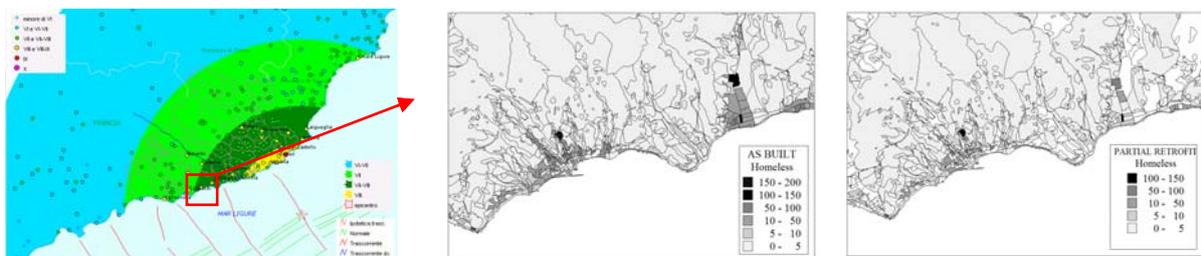


Figure 3. Loss estimation on the study case region before and after retrofitting: a) IEMS-98 deterministic hazard scenario for the 1887 event and comparison with the observed intensities; b) homeless people expected for as built conditions; c) homeless people expected after a partial retrofit intervention.

Table 1 summarises the expected outcomes in terms of net Present Value, NPV, assuming alternative retrofit strategies for the study case, as resulting from a previous implementation (Giovinazzi and Pampanin 2007). The NPV has been evaluated at different periods (1-50 years) assuming a discount rate of 4%.

It can be highlighted that the hypothesis to retrofit the total stock of the pre'71 buildings would be economically inconvenient either in the case of a partial or a total retrofit intervention regardless of the time frame considered. On the other hand, retrofit interventions restricted to the most vulnerable pre'71 R.C. building typologies (i.e. pilotis buildings) are shown to be effective from a cost-benefit point of view. Similarly as partial retrofit solution localized within targeted areas seems to be a valuable solution even in a medium term plan. A partial retrofit together with an adequate selection of the spatial distribution of the retrofit intervention can thus result into an attractive cost-effective intervention when initial constraints due to limited budget/resources have to be accounted for.

Furthermore, as expected, in all cases, the longer the period prior to the occurrence of the earthquake event, the more negligible are the direct benefits (until they becoming negative) of a retrofit intervention as highlighted by a basic cost-benefit analyses.

It is clear, from all the above considerations, how additional socio-political criteria have to be considered when analysing the validity of territorial scale mitigation strategies.

Table 1. Cost-benefit analyses of alternative retrofit solutions (Giovinazzi and Pampanin 2007)

Retrofit interventions	<'71 all			<'71 pilotis only			localized <'71 pilotis only		
	AB	PR	TR	AB	PR	TR	AB	PR	TR
<i>1 year</i>	-	-436	-1296	-	75	61		27	26
<i>Benefits minus Costs</i>									
<i>10 years</i>	-	-571	-1313	-	4	-32		17	15
<i>(NPV)</i>									
<i>20 years</i>	-	-662	-1324	-	-43	-95		9	7
<i>50 years</i>	-	-793	-1340	-	-112	-186		-1	-4

### 3 MULTI-CRITERIA DECISION ANALYSIS FOR THE EVALUATION OF ALTERNATIVE RETROFIT OPTIONS AT TERRITORIAL SCALE

#### 3.1 Features of Multi-Criteria Decision Analysis

Multi-criteria decision analysis (MCDA) is a dynamic process, widely applied in several fields, in which both management and engineering levels can be distinguished. The management level defines the goals and chooses the final “optimal” solution amongst several technically-sound alternative options proposed by engineers.

The basic steps for the implementation of MCDA include the identification of the decision-maker DM (or group of Decision-Makers, here referred to as DMs) involved in the decision-making process, along with their preferences, and the statement of the objective or a set of objectives the decision makers attempts to achieve. Secondly, the main objectives are decomposed into a hierarchy of evaluation criteria,  $C_j$  and decision alternatives,  $A_i$  (herein referred to as alternative retrofit solution  $RS_i$ ), and the relationships between the main criteria  $C_j$ , and the alternatives  $RS_i$  are clarified (Fig. 4a). Pairwise comparisons among the decision elements (criteria and sub-criteria) are judged by the DMs and an evaluation function is assumed in order to estimate the relative weight of the decision elements. Finally the set of outcomes or consequences associated with each alternative-criterion pair, namely the performance measure  $RS_iC_j$  of the  $i$ -th retrofit alternative, is evaluated and arranged in terms of the so-called Decision Matrix  $D=[RS_iC_j]$  (Fig. 4b).

In this paper, the aforementioned steps have been implemented according to one of the more widely adopted MCDA process, the Analytic Hierarchy Process, AHP, proposed by Saaty (1980).

The TOPSIS technique (Technique for Order Preference by Similarity to Ideal Solution) proposed by

Hwang and Yoon (1981), has been adopted as a decision rule (or combination rules) for selecting the most appropriate alternative from the decision matrix.

It is worth noting that a fuzzy set theory (Ross 1995) could be implemented within a MCDA to represent the fuzziness and vagueness inherently associated to any human decision-making process. However, for the sake of an easier understanding of the overall procedure, crisp numbers will be adopted in this paper, while the implementation of a fuzzy multi-criteria approach for multi-level performance-based retrofit will be proposed in future publications.

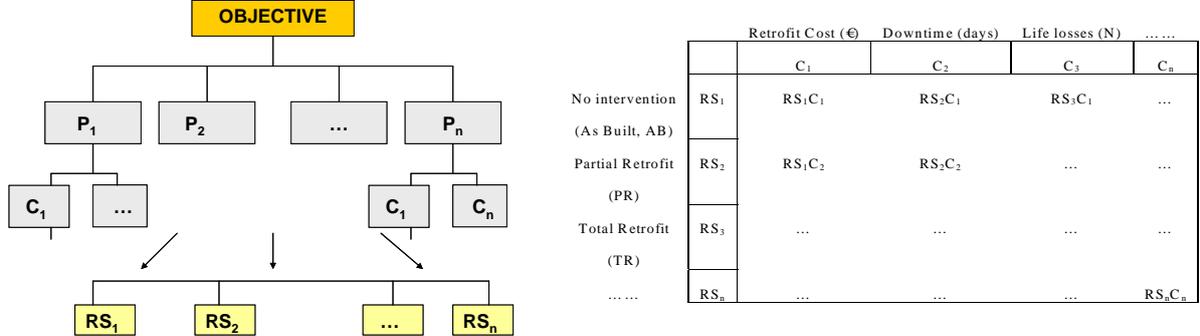


Figure 4. Features of a MCDA: a) decision criteria  $C_j$  and alternatives  $RS_i$ , represented in term of a decision tree; b) decision matrix  $D=[RS_iC_j]$

### 3.2 Evaluation Criteria

A set of eleven evaluation criteria is herein suggested. They are organised under three major perspectives of the seismic risk reduction, namely to guarantee: 1) a sustainable retrofit intervention, 2) an effective emergency management and 3) a resilient post-earthquake reconstruction. An attempt has been made to propose comprehensive, non redundant (avoiding double-counting of decision consequences), measurable (both qualitative and quantitative) and operational criteria trying to cover the main aims of a seismic retrofit intervention at territorial scale.

It is worth underlying that the evaluation criteria herein proposed are not intended to be exhaustive and are mainly proposed to facilitate a scientific discussion of the problem. Refinements could, for example, be achieved by liaising with local decision makers confronted with a simulated earthquake scenario exercise.

The assumed criteria are described and evaluated as follows:

#### Sustainable Retrofit Intervention (SRI) Perspective

$C_1 = installation\ cost$  (fuzzy or crisp number, in  $\text{€m}^2$ ). This criterion represents the total cost for the practical implementation of each alternative, including the required materials and labour. It has been evaluated according to FEMA (1994) assuming that TR would target a performance level in between “Immediate Occupancy” and “Damage Control” while PR would target a “Life Safety”. As a result,  $AB=0\ \text{€m}^2$ ,  $PR=200\ \text{€m}^2$ ,  $TR=350\ \text{€m}^2$ . More details can be found in Giovinazzi and Pampanin (2007).

$C_2 = disruption\ of\ use$  (qualitative relative parameter). This criterion represents the total duration of the retrofit intervention from the required demolition to the completion, considering all phases of the intervention. It is herein assumed that a TR would require a disruption of use 30% to 50% higher than that associated to a PR.

$C_3 = incremental\ rehabilitation$  (qualitative relative parameter). This criterion represents the feasibility of reaching the targeted goal (e.g. the correction of the priority deficiencies as soft-storey, etc.) through an incremental rehabilitation. The incremental rehabilitation phases the seismic rehabilitation into an ordered series of discrete actions implemented over a period of several years, and, whenever feasible, timed to coincide with regularly scheduled repairs, maintenance, or capital improvements. It is here assumed that a PR intervention would be three times more suitable for an incremental

rehabilitation when compared to a TR intervention.

### Effective Emergency Management (EEM) Perspective

The quantification of all the following emergency management criteria have to be evaluated via the implementation of either deterministic or stochastic GIS-based damage scenario analysis. For the description of the physical damage to the building, the EMS-98 macroseismic scale (Grunthal 1998) damage grades have been considered, describing the observed damage for structural and non structural components. Five damage grades are identified  $D_k$   $k=0\div5$ :  $D_1$  – slight,  $D_2$  – moderate,  $D_3$  – heavy,  $D_4$  – very heavy,  $D_5$  – destruction (collapse), plus the absence of damage  $D_0$  – no damage.

$C_4 =$  *amount of debris* (damage scenario-based quantitative parameter [tons  $\times 10^3$ ]). This criterion represents the amount of debris due to structural and non structural damage of buildings and has been evaluated according to the approach implemented in HAZUS (1999).

$C_5 =$  *trapped people* (damage scenario-based quantitative parameter, number). This criterion represents the number of people requiring the intervention of SAR (Search and Rescue) teams. It has been evaluated as a function of the number of people living in collapsed building,  $D_5$ .

$C_6 =$  *injured people* (damage scenario-based quantitative parameter, number). This criterion represents the number of people requiring healthcare assistance. It has been evaluated as a function of the number of people living in building that have sustained very heavy damage,  $D_4$  and collapse,  $D_5$  according to the statistical correlation for the Italian regions proposed by Bramerini et al. (1995) on the basis of data from recent earthquakes.

$C_7 =$  *homeless people* (damage scenario-based quantitative parameter, number). This criterion represents the number of people requiring temporary shelter. It has been evaluated as a function of the number of people living in building that have sustained heavy damage,  $D_3$  to collapse,  $D_5$  (according to Bramerini et al. 1995).

### Resilient Reconstruction (RR) Perspective

$C_8 =$  *Earthquake costs* (damage scenario-based quantitative parameter, number in M€). This criterion represents the earthquake costs limited to the building reconstruction costs, and the costs sustained for the injuries (6,250 €/person), the casualties (195,000 €) and the relocation of homeless people (6,250 €/4 person). In accordance with what observed in the 2002 Molise earthquake (Giovinazzi et al. 2007) the building reconstruction costs have been assumed as follow: new construction and repair for  $D_4=1,400$  €/m<sup>2</sup>,  $D_3= 875$  €/m<sup>2</sup>,  $D_2= 250$  €/m<sup>2</sup>,  $D_1=25$  €/m<sup>2</sup>. A regional economic impact in terms of direct and indirect economic effects should be accounted for.

$C_9 =$  *Reconstruction feasibility* (damage scenario-based quantitative parameter, crisp number). This criterion represents the estimated duration (in number of day) of the physical restoration and has been evaluated according to HAZUS approach (1999). Material availability, skilled labour required should be as well included.

$C_{10} =$  *Acceptability by the local public* (damage scenario-based quantitative parameter, number). This criterion tries to quantify the expected social aspects connected with the permanent relocation, the loss of memorabilia and properties. Reference should be made to the research in the field of social-science for the quantification of this criterion (Baradan 2006). The criterion has been temporarily evaluated as a function of the number of building very heavily damaged,  $D_4$  and collapsed,  $D_5$ .

### 3.3 *Weighting the retrofit perspectives and the evaluation criteria*

Importance weights  $w_k$  are introduced to measure the relative importance when considering the perspectives and the (qualitative and quantitative) criteria  $C_j$ , described in Par. 3.2. This evaluation has been carried out according to the analytic hierarchy process AHP (Saaty 1980). The importance weights  $w_k$  are key factors in the process of multi-criteria decision making, as are the ones reflecting the decision maker's experience, judgment and preference in the framework of the MCDA approach.

The fundamental input to the AHP is the DMs informed judgment to pairwise comparisons. DMs responses to the set of questions “How important is criterion A relative to criterion B?” are gathered

in verbal form and subsequently codified according to a nine-point scale (Tab. 2) and finally organised in terms of a pairwise comparison matrix  $C=[a_{ij}]$ .

The number in the  $i^{\text{th}}$  row and  $j^{\text{th}}$  column, corresponding to the element  $a_{ij}$  of the pairwise comparison matrix  $C=[a_{ij}]$  represents the relative importance of the criterion  $c_i$  as compared with the criterion  $c_j$ , as follows:  $a_{ij}=1$  if the two objectives are *equal in importance*;  $a_{ij}=3$  if  $c_i$  is *weakly more important* than  $c_j$ ;  $a_{ij}=5$  if  $c_i$  is *strongly more important* than  $c_j$ ;  $a_{ij}=7$  if  $c_i$  is *very strongly more important* than  $c_j$ ;  $a_{ij}=9$  if  $c_i$  is *absolutely more important* than  $c_j$ . As  $a_{ij}=1/a_{ji}$  and  $a_{ii}=1$ , decision makers are requested to assign  $n(n-1)/2$  judgements being  $n$  is the number of criteria accounted for in the decision process.

Table 2. Rating scale assumed for the hierarchy process AHP pairwise comparison.

Less important									Equally Important	More important								
Extremely	Very Strongly			Strongly	Moderately			Moderately		Strongly	Very Strongly			Extremely				
..	1/9	1/8	1/7	1/6	1/5	1/4	1/3	1/2	1	2	3	4	5	6	7	8	9	..

Within the AHP approach the importance weight  $w_k$  are evaluated according to (Saaty, 1980) applying the eigenvalue theory to the pairwise comparison matrix  $C=[a_{ij}]$ . The weights are evaluated as the element in the eigenvector associated with the maximum eigenvalue on the matrix:

$$C[a_{ij}]W = \lambda_{\max} W \quad (1)$$

where  $W$  is the eigenvector, referred to as the weight vector, of the matrix  $C=[a_{ij}]$  and  $\lambda_{\max}$  is the largest eigenvalue of  $C=[a_{ij}]$ .

In order to ensure the consistency of judgments in the pairwise comparison, the consistency ratio CR is evaluated, defined by Saaty (1980) as:

$$CR = \frac{1}{RI} \left( \frac{\lambda_{\max} - n}{n - 1} \right) \quad (2)$$

where  $n$  is the number of items being compared in the matrix and RI is a random index, the average consistency index of randomly generated pairwise comparison matrix of similar size. The upper threshold values consistency index CR have been evaluated by Saaty (1994) as follow: CR=0.05 for matrices  $C_{3 \times 3}$ , CR=0.08 for matrices  $C_{4 \times 4}$ , CR=0.1 for matrices larger than  $C_{4 \times 4}$ . If CR overcome the upper threshold, the preference assignment need to be revised.

### 3.4 Implementation of MCDA to the study case

A practical implementation of a MCDA is carried out on the case study area. A pairwise comparison matrix  $P$  (Eq. 3) has been generated in order to assess the priority weight of the three different seismic retrofit perspectives considered (as defined in Par. 3.2), namely: sustainable retrofit intervention, SI, effective emergency management, EEM, and resilient reconstruction, RR.

$$P = \begin{array}{c|ccc} & SI & EEM & RR \\ \hline SI & 1 & 1/3 & 1/5 \\ EEM & 3 & 1 & 1/3 \\ RR & 5 & 3 & 1 \end{array} \quad (3)$$

The maximum eigenvalue  $\lambda_{\max} = 3.033$  has been calculated according to Eq. 1 and the consistency property of the matrix has been checked by evaluating the Consistency Ratio (as per Eq. 2) resulting in CR= 0.028. The perspectives eigenvector  $W_P$  of  $P$  results in the sought weight  $w_{SI}$ ,  $w_{EEM}$ ,  $w_{RR}$  (Eq. 4), referring to the aforementioned perspectives SI, EEM and RR, respectively:

$$W_P = \{w_{SI}, w_{EEM}, w_{RR}\} = \{0.11, 0.31, 0.58\} \quad (4)$$

Following the same procedure adopted for the evaluation of the perspective weights, the relative importance weights  $w_k$  for both qualitative and quantitative criteria  $C_j$  assumed as performance indicators of the three seismic retrofit perspectives (as described in Par.3.2) have then been evaluated considering a sample area within the study region.

Figure 5 shows the values of the importance weights  $w_i$  resulting from three pairwise comparisons matrixes built for: sustainable retrofit intervention criteria  $C_{SI[3 \times 3]}$ ,  $C_{SI}=\{0.3; 0.09; 0.61\}$ ; effective emergency management,  $C_{EEM[4 \times 4]}$   $C_{EEM}=\{0.18; 0.54; 0.22; 0.06\}$ ; and resilient reconstruction  $C_{RR[3 \times 3]}$ ,  $C_{RR}=\{0.16; 0.66; 0.18\}$ ; . The resulting consistency ratios for the three matrices result respectively in  $CR_{SI}=0.028$ ,  $CR_{EEM}=0.072$ ,  $CR_{RR}=0.01$ .

Geometric average has been applied to combine the importance weights of the perspectives (Eq. 1) with the ones resulting for the criteria. The relative weights are shown in Fig. 5 (in italic).

In the simulated case study, the Resilient Reconstruction, RR with a priority weight of 0.59, is the most important perspective for a seismic retrofit intervention at a territorial scale, following by Effective Emergency Management, EEM, with a priority weight of 0.33.

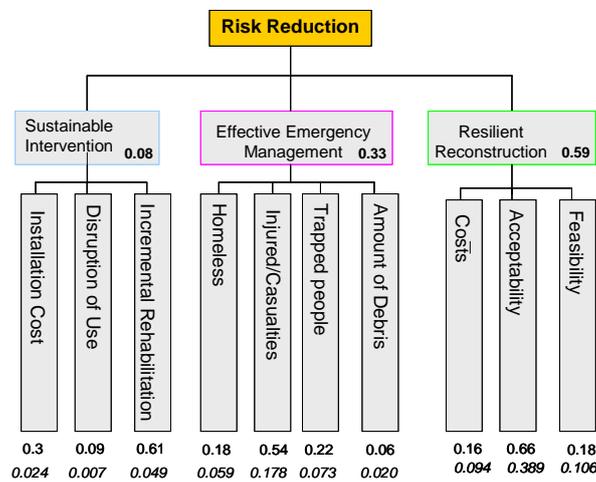


Figure 5. Hierarchical structure in terms of perspectives and criteria for a seismic retrofit intervention at territorial scale and values of: a) priority weights for the perspectives; b) priority weights of the criteria under the same perspective; c) relative priority weights of the criteria among all the criteria (in *italic*).

According to this analysis, the “acceptability of the reconstruction” appears as the most important criterion overall (0.389), with a weight of 0.66 within the Resilient Reconstruction perspective. This means that, according to this analysis, a crucial feature of the seismic retrofit intervention at a territorial scale would be to speed up the reconstruction process. ‘Limitation of injuries and casualties’ results as the most important criterion within the Effective Emergency Management, EEM perspective with a priority weight of 0.54 and ranks the second position overall (0.178). The third most important criterion is the “reconstruction feasibility” with an overall score of 0.106, followed by the “reconstruction costs” (0.094). It is worth noting that although the financial issues, namely the retrofit installation costs, are usually emphasized as the discriminating parameter while planning for a retrofit intervention, according to this MCDA implementation they appear in a relative low rank among all indicators (0.024).

It is also worth observing that, according to the hierarchical structures assumed in terms of three main perspectives and performance criteria, a cost-benefit analysis would be an extreme case of a MCDA, corresponding to the following perspectives eigenvector  $W_p=\{1, 0, 1\}$ . The performance criteria eigenvector for the sustainable intervention, SI and for the resilient reconstruction, RR would therefore be  $W_{SI}=\{1,0,0\}$ , and  $W_{RR}=\{1,0,0\}$  representing, respectively, the cost of the retrofit intervention and the benefits due to the reduction of the earthquake costs.

### 3.5 Ranking the alternative retrofit solutions

The set of outcomes or consequences associated with each  $i^{\text{th}}$  retrofit solution and  $j^{\text{th}}$  criterion pair (with  $i=1\div 3$  and  $j=1\div 10$ ), namely the performance measure  $RS_iC_j$  have been evaluated and arranged within a decision matrix  $D=[RS_iC_j]$  as shown in Table 3.

Table 3. Decision matrix  $D=[RS_iC_j]$

		SI		EEM				RR			
		Installation Cost [M€]	Disruption of use [Q]	Incremental rehabilitation [Q]	Debris [thousand Ton]	Trapped [N. people]	Injured [N. people]	Homeless [N. people]	Reconstruction Costs [M€]	Reconstruction Feasibility [N day]	Reconstruction Acceptability [N buildings]
		C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>	C <sub>4</sub>	C <sub>5</sub>	C <sub>6</sub>	C <sub>7</sub>	C <sub>8</sub>	C <sub>9</sub>	C <sub>10</sub>
Retrofit Alternative	A <sub>1</sub> =AB	0	0	0	18	53	79	6129	592	1102	174
	A <sub>2</sub> =PR	815	0.17	0.87	10	13	20	2999	386	592	67
	A <sub>3</sub> =TR	4095	0.83	0.13	8	7	10	2182	1426	452	44

The performance measures  $RS_iC_j$  have been evaluated with to the damage scenario (described in Par. 2.2), with the exception of the qualitative criteria under the reduction category, namely the “disruption of use” and the “incremental rehabilitation” (criteria C<sub>2</sub> and C<sub>3</sub> in Table 3) that have been translated in terms of crisp number on the basis of expert judgments. After normalising the  $RS_iC_j$  values, the decision matrix  $D=[RS_iC_j]$  has been weighted by multiplying the original matrix by the relative priority weight vector  $\{w_k\}$  (Fig. 4), obtaining the matrix  $D^*=[RS_iC_j] \cdot \{w_k\}$  shown in Table 4.

Table 4. Normalised and weighted decision matrix  $D^*=[RS_iC_j] \cdot \{w_k\}$ : anti-ideal and ideal solution according to the TOPIS method (Hwang and Yoon, 1981)

	Intervention Sustainability			Effective Emergency Managent				Resilient Recostruction		
	C <sub>1</sub>	C <sub>2</sub>	C <sub>3</sub>	C <sub>4</sub>	C <sub>5</sub>	C <sub>6</sub>	C <sub>7</sub>	C <sub>8</sub>	C <sub>9</sub>	C <sub>10</sub>
A <sub>1</sub> =AB	0.000	0.000	0.000	0.030	0.121	0.049	0.010	0.023	0.197	0.06
A <sub>2</sub> =PR	0.012	0.005	0.010	0.046	0.030	0.012	0.005	0.015	0.106	0.02
A <sub>3</sub> =TR	0.059	0.024	0.001	0.014	0.016	0.006	0.003	0.055	0.081	0.02
<i>Anti-ideal</i>	<i>0.059</i>	<i>0.024</i>	<i>0.000</i>	<i>0.046</i>	<i>0.121</i>	<i>0.049</i>	<i>0.010</i>	<i>0.055</i>	<i>0.197</i>	<i>0.064</i>
<i>Ideal</i>	<i>0.000</i>	<i>0.000</i>	<i>0.010</i>	<i>0.014</i>	<i>0.016</i>	<i>0.006</i>	<i>0.003</i>	<i>0.015</i>	<i>0.081</i>	<i>0.016</i>

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) proposed by (Hwang and Yoon, 1981) has been then used to identify the most appropriate alternative, by evaluating the shortest distance from an ideal solution and the longest distance from the worst possible (anti-ideal) solutions (corresponding to the best and the worst performance value in Table 4, respectively, according to each criteria). Each criterion would thus reach its minimum or maximum possible value, for the ideal and anti-ideal solution, respectively. The only exception occurs for the criterion C<sub>3</sub> (incremental rehabilitation) where the maximum value represents the ideal solution whilst the minimum value corresponds to the anti-ideal one. The Euclidean distance for each  $i^{\text{th}}$  alternative retrofit solution  $RS_i$  from the ideal and anti-ideal solution are shown in Table 5 and indicated as  $D_i$  and  $D_i^-$ , respectively. Shown in the same Table 5 is also the closeness coefficient  $CC_i$  (known also as relative closeness), evaluated as the distance to anti-ideal solution divided by the sum of the ideal and anti-ideal solutions (Table 5). According to the TOPIS method, the best alternative is the one with the

largest  $CC_i$  value, i.e. with the shortest distance from the ideal solution.

Table 5. Euclidean distances from the alternative i-th to the ideal  $D_i$  and to the anti-ideal  $D_i^-$  solution and closeness coefficient  $CC_i$ .

	$D_i$	$D_i^-$	$CC_i$
$A_1=AB$	0.073	0.170	0.300
$A_2=PR$	0.154	0.034	0.818
$A_3=TR$	0.172	0.081	0.679

For the implementation presented in this contribution, the best solution for a retrofit intervention at a territorial scale results to be a partial retrofit RP intervention while the worst solution, as rationally expected, would be the “no-action” approach, thus maintaining the as-built condition AB).

It is worth noting that these results have been obtained in the hypothesis of retrofitting the total stock of the pre’71 buildings. When implementing a simple cost-benefit analysis for the same case (shown in Table 1), any retrofit option (either partial or total) would have instead resulted economically inconvenient and not justifiable.

#### 4 CONCLUSIONS

The advantages of implementing a Multi-Criteria Decision Analysis, MCDA, to support decision makers in the selection of an effective seismic retrofit strategy at a territorial scale have been discussed and demonstrated. The proposed multi-criteria approach is able to account for both monetary and non-monetary aspects related to technical (e.g. structural performance) or social issues (e.g. occupancy disruption, reconstruction acceptability, etc.), while accommodating the wishes, sometime controversial, of several decision makers.

Focus in the analysis has been given to three main targeted perspectives as part of the risk reduction strategy, namely a) maximising the sustainability of the retrofit strategy, b) minimizing the consequences of the event aiming to guarantee an effective emergency management, c) minimizing the expected losses after an earthquake scenario in order to guarantee the maximum resilience of the community during the reconstruction process.

The effectiveness of alternative retrofit solutions has been assessed according to the MCDA with reference to a case study area subjected to a deterministic earthquake scenario within a GIS environment. When comparing the results with those obtained by a more traditional and simplistic cost-benefit approach, it appeared clear that a multi-criteria approach, which naturally tends to reproduce our rational approach within a decision making process, can more properly appreciate the benefit of a retrofit intervention, particularly when targeting an intermediate performance upgrade and limited to selected typologies and number of buildings due to budget constraint (e.g. Partial Retrofit vs. Full Retrofit).

It is also worth noting that, although a deterministic damage scenario analysis has been adopted in this contribution, focused on the conceptual proof of the method, a probabilistic seismic analysis approach can be alternatively implemented within the same framework. Comparative results of a deterministic vs. a probabilistic MCDA will be given in future contributions.

#### ACKNOWLEDGMENTS

The financial support provided by the NZ Foundation of Science, Research and Technology, FRST, through the Research Project “Retrofit Solutions for NZ” is acknowledged.

## REFERENCES:

- Baradan, B. 2006. Analysis of the post-disaster reconstruction process following Turkish earthquakes, 1999. *Proc of. 3<sup>th</sup> i-Rec International Conference on post-disaster reconstruction "Meeting stakeholder interests, analysis of the post-disaster reconstruction"*. Florence, Italy.
- Bramerini F., Di Pasquale G., Orsini A., Pugliese A., Romeo R., Sabetta F., 1995. Seismic risk for the Italian territory. Proposal for a methodology and preliminary results. Technical report of the Servizio Sismico Nazionale SSN/RT/95/01, Roma, Italy (In Italian).
- FEMA156 1994. Typical Costs for Seismic Rehabilitation of Existing Buildings. Washington, D.C.
- Giovinazzi S., Pampanin S. and Lagomarsino S., 2006. Alternative Retrofit Strategies for pre' 70 buildings: vulnerability models and a damage scenarios. *1<sup>st</sup> ECEES*, Geneva, Switzerland.
- Giovinazzi S., Lemme A. Podestà S., Resemini S., 2007. Analysis of observed damage data finalised to the calibration of vulnerability, damage and cost and reconstruction models for residential and strategic buildings. *Proc. of 12<sup>th</sup> Italian Conference on Earthquake Engineering*, Pisa, Italy (In Italian).
- Giovinazzi S. and Pampanin S., 2007. Mitigation Analyses for the Selection of Effective Seismic Retrofit Strategies at a Territorial Scale. *Proceedings NZSEE 2007 New Zealand Society for Earthquake Engineering Annual Conference*. Palmerstone North, New Zealand, March/April 2007.
- Grunthal G., 1998. European Macroseismic Scale, European Centre of Geodynamic&Seismology, Luxemburg.
- HAZUS 1999. Earthquake Loss Estimation Methodology - Technical and User Manuals. Federal Emergency Management Agency, Washington, D.C.
- Hwang, C.L. and Yoon, K. (1981), Multiple Attribute Decision Making, Lecture Notes in Economics and Mathematical Systems, Springer-Verlag: Berlin.
- INGV-GNDT 2004. Earthquake scenario in Western Liguria, Italy, and strategies for the preservation of historic centres, Research Project (2002-2004) funded by the INGV, Civil Protection Department, Italy.
- Lagomarsino S. and Giovinazzi S. 2006. Macroseismic and Mechanical Models for the Vulnerability assessment of current buildings. *Bulletin of Earthquake Engineering*, Special Issue "Risk-Ue Project". 4(4).
- Pampanin S. and Christopoulos C. 2003. Non-invasive Retrofit of Existing RC Frames Designed for Gravity Loads only, paper n. 170, fib Symposium Concrete Structures. in Seismic Regions, Athens.
- Pampanin, S., Christopoulos, Chen, T-H., 2006 Development And Validation of a Haunch metallic Seismic Retrofit Solution for Existing Under-Designed RC Frame Buildings, *Earthquake Engineering and Structural Dynamics*; 35:1739–1766.
- Pampanin, S., Bolognini, D., Pavese, 2007 Performance-based Seismic Retrofit Strategy for Existing Reinforced Concrete Frame Systems using FRP composites, *ASCE Journal of Composites for Construction*, Special Issue on "Recent International Advances in FRP Research and Application in Construction", 11(2): 211-226.
- RISK-EU 2004 The European Risk-Ue Project: An Advanced Approach to Earthquake Risk Scenarios (2001-2004) [www.risk-ue.net](http://www.risk-ue.net).
- Ross T.J. 1995. Fuzzy Logic with Engineering Applications. McGraw Hill, New York.
- Saaty, T. L. 1994. How to make a decision: the analytic hierarchy process. *Interfaces*, 24(6), 19–43.
- Saaty, T.L., 1980. The Analytic Hierarchy Process, New York, N.Y., McGraw Hill. Reprinted by RWS Publications, Pittsburgh, 1996.