Multi Criteria Decision Making Tool for the Selection of Seismic Retrofitting Techniques

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Abstract

Upgrading existing buildings to meet current seismic design codes is important in high seismic hazard regions. Decision makers must choose from many possible retrofitting options, each with inherent advantages and disadvantages. The two main decision drivers that are commonly used are: increasing engineering performance (ductility, strength, etc.) and reducing cost. There is currently little information that incorporates socio-economic factors (e.g., aesthetics, sustainability) into the decision making process. The aim of this paper is to develop a multi criteria decision making tool that takes both the engineering and socio-economic factors into consideration for retrofit selection. Since the importance of each factor varies based on building type, location, and attitude of the decision makers, OWA operators will be utilized. As well, for multiple decision makers, credibility factors will be introduced. This model can be expanded in the future to incorporate new retrofitting techniques and selection criteria.

Keywords: seismic retrofitting, decision making, fuzzy

1 INTRODUCTION

Most of the buildings in existence today have not been built or maintained according to current seismic design codes (Thermou and Elnashai 2006). These buildings may be at risk to seismic induce damage for several reasons: poor design standards and detailing, changes to seismic hazard zoning, lack of code enforcement, or the use of outdated, inadequate design codes (Tesfamariam and Saatcioglu 2010). In most cases, it is not economically viable to reconstruct these buildings according to code. Instead, a common approach is to retrofit and strengthen these buildings in order to increase their seismic performance to meet current code requirements for new construction (Thermou and Elnashai 2006; Foo and Davenport 2003).

Retrofitting existing buildings is important to protect both the building and its occupants in the event of seismic activity. The buildings at risk are not limited to a certain occupancy or construction type. However, buildings of higher occupancy, such as schools and hospitals, pose a greater risk to human life. Over the past years, the technologies and solutions available for the strengthening of existing buildings have increased in number (Caterino *et al*. 2008; Thermou and Elnashai 2006). Each possible solution has inherent advantages and disadvantages in terms of increasing engineering performance as well as many socio-economic criteria that may be important to the decision maker. The increase in possible solutions has left decision makers with a more difficult decision than in the past. They must now consider many different factors when deciding upon the best retrofitting solution for their circumstances.

For the most part the two main decision drivers will typically remain cost and engineering performance (strength, ductility, etc.). However, there is a multitude of socio-economic factors to be considered as well. Some of the factors can include aesthetics/preservation of architecture, duration of work/disruption of use, cost (installation and maintenance), sustainability, and availability of workmanship and materials (Figure 1) (Tesfamariam *et al.* 2010).

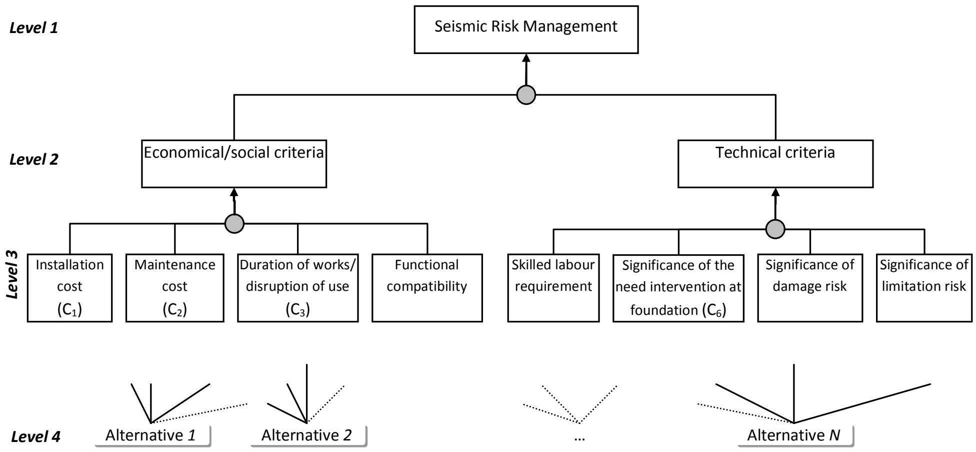

Figure 1. Hierarchical framework for seismic risk management
(after Tesfamariam *et al*. 2010)

One of the main problems associated with choosing and implementing retrofitting techniques is that there are no specific code requirements (Prebix *et al*. 1989). It is then for this reason that a multi criteria decision making (MCDM) tool is necessary. Multi criteria decision-making (MCDM) techniques deal with problems where alternatives are predefined and the decision-maker ranks available alternatives. In this paper, ordered weighted averaging (OWA) operators (Yager 1988) are proposed to select desired retrofit technique. The motive behind selecting the OWA operator for aggregation of input parameters is their capability to encompass a range of operators from minimum to maximum including various averaging (compromising) operators like arithmetic mean. The OWA operator provides a flexibility to incorporate decision maker's attitude or tolerance towards risk, which can also be related to the criticality of the particular system under investigation.

2 HIERARCHICAL EARTHQUAKE RISK ASSESSMENT

2.1 *Selection of general decision making criteria*

2.1.1 *Cost*

The cost factor includes both the installation and maintenance costs associated with the retrofit technique. Installation cost is defined as the cost of all materials and work associated with the design and construction of the retrofitting solution. This may include some demolition and reconstruction of non-structural components and finishing (Caterino *et al.* 2008). Maintenance cost is defined as the cost of any upgrade, treatments, and inspections that must be performed throughout the lifetime of the retrofit alternative.

2.1.2 *Aesthetics/preservation of architecture*

Aesthetics includes the change in physical appearance to a structure after a retrofitting solution has been implemented. For many buildings it is important to preserve the architectural elements of both the interior and exterior of the building. Some retrofitting techniques have little visible impact on the appearance of the structure, such as fibre reinforced polymer (FRP) wrap which is often covered or painted after application. Whereas other techniques, such as steel bracing, may cause drastic changes to the architecture and physical appearance of the building.

2.1.3 *Availability of workmanship/materials*

Depending on the region in which the retrofitting will take place, the materials and technical equipment required to implement certain techniques may be scarce. This criteria is particularly an issue in developing countries where the cost to import materials and skilled labour is far greater. Workmanship is defined as any skilled persons required to design and/or implement the retrofitting technique (i.e. engineers, architects, masons, skilled labour persons). Materials may include tools and machinery as well as construction materials.

2.1.4 *Duration of work/disruption of use*

The duration of work required to implement each technique is directly linked to disruption of use or disruption to occupants. If a great deal of interior construction is required then the duration of work becomes a very important criterion because of business and building use interruptions. Whereas, if little construction is required to implement a technique then the duration will have far less affect on the decision.

2.1.5 *Post-disaster importance of building*

The post-disaster importance of a building refers to whether the building has any special usage after a disaster. For instance fire halls and police stations are important for search and rescue efforts while schools and other places of assembly are often used for temporary housing when people have been displaced from their homes. Hospitals also fall under this category. If a building plays an important role in post-disaster relief efforts then more emphasis should be placed on the technical criteria to ensure adequate structural response in the event of an earthquake.

2.1.6 *Historic/cultural significance*

The historical or cultural significance of a building is defined as its heritage value to society. The preservation of architecture may be extremely important if the building holds some historical significance. Retrofitting techniques and detailing should either have little impact on the appearance of the building or else conform to the existing character and detailing of the architecture (Charleson *et al*. 2001). The cultural significance of the building will also dictate the necessary performance requirements. Preserving cultural heritage is an important factor in many communities.

2.1.7 *Sustainability*

Sustainability is a multi-faceted criterion with many possible definitions within the context of retrofitting techniques. For the purposes of this analysis, sustainability will encompass: transportation of materials, amount of material and machinery required, and recycled content of materials. Transportation of materials is directly related to the availability of materials criterion. If the necessary materials are not available in the region then high transportation costs and carbon emissions are associated with their delivery to the site. The amount of material required for a technique includes all material and machinery for construction, demolition, and repair of the structure. Excessive use of materials leads to a decrease in natural resources as well as carbon emissions associated with their processing. Some materials, such as steel, are known to contain a much higher percent of recycled content than other materials. Materials produced from recycled content are preferred because they reduce waste as well as the harvesting of natural resources.

2.2 *Selection of technical decision making criteria*

2.2.1 *Increase strength*

Strength refers to the ability of a structure or system to resist the seismic induced load demand (e.g. shear and flexural loads). A structure with high strength has the ability to resist both lateral and vertical forces generated from seismic activity. Increase in strength is one of the most common criteria used to evaluate retrofitting techniques, however it is not always the most effective. Generally increasing strength also corresponds to increased weight and strain on the foundational system.

2.2.2 *Increase ductility*

Ductility here refers to the amount to which a structure can be deformed in the plastic region. A ductile structure has the ability to absorb and reduce energy and forces from seismic activity (Wright, 1998). Damage to the building can be minimized by increasing the amount of plastic deformation it can endure without fracture or failure. In many retrofitting cases it is more cost efficient to increase ductility rather than strength (Wright, 1998). Increasing ductility can be particularly beneficial in regions of high seismic activity.

2.2.3 *Increase strength and ductility*

Oftentimes it is most effective, and efficient, to find a balance between increasing the strength and ductility of the structure. Increasing ductility can help increase the overall strength of a member and reduce permanent deformations. Alternatively, increasing strength means less ductility is required to prevent deformations and failure. It is effective to increase either strength or ductility to the necessary level. But it is possible and sometimes more effective to increase both parameters to a lesser degree than would be required individually.

2.2.4 *Compatibility of existing structural system*

Some structural systems are more suitable for alteration than others. The type and strength of the existing structural system may severely limit the retrofitting techniques that can be effectively applied to the structure. It is also important to consider the existing and available capacity of the foundation system (Thermou and Elnashai, 2006). For instance, some retrofitting techniques, such as steel jacketing, may add considerable weight to the structure, requiring an adequate foundation system.

3 **OWA AGGREGATORS**

An OWA operator of dimension n is a mapping of $R^n \rightarrow R$ (where $R \in [0, 1]$), which has an associated n number of performance modifiers $W=(w_1,w_2,\ldots,w_n)^T$, where $w_j \in [0, 1]$ and $\sum_{j=1}^{n} w_j = 1$. Hence, for a given n performance modifiers vector ($a_1, a_2,...,a_n$), the OWA aggregation is performed as follows:

$$OWA(a_1, a_2, ..., a_n) = \sum_{j=1}^{n} w_j b_j \tag{1}$$

where b_j is the j^{th} largest element in the vector ($a_1, a_2,...,a_n$), and $b_1 \geq b_2 \geq ... \geq b_n$. Therefore, the weights w_j of OWA are not associated with any particular value a_j, rather they are associated with the ordinal position of b_j. The linear form of OWA equation aggregates multiple performance modifiers vector ($a_1, a_2,...,a_n$) and provides a nonlinear solution (Yager and Filev 1999).

One of the major challenges in OWA method is to generate weights. Since the introduction of OWA operators by Yager (1988), different methods of OWA weight generation and extension of OWA operators have been proposed in the literature. Sadiq and Tesfamariam (2007) have discussed the current state of the art for OWA weight generation. Yager (1988) further introduced two characterizing measures called *orness* and *dispersion* ($Disp$) or entropy, which are associated with the weighting vector W and are computed as

$$orness(W) = \frac{1}{n-1}\sum_{i=1}^{n} w_i (n-i) \text{, where } orness \in [0,\ 1] \tag{2}$$

$$Disp(W) = -\sum_{i=1}^{n} w_i \ln(w_i) \tag{3}$$

The *orness* characterizes the degree to which the aggregation is like an *or* (or *and*). Therefore, when *orness* = 0, the OWA becomes a *minimum* operator and conversely, when *orness* = 1, the operator becomes a *maximum* operator. The measure $Disp$ provides a degree to which the information is distributed and is bounded by $0 < Disp < \ln(n)$. For *orness* = 0 or 1, the dispersion becomes zero, and when $w_i = 1/n$ (like a uniform distribution), the dispersion is maximum, i.e., $\ln(n)$.

The procedure adopted here to generate weights was proposed by O'Hagan (1988), which entails the use of *orness* (equation 2) and optimizes the $Disp$ function (entropy) (equation 3). These calculated weights are referred to as maximum entropy (ME-) OWA weights.

4 ILLUSTRATIVE EXAMPLE

The structure considered in the application is a three-story RC structure built at the European Laboratory for Structural Assessment (ELSA) of the Joint Research Center (JRC) in Ispra, Italy (Caterino *et al*. 2009). The building is representative of pre-seismic code constructions in southern Europe. A total of five seismic resistance upgrading options are considered, three of those aiming at a seismic capacity enhancement (A_1, A_2, A_3), the last two providing a seismic demand reduction (A_4, A_5). The five retrofitting options are:

1) A_1, confinement by glass FRP of columns and joints (increases the building displacement capacity)
2) A_2, addition of steel braces (provides a global strength (and stiffness) enhancement);
3) A_3, concrete jacketing of selected columns (partial but simultaneous enhancement of strength and ductility);
4) A_4, base isolation of the structure (reduction of the seismic forces); and
5) A_5, installing four viscous dampers at the first story of the building (attenuates the seismic demand).

Each of the five alternatives is evaluation based on six criteria (x_{ij}, *i* represents the alternative used and *j* represents the criterion) (Table 1). Results of the six evaluation criteria with respective to the five alternatives are provided in (Table 2).

Table 1 Description of eight evaluation criteria

Criterion	**Application**
C_1	Installation cost
C_2	Maintenance cost
C_3	Duration of work/disruption of use
C_4	Functional compatibility
C_5	Skilled labour requirement/needed technology level
C_6	Significance of the needed intervention at foundations

Table 2 Decision matrix for the five retrofit alternatives with respect to eight decision criteria adopted from Caterino et al. (2009)

Alternative	Decision criteria					
	C_1 (€)	C_2 (€)	C_3 (days)	C_4	C_5	C_6
A_1	23,096	23,206	33	0.482	0.374	2.90
A_2	53,979	115,037	122	0.063	0.104	15.18
A_3	11,175	40,353	34	0.255	0.044	2.97
A_4	74,675	97,884	119	0.100	0.374	2.65
A_5	32,309	36,472	19	0.100	0.104	2.87

The decision criteria summarized in Table 2 are non-commensurable (e.g. C_1 is defined as cost in € and C_3 is defined as duration in days), and consequently cannot be directly aggregated using the MCDM. Therefore, non-commensurate input parameters have to be transformed into commensurate units. For simplicity, the transformation t_{ij} is done by normalizing the decision matrix x_{ij} summarized in Table 2, using TOPSIS normalization method:

$$t_{ij} = \frac{x_{ij}}{\sqrt{\sum_{k=1}^{5} x_{kj}^2}} \quad (6)$$

The normalized values are summarized in Table 3. The values summarized in Table 3 have cost criterion, where lower number is better alternative.

Table 3 Normalized payoffs x_{ij} values for the five retrofit alternatives with respect to eight decision criteria

Alternative	Decision criteria					
	C_1	C_2	C_3	C_4	C_5	C_6
A_1	0.23	0.14	0.19	0.85	0.68	0.18
A_2	0.53	0.71	0.69	0.11	0.19	0.94
A_3	0.11	0.25	0.19	0.45	0.08	0.18
A_4	0.74	0.60	0.67	0.18	0.68	0.16
A_5	0.32	0.22	0.11	0.18	0.19	0.18

Tesfamariam *et al*. (2010) have proposed a linguistic transformation function to quantify *Orness* values (Table 4). For each *orness* values, the ME-OWA weights are computed, the five alternatives are ranked, and results are summarized in Table 4. It can be noted that, for *orness* = 0.90, 0.70, 0.50, A_5 and A_2 are most and least desired retrofit alternative, respectively. It is interesting to note that, with decreasing *orness* values, there is rank reversals, where for example, for *orness* = 0.10, A_3 and A_4 are most and least desired retrofit alternative, respectively.

Table 4 Transformation of linguistic degree of optimism to *orness* values

Degree of optimism	*Orness*	*ME-OWA Weights*	*Ranking of alternatives*
Optimistic	0.9	{0.67, 0.21, 0.07, 0.03, 0.01,0,0}	$A_5(0.28) > A_3(0.38) > A_4(0.71) > A_1(0.74) > A_2(0.85)$
Moderately optimistic	0.7	{0.34, 0.25, 0.17, 0.11, 0.08, 0.06}	$A_5(0.23) > A_3(0.28) > A_1(0.54) > A_4(0.62) > A_2(0.69)$
Normative	0.5	{1/6, 1/6, 1/6, 1/6, 1/6, 1/6}	$A_5(0.20) > A_3(0.22) > A_1(0.39) > A_4(0.51) > A_2(0.54)$
Moderately conservative	0.3	{0.06, 0.08, 0.12, 0.18, 0.27, 0.29}	$A_3(0.15) > A_5(0.17) > A_1(0.26) > A_2(0.37) > A_4(0.38)$
Conservative	0.1	{0, 0.02, 0.04, 0.08, 0.23, 0.63}	$A_3(0.10) > A_5(0.14) > A_1(0.17) > A_2(0.20) > A_4(0.23)$

The OWA aggregator is used for the five alternatives or orness values of 0 to 1 interval. The results are summarized in Figure 2.

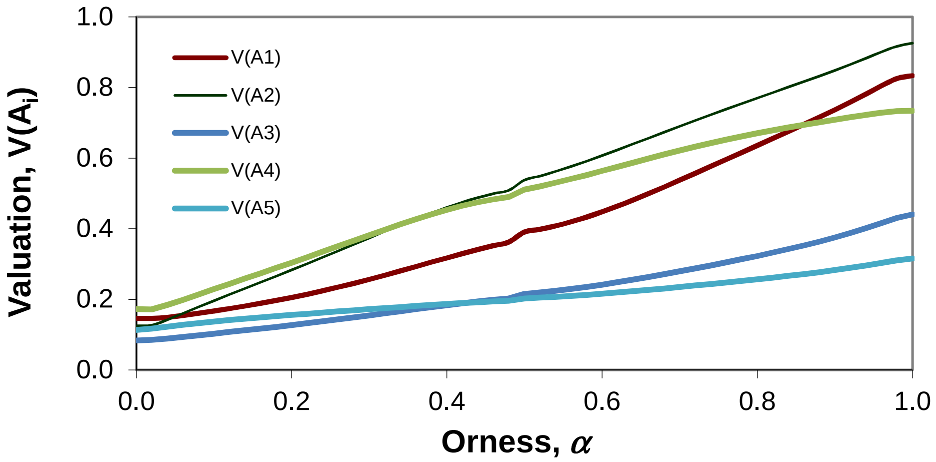

Figure 2. Valuation of different retrofit alternatives with respect to *orness*

5 CONCLUSIONS

Vast numbers of non-code conforming buildings are vulnerable to seismic induced damages. The risk to lives and financial loss can be minimized by retrofitting these buildings. The decision drivers used to select the desired retrofit alternatives are often related with strength and ductility improvements. However, past earthquake damages and challenges in retrofit selection has highlighted the need for multiple criteria decision making, such as availability of skilled workmanship, duration of retrofitting, etc. In this paper, a multi-criteria based decision support tool is proposed for retrofit selection. The OWA aggregators are used for the MCDM tool, and the utility of the proposed method is illustrated with an example. The OWA operator provided a flexibility to incorporate decision maker's attitude or tolerance. Indeed, with changing the decision maker's attitude, there was a rank reversal in the desired retrofit technique.

6 REFERENCES

Caterino, N., Iervolino, I., Manfredi, G. and Cosenza, E. (2008) Multi-criteria decision making for seismic retrofitting of RC structures, Journal of Earthquake Engineering, vol 12, No 4, pp 555-583.

Caterino, N., Iervolino, I., Manfredi, G. and Cosenza, E. (2009) Comparative analysis of multi-criteria decision-making methods for seismic structural retrofitting, Computer-Aided Civil and Infrastructure Engineering, vol 24, pp 432–445.

Charleson, A., Preston, J., & Taylor, M. (2001) Architectural expression of seismic strengthening, Earthquake Spectra, vol 17, No 3, pp 417-426.

Foo, S. and Davenport, A. (2003) Seismic hazard mitigation for buildings, Natural Hazards Vol 28, pp 517-535.

O'Hagan M. (1988) Aggregating template or rule antecedents in real-time expert systems with fuzzy set logic. Proc. 22nd Annual IEEE Asilomar Conference on Signals, Systems and Computers, IEEE and Maple Press, Pacific Grove, CA, pp 681–689.

Prebix, T.W. and Burke, P. (1989) Toward a philosophy for seismic retrofit: the Seattle experience, Earthquake Spectra, vol 5, No 3, pp 557-569.

Sadiq, R. and Tesfamariam, S. (2007) Probability density functions based weights for ordered weighted averaging (OWA) operators: an example of water quality indices, European Journal of Operational Research, vol 182, pp 1350–1368.

Tesfamariam, S. and Saatcioglu, M. (2010) Seismic vulnerability assessment of reinforced concrete buildings using hierarchical fuzzy rule base modelling, Earthquake Spectra, Vol 26, No 1, pp 235-256.

Tesfamariam, S., Sadiq, R. and Najjaran, H. (2009) Decision-making under uncertainty - an example for seismic risk management, Risk Analysis, Vol 30, No 1, pp 78-94.

Thermou, G.E. and Elnashai, A.S. (2006) Seismic retrofit schemes for RC structures and local-global consequences, Progress in Structural Engineering and Material, Vol 8, No 1, pp 1-15.

Wright, R. N. (1998) Assessment, strengthening, and repair technologies for buildings, industrial facilities, and lifelines. Common Agenda for Cooperation in Global Perspective U.S./Japan Earthquake Policy Symposium, Kobe, Japan.

Yager, R.R. (1988) On ordered weighted averaging aggregation in multicriteria decision making, IEEE Transaction System, Man and Cybernetics, vol 18, pp 183–190.

Yager, R.R. and Filev, D.P. (1999) Induced ordered weighted averaging operators, IEEE Transaction System, Man and Cybernetics, vol 29, pp 141–150.