I J C T A, 9(24), 2016, pp. 125-135 ISSN: 0974-5572

A Multi-Criteria Ranking Method for Selecting the Retrofitting Alternatives of Buildings

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ABSTRACT

Recent development of viable and low-cost retrofit solutions within a performance-based approach, suggest the possibility to implement "standardized solutions at buildings. However, different and complex criteria propose in order to define the most effective retrofit strategy able to minimize the overall risk. In this paper, Analytical Hierarchy Process (AHP) is used for proposing a new methodology in order to select the best retrofitting alternative of buildings. Structural, operational, financial, and architectural criteria are selected as the main criteria, and for each of them all of the effective sub criteria are considered as the hierarchical pattern. By questionnaire from expert, the improved default weights and also matrix of Pair Wise Comparison (MPC) are considered for weighting of the criteria depending on the usage of the building and then an appropriate rating model is used for scoring the alternatives with respect to each criterion. This method is useful for selecting the best alternative of different types of small buildings in earthquake prone urban areas and especially useful for screening the alternatives in tall and important buildings and then the limited alternatives can be analyzed and designed with common and time consuming procedures. The proposed approach is applied to a case study and is shown to be successful, ultimately providing a new managerial tool for decision making more effectively.

Keywords: Retrofitting; Analytical Hierarchy Process (AHP); Rating Method, Decision Making

1. INTRODUCTION

Violent, swift, and unpredictable, earthquakes result from sudden movements of the geological plates that form the earth's crust, generally along cracks or fractures known as "faults." If a building has not been designed and constructed to absorb these swaying ground motions, then major structural damage, or outright collapse, can result, with grave risk to human life. Historic buildings are especially vulnerable in this regard. As a result, more and more communities are beginning to adopt stringent requirements for seismic retrofit of existing buildings.

As a general rule, at codes of FEMA 356 (2001), NZSEE (2015) and IRI 360 (2014), all of the old buildings that couldn't meet the current codes should be evaluated with regards to their resistances against earthquake. They probably need to be retrofitted due to some deficiencies related to their gravities and lateral resistances, material and construction weaknesses and so forth. In some countries such as Iran, after evaluating of a building and selecting some appropriate alternatives by screening, the best alternative is selected by retrofit designer through a logic comparison and then they fulfill detailed design for the best selected alternative. Although, lots of alternatives have been proposed in codes and articles for retrofitting of buildings, a few patterns are available for selecting the most appropriate alternative. Having a simplified method can help designers to select the best alternative for retrofitting of buildings.

The goal of this paper is propose the way how science can help in decision making and implementation for retrofitting buildings in earthquake prone urban areas. In such interventions actors from various spheres

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are involved. Their interests range among minimizing the intervention for maximal preservation or increasing it for seismic safety.

This paper is organized as follows. Section 2 provides a brief literature review summarizing the current state of the art and highlighting deficiencies that the proposed work responds to. The methodology for the problems is detailed in Section 3, in the form of a Multi-Criteria Decision Making (MADM). Section 4 provides a case study with extensive discussion of the results. Finally, Section 5 summarizes the primary contributions, discussion broader implications of the work, and itemizes potential areas for future work.

2. LITERATURE REVIEW

Choosing the best alternative considering all of the effective criteria is yet a complex process, because the criteria can be either quantitative or qualitative and they are not commensurable. Therefore a method is needed for choosing an alternative among finite numbers of screened alternatives which are measured by some relevant criteria. After searching most of engineering algorithms, it is recognized that the problem falls under the heading of Multi-Criteria Decision Analysis (MCDM) and this method is an appropriate method for solving and computerizing the problem (Hwang and Yoon (1981)).

Analytic hierarchy process (AHP), which is a technique of Multi-criteria Decision Making (MCDM), was developed by Saaty (2001). AHP is used to solve complex decision-making problems in different areas. As a decision method that decomposes a complex multi-criteria decision problem into a hierarchy (Saaty, 1980), AHP is also a measurement theory that prioritizes the hierarchy and consistency of judgmental data provided by a group of decision makers. AHP incorporates the evaluations of all decision makers into a final decision, without having to elicit their utility functions on subjective and objective criteria, by pair-wise comparisons of the alternatives.

For the first time, Gregory et al (1995) published the usage of Analytical Hierarchy Procedure (AHP) for building systems such as selecting a good area for a company or choosing an appropriate heating system for a building. Just during the past few years, there have been a few attempts on making decision for finding an appropriate alternative for retrofitting buildings, because of development in retrofitting systems. Bostenaru Dan (2004) proposed a multi criteria decision model for retrofitting existing building. A spatial multi-criterion based on research by Malczewski (1999) was considered on three steps; intelligence phase, design phase and choice phase. His hierarchy framework consists of four levels that include: main problem (retrofit), actors (engineer, architect, investor, and user), main-criteria, and sub-criteria. For each alternative, according to the outcome of analysis for all of the alternatives based on assigned weights, scoring and ranking of alternatives can be performed. Therefore, his method is needed to allocate lots of time and budget for designing, drawing, and estimating for all of the considered alternatives, especially, in some cases using a nonlinear (static or dynamic) approach is indispensable.

An extensive research on models for achieving seismic resilience was done by Daniel et al. (2004). Framework on this research is based on nodes, which include the alternative under the decision maker's control (rehabilitation and financing) and chance nodes that include events outside the decision makers' control (seismic event, damage states, consequences). To evaluate the retrofitting alternatives, the analysis approach includes a value model for possible consequences. This value model consists of two stages. In the first stage all consequences are converted to a common unit (either utilities or economical cost equivalents). Next a multi-criteria utility model is used to aggregate across consequences. They used two approaches that both led to similar conclusion. The first is simulation approach in which the costs and benefits are estimated for each combination of Peak Ground Accelerations (PGA), damage states and rehabilitation options. This approach results in probability distributions over Net Present Value (NPV) for the different rehabilitation options. The other approach is to translate probabilistic information into tree to assign costs and benefits at the end of the tree or anywhere else in the tree, and to calculate expected values or expected utilities. The most criticism about this research can be related to the required criteria for evaluation the alternatives. Another research for the mitigation of the seismic risk at territorial scales has been carried out by Giovinazzi and Pamanin (2008). They introduced multi criteria decision for both monetary and non monetary aspects were used and compared with a more standard cost-benefit analysis. Just eleven criteria under three major categories were suggested in their research.

The main goal of this paper is to introduce a new methodology for making decision for finding the best alternative with considering all of the intervention criteria with allocating lowest time and cost of designing for retrofitting of buildings. Analytical Hierarchy Process (AHP) is used for proposing a methodology in order to select the best retrofitting alternative. Structural, operational, financial, and architectural criteria are selected as the main criteria, and for each of them all of the effective sub criteria are considered as the hierarchical pattern. The proposed approach is shown to be successful, ultimately providing a new managerial tool for decision making more effectively.

3. METHODOLOGY

This study is based on four fundamental subjects that includes; finding and categorizing the effective criteria, considering the building’s usage, using the appropriate methods for weighting the criteria and scoring the alternatives. According to this pattern a Computer program proposed for evaluating and scoring the alternatives.

3.1. Effective criteria on making decision

Many criteria have been involved on making decision for retrofitting of buildings. These criteria have been categorized in four main-criteria that consist of structural, operational, architectural and economic criteria and each of them includes some sub-criteria that show in Figure 1.

3.1.1. Structural criteria

In order to compare the alternatives in terms of structural criteria, analysis and design should be completed and it is certainly a time-consuming process, especially when a nonlinear analysis is needed many parameters should be considered (Pashaei, R., and Torabi, A., 2007), however some sub-criteria can be driven from a linear static analysis in a short time. Stability coefficient, Torsional strength irregularity, and Vertical mass and stiffness irregularity are three important structural sub-criteria that are used by FEMA 356(2001) and they can be considered by using linear static procedure (LSP) by analyzing:

- *Stability Coefficient*: The stability coefficient (θ) shall be evaluated for each story and for two directions of a building.

$$\theta_i = P_i \delta_i / v_i h_i \tag{1}$$

where,

Pi: Portion of the total weight of the structure including dead, permanent live, and 25% of transient live loads acting on the columns and bearing walls within story level *i*

vi: The total calculated lateral shear force in the direction under consideration at story *i* due to earthquake response to the selected ground shaking level, as indicated by the selected linear analysis procedure.

hi: Height of story *i*

äi: Lateral drift in story *i*, in the direction under consideration, at its center of rigidity, using the same units as for measuring hi.

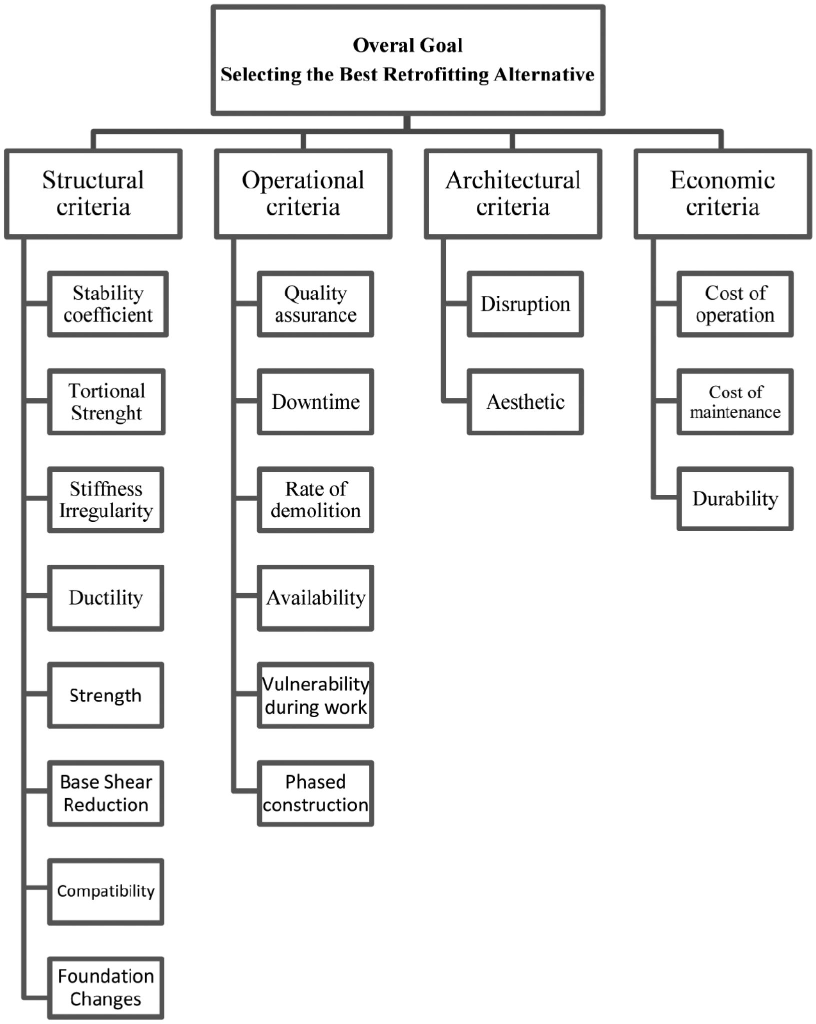


Figure 1: The hierarchical pattern of main and sub criteria

- *Torsional Strength Irregularity*: This criterion (β) plays an important role in behavior of retrofitting buildings and shall be evaluated for each story and direction of a building.

$$\beta = \text{Drift max/Drift} \tag{2}$$

- *Vertical Mass and Stiffness Irregularity*: This criterion (λ) is derived easily (after deriving β) and shall be evaluated for each story and direction of a building. The general formulation in accordance with FEMA 356 (2001) is:

$$\lambda = \max\,[(\text{Drift})\ i,\ (\text{Drift})\ i{+}1] \,/\, \min\,[(\text{Drift})\ i,\ (\text{Drift})\ i{+}1] \tag{3}$$

In order to decrease the time and cost of design in most of small buildings, it also provides a short and simple way in the program to consider all of three sub-criteria by verbal ratings without any analysis and just with judgment through screened alternatives. Since the stability coefficient is the only criterion that is difficult to judge by verbal ratings, it is replaced by displacement (drift) and it is judged easily among the alternatives such as shear wall, bracing and bending moment. Two other criteria can be judged through verbal ratings by designer.

- *Ductility and dissipation*: mentioned by some researcher such as Bostenaru Dan and Jong-Wha Bia as the effective criteria related to seismic behavior of structure.
- *Strength and stiffness*: focused on by FEMA 547(2006), Dan and Wha Bia (2003) as the main factors to control drift and configuration problems by adding new lateral force-resistance.

- *Base shear reduction*: can be applied by some innovation systems such as active, semi-active and intelligent damper or base isolation, which was considered as “reduced demand” by Dan and Cheung et al (2002).
- *Compatibility*: the new system should be compatible with existing structure that was mentioned by FEMA 547(2006) and Wha Bia (2003).
- *Foundation change*: is the worrying criterion for the retrofit designer. Enlargement of the size of foundation and adding new reinforcement are indispensable factors that are caused by some methods such as shear walls and bracings and considered by FEMA 547 (2006).

3.1.2. Operational criteria

Operational criteria are considered by FEMA 547 (2006), and Giovinazzi and pampanin (2008). The most important sub-criteria for comparing the alternatives consist of:

- *Availability*: Availability of Material, equipment and skilled workers has been summarized as availability. Conventional alternatives are easily performed, but some new alternatives such as installation of base isolation or smart dampers may be encountered with some difficulty related to trained workers, equipments etc.
- *Rate of Demolition*: some members such as beams, columns and walls need to be changed and demolished while installation of damper or bracing does not require demolishing any member in existing building. In some cases such as hospitals, this factor can play an essential role for choosing the best alternatives.
- *Down time*: Duration of retrofitting has always been a worrying aspect with respect to the disruption of occupancy. This sub-criterion will be more important for buildings such as hospitals, police stations, schools etc and can be evaluated qualitatively or quantitatively in different alternatives.
- *Quality Assurance (Q.A)*: rate of Quality assurance is an essential criterion for all of the selective alternatives that should be evaluated.
- *Vulnerability during Work*: For Some alternatives, building needs to be temporarily supported, for example, replacement the shear walls instead of masonry walls.
- *Possibility of phased work*: this criterion allows owners to continue their activities. This criterion plays a dispensable roll in all of officials and emergency buildings.

3.1.3. Functional and Architectural criteria

- *Tribulation*: For summarizing this sub-criterion, tribulation in architectural (such as restriction in parking, and other space of a building by adding shear walls or bracing), mechanical and electrical are evaluated as a sub-criterion and regarded as tribulation.
- *Aesthetic aspects*: Some retrofitting systems such as adding shear walls can influence the facade, and the other systems such as enlargement of columns and beams or adding bracing systems in the interior of a building can be evaluated as a negative aspect.

3.1.4. Economic criteria

- *Cost of Operation*: Cost of operation consists of the cost of the demolition, providing materials, and equipments and the cost of performance. Although the operation cost of alternatives can be exactly determined when design and drawing are completed, it can be approximately estimated and compared qualitatively among alternatives without completing the process of design and drawing.

- *Cost of Maintenance*: Some innovation systems need to be maintained and monitored by electronic equipment and skilled workers, and the others need to be inspected in a specific period. It can be exemplified by intelligent and smart damper, base isolation and so forth.

3.2. Building's Usage

Usage of a building is an indispensable factor that should be considered, because the weight of Criteria can be changed in terms of their usages. Although there has not been any consideration for this factor in research, seven usages have been proposed due to their special conditions.

- *Residential Buildings*: There are lots of these types of buildings and most of governments couldn't allocate enough budgets for them, therefore some conventional and economical alternatives should be taken into account for enhancing their resistance.
- *Educational Buildings*: Some old schools and colleges are vulnerable to collapse during earthquake. Duration of retrofitting is one of the most important criteria that are limited to one or two months during the holiday seasons.
- *Medical Centers*: These types of buildings can be categorized under emergency buildings and they are expected to remain stable after a severe earthquake. Down time, rate of demolition and possibility of phased work are important criteria at these buildings.
- *Cultural Heritage Buildings*: National museums, monuments, traditional buildings etc can be put into this category and usually they aren't allowed to change their function and facade. Also some criteria such as vulnerability during work, rate of demolition and structural criteria are indispensable sub-criteria.
- *Commercial Buildings*: Most of all, owners of this type of buildings aren't interested in retrofitting their buildings because of the disruption in their business. So rate of demolition and down time can be very important in this type of buildings.
- *Cultural & Sport Complex*: In this type of building some aspects such as Aesthetic and possibility of phased work are important.
- *Very Important Buildings*: Emergency buildings such as police station, Fire station and military buildings should be on service during and after an earthquake. All of structural criteria, possibility of phased work and down time are essential criteria with respect to this type of buildings.

3.3. Weighting and scoring by analytical hierarchy process

Among the all of applicable MCDM, "additive weighting methods" are the best known methods, because of their simple, intuitive logic, and incorporation of compensatory tradeoffs among criteria. The overall desirability score of an alternative can be cited by (Hwang and Yoon 1981):

$$D_i = \sum_{j=1}^{N} W_j X_{ij} \tag{4}$$

Di: desirability scores for each of the m alternative. i = 1... m.

Wj: cardinal weights; which the decision-maker assigns to each of the *n* criteria. The weights should be normalized so that they sum to 1.

Xij: criteria scores; the performance of each alternative *i* with regard to criterion *j*.

The first step of AHP is to construct a decision hierarchy which the top level is the decision goal; the second level is the collection of consideration factors, and the third level is composed of Buildings alternatives. AHP has thus been successfully applied to a diverse array of problems, with the calculation procedure as follows:

First, it must establish the pair-wise comparison matrix *A* To let *C1*, *C2*, ···,*Cn* denote the set of elements, while *aij* represents a quantified judgment on a pair of elements *Ci*, *Cj*. This yields an n-by-n matrix *A* as follows:

$$A = \left(a_{ij}\right) n \times n = \begin{bmatrix} a_{11} & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & a_{22} & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & \cdots & a_{nn} \end{bmatrix} \tag{5}$$

$$W = \left(W_k\right)_{n\times 1} = \begin{bmatrix} W_1 \\ W_2 \\ W_3 \\ \cdots \\ W_n \end{bmatrix} k = 1,\ 2,\ 3,\ \ldots,\ n \tag{6}$$

where *aij =1 and aij =* $1/a_{ij}$, *i, j =1, 2…, n*. In matrix *A*, the problem becomes one of assigning to the n elements *C1, C2…Cn* a set of numerical weights *W1, W2,* ···*, Wn* that reflects the recorded judgments. If *A* is a consistency matrix, the relations between weights *Wi* and judgments *aij* are simply given by $W_j/W_i = a_{ij}$ *(for i, j = 1, 2, 3… n)*. Saaty (1990) suggested that the largest value λ *max* would be

$$\lambda_{max} = \sum_{j=1}^{n} a_{ij} \frac{W_j}{W_i} \tag{7}$$

$$W_i = \frac{1}{n} \sum_{j=1}^{n} \left(a_{ij} / \sum_{k=1}^{n} a_{kj} \right), i = 1,\ 2,\ 3,\ \ldots,\ n \tag{8}$$

If A is a consistency matrix, eigenvector X can be calculated by

$$(A - \lambda_{max} I)X = 0 \tag{9}$$

Saaty (1990) proposed utilizing the consistency index (*C.I.*) and consistency ratio (*C.R.*) to verify the consistency of the comparison matrix. *C.I.* and *R.I.* are defined as follows:

$$C.I. = \frac{\lambda_{max} - n}{n-1} \tag{10}$$

$$R.I. = \frac{C.I.}{R.I.} \tag{11}$$

where,

R.I. represents the average consistency index over numerous random entries of same order reciprocal matrices. If the *C.R<0.1*, the estimate is accepted; otherwise, a new comparison matrix is solicited until *C.R <0.1*.

3.4. Criteria and Sub Criteria Weights

Matrix of pair-wise comparison (MPC) can be as an intermediate step intended to facilitate the development of cardinal weights for the main and sub-criteria. Since there are four main criteria, the MPC contains four rows and columns, and only the six (4(4-1)/2) upper elements of the MPC contain judgments. Alternatively, for structural and operational sub-criteria twenty eight (8(8-1)/2) and nine (6(6-1)/2) judgments are needed. Since these numbers of judgments are difficult for designer, according to the questionnaires filled out by some member companies of Iranian Society of Consulting Engineers (IRSCE) and taking average among them, the default weights have been considered at the computer program for each of the main and sub-criteria considering all of building's usages. Decision makers can apply them; however, they will be able to change the weights directly by their own ideas.

3.5. Scoring the alternatives

Desirability or performance of the alternatives with respect to some criteria can be qualitative (such as compatibility and availability) or quantitative (such as downtime and cost of operation). The equation (4) can not be used for quantitative criteria because they are neither commensurate, Comparable, nor retractable. These types of criteria should first be normalized in the decision matrix. Two popular normalization approaches are division by sum (DBS) and division by maximum value (DBM). According to the Expert Choice User's Guide (1993) DBS is the preferred approach in AHP except when the analysis is concerned only with identifying the highest-ranking alternatives or when several alternatives exhibit very similar performance with respect to several criteria, therefore DBM is used at the program for finding the best choice; however the results of the two methods usually are similar. On the other hand, both types of quantitative and qualitative criteria can be categorized to positive trends for criteria such as ductility and compatibility (higher values are preferred) and negative trends for criteria such as cost of operation and maintenance (lower values are preferred). In order to use the equation (4) for quantitative criteria with negative trends, they should first be inverted and then can be normalized by DBM or DBS. Verbal rating or verbal equivalent is a reliable and common method for scoring the alternatives with respect to qualitative criteria (Saaty 2008). In this study, except for three structural criteria (θ, β and λ), the other criteria are scored with two Examined appropriate verbal rating for both positive and negative trends, however decision maker are allowed to use verbal rating even for θ, β and λ for different alternatives.

4. A CASE STUDY

4.1. Problem description

Although the model has been surveyed and checked logically, it is applied for a case study for choosing the best alternative among three screened alternatives .This commercial building consists of five floors that is located in Tehran the capital of Iran and was built about 20 years ago. In two directions steel frames resist against gravity and earthquake loads, without any bracing and shear walls. Basic safety objective (BSO) according to IRI 360 was considered as rehabilitation objective. After evaluation of building by doing geotechnical and welding test, analysis of building was done by SAP 2000. The result of analysis demonstrated that the building required to be retrofitted. Three screened alternatives were proposed by an Iranian consulting engineering company including: strengthening the building frames, adding bracing, and adding shear walls. Comparison and the decision for selecting the best alternatives by the company were based on just five criteria that include: architectural changes, building performance, down time and tribulation during work, without any weighting and scoring.

4.2. Results and discussions

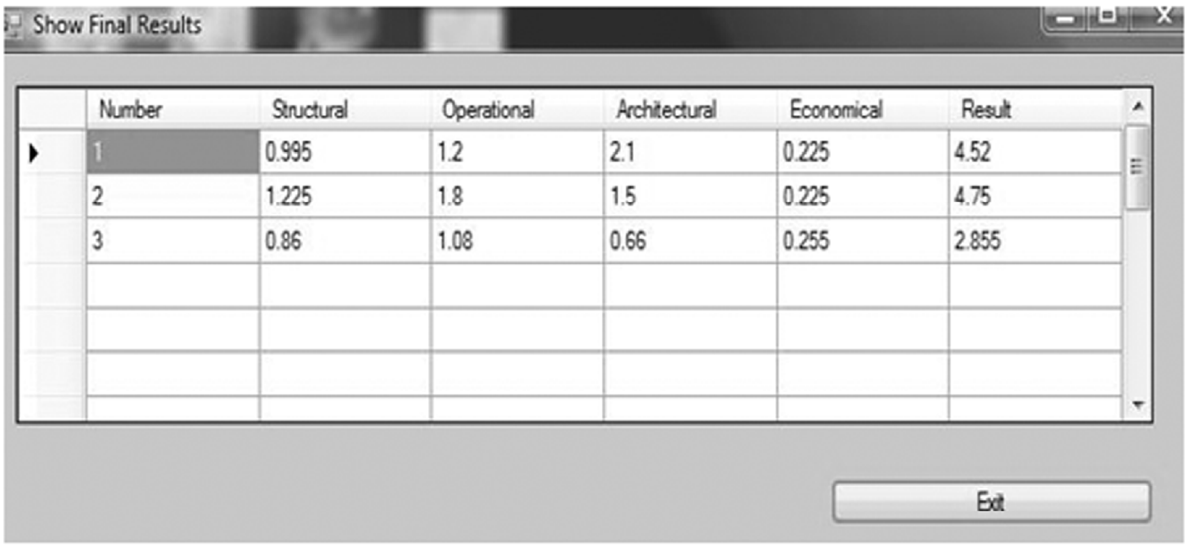
In the first step, the commercial building was considered at the program as building's usage. Then, among three available options for weighting the criteria, default weight are accepted. Finally, scoring was assigned

Table 1
Verbal ratings and corresponding numerical values for positive trends

Performance	*Weak*	*Fair*	*Good*	*Very good*	*Excellent*
Score	1	3	5	7	9

Table 2
Verbal ratings and corresponding numerical values for negative trends

Performance	*Very high*	*High*	*Fair*	*Low*	*Very low*
Score	1	3	5	7	9



Number	Structural	Operational	Architectural	Economical	Result
1	0.995	1.2	2.1	0.225	4.52
2	1.225	1.8	1.5	0.225	4.75
3	0.86	1.08	0.66	0.255	2.855

Figure 2: Result of the program for selecting the best retrofitting alternative

to alternatives with respects to all of the criteria (even for structural criteria) based on verbal ratings that was taken into consideration in Table 1 and 2.

In order to enhance the accuracy of result, the ratings in the Table 1 and 2 several times were changed and examined. High number of used criteria and tradeoffs of law versus high performance among criteria can be compensated the possible errors in judgments among different decision makers. Figure 2 shows the result of the program for three considered alternatives. Although the second alternative (braced frame) has got the most score and is the best choice for designing, drawing and proposing to client, the scores of first alternative is indispensable. The outcome of the computer program is similar to the choice which was selected by the consultant engineering, however, evaluation at the program is based on nineteen criteria, and it is expected to have more accurate results in different retrofitting projects. Available practical methods for choosing the best alternatives are typically based on comparison among the screened alternatives with respect to their structural performance and some intervention criteria or cost-benefits through designing and estimating the alternatives .whenever the allocated money for designing is low, selecting the best retrofitting alternative carry out without designing and just through a simple judgments (depends on the compulsory rules or client opinion and allocated money for designing). In both methods, comparison plays an essential role for making decision, while lacking in necessary criteria, appropriate method for weighting the criteria and scoring the alternatives may present unacceptable results.

5. CONCLUSIONS

In this paper, proposed methodology can help engineers and companies in decision making and implementation for retrofitting buildings in earthquake prone urban areas. In such interventions actors from various spheres are involved. Their interests range among minimizing the intervention for maximal preservation or increasing it for seismic safety.

This new approach provides the following advantages:

- This model is useful for retrofitting a large number of old buildings with different types of structures in order to select an appropriate alternative without designing and estimating all of the considered alternatives, and consequently just one selected alternative need to be designed and estimated.
- This model is especially useful for screening the lots of alternatives for retrofitting tall and important buildings and then the limited alternatives could be analyzed and designed with common and time consuming procedures.
- Authorities, clients and owners can observer the results of scoring the main criteria; therefore they can claim for logical changing in order to change the selected alternative.
- The methodology used multi-criteria decision making methods such as Analytical Hierarchy Process (AHP) providing a new managerial tool for decision making more effectively.

A primary direction for further research is using special categories for all classes of concrete, steel, and masonry buildings at the program in order to improve default weights for specified buildings. A second direction for further research is using default scores for all of the available alternatives for specified buildings in order to decrease the possible errors in scoring the alternatives.

ACKNOWLEDGMENT

This research is a part of Ph.D. dissertation of Mr. Reza Pashaei at the Universiti Teknologi Malaysia (UTM). This dissertation has been supervised by Prof. Wahid B. Omar and Iranian associated Prof. A. S. Moghadam. Technical contribution of department of structure and retrofitting of Iran Society of Consulting Engineers (IRSCE) and International institute of earthquake engineering and seismology (IIEES) are hereby acknowledged.

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