Prioritization of Highway Bridges for Seismic Retrofitting Using Multi Criteria Decision Making

T. A. Majid* & A. Yousefi
Disaster Research Nexus, School of Civil Engineering, Universiti Sains Malaysia, Pulau Pinang, Malaysia

SUMMARY
Most bridges have been built with no enough attention for seismic demand therefore; their seismic performances may not be acceptable during and after an earthquake. Bridge retrofitting, as one of the structural improvement methods, is the most common alternative but this process is extremely costly and time consuming. On the other hand, decision makers in infrastructure management have limit selection due to lack of resources. Hence, it requires developing a ranking system as tool for prioritizing the bridges retrofitting based on a set of criteria, but these criteria are conflicting generally. Therefore, the decision makers may face with many hardships to prioritize the bridges. This study presents a simple approach using Multi Criteria Decision Making (MCDM) to rank bridges in the inventory for retrofitting and seismic upgrading. The alternatives are analyzed based on a set of criteria including Structural Vulnerability (V), Seismic Hazard (H), and Importance Classification (I). The output of this study can be used to develop a prioritization method on bridge retrofitting.

Keywords: Highway bridges, Retrofitting, Prioritization, Multi Criteria Decision Making (MCDM)

1. INTRODUCTION

The highway system is highly dependent upon its bridges, and lateral ground shaking is hazardous to all bridges around the earthquake epicenter. Past earthquakes revealed the vulnerability of transportation structures and the catastrophic impacts of a bridge closure on national and regional economy. Disturbance on lifelines costs more than the revenue lost (Yashinsky and Karshenas 2003). Seismic retrofitting is one of the most common and effective approaches in seismic risk reduction for existing buildings (Caterino et al. 2009, Shanian and Savadogo 2009). Usually, limitation of resources does not allow the accomplishment of retrofitting for all bridges simultaneously. Hence, before seismic retrofitting can be undertaken for a group of bridges, they must be prioritized first. The prioritization is determined by some specific criteria.
In fact, the prioritization of existing bridges for seismic upgrading is difficult owing to there are many deficient bridges in the inventory. Furthermore, many generally conflicting options have to be considered. Decision support systems like the so-called Multi Criteria Decision Making (MCDM) method has been of major aid for lifeline managers in recent years. This article investigates the applicability and effectiveness of one of the most widely adopted and consolidated MCDM methods for the prioritization of bridges.

2. BACKDROUND

Many screening and prioritization methods had been proposed in the past. In 1983, Federal Highway Administrative (FHWA) published a set of guidelines for the seismic retrofitting of highway bridges. These guidelines represented what was then the state-of-the-art for screening, evaluating, and retrofitting of seismically deficient bridges (Administration, Center and Council 1983). In order to capture some advances in seismic retrofitting and to make the current state-of-the-art available to bridge owners and engineers, FHWA initiated a project to update the 1983 guidelines. This effort had resulted in a new document titled the "seismic retrofitting manual for highway bridges" (NCEER, 1994) which was completed in early 1994 by NCEER under contract with the FWHA (Buckle Ian and Freidland Ian 1995). Seismic retrofitting manual for highway bridges (NCEER, 1994) describes procedures for preliminary screening of bridges along with two alternative procedures for the detailed evaluation. Seismic Retrofitting Manual for Highway bridges (FHWA-2006), which is a replacement for (FHWA-1995), contains procedures for preliminary screening process to identify and prioritize bridges that need to be evaluated for seismic retrofitting (Buckle et al. 2006). FHWA (1995, 2006) and most seismic bridge ranking methods develop a seismic rating system first, and then use the results of this rating to prioritize the inventory. Factors considered in the rating exercise usually include structural vulnerabilities, and seismic and geotechnical hazards. Some also include bridge importance and network redundancy at this stage, but others use these factors only when prioritizing the list of deficient structures. These methods assign a structure vulnerability index and a hazard index, and combine them in various ways to obtain an overall seismic rating.

Bana e Costa et al. in 2008 presented a multi-criteria model (MACBETH) enabling the prioritization of bridges and tunnels based on their structural vulnerability and importance. Valenzuela et al. in 2010 used the needs-based framework to develop an Integrated Bridge Index (IBI) as an aid for prioritization and decision making on the maintenance and rehabilitation of bridges. The index weighed the structure distresses, hydraulic vulnerability, seismic risk, and strategic importance of the bridge. The index was calibrated using visual inspection, survey by experts, and regression analysis.

Weighted coefficients of different criteria or non-technical issues usually are not included in such methods since the criteria are generally conflicting with each other in most cases. Owing to this, the final decision is based on common sense and engineering judgment (Ramirez et al. 1996, Caterino et al. 2009). It has been shown that MCDM methods can give a significant help to this aim (Caterino et al. 2008). These methods are commonly used in different fields, for example, the resources allocation planning (Opricovic 2009, lodzimierz Ogryczak 2007), locating a special facility (Queiruga et al. 2008), seismic structural retrofitting (Caterino et al. 2009, Caterino et al. 2008), material selection (Shanian and Savadogo 2009), selection of the best medical therapy for a patient (Encinas et al. 1998, Ehrgott and Burjony 2001), and imaging techniques for breast cancer detection (Azar 2000).

3. GENERAL ASPECTS AND STEPS OF MCDM

MCDM is one of the most widely used approaches for conflict management. In this approach, practical problems are often characterized by a set of criteria, while there is no solution satisfying all the criteria simultaneously. Thus, a compromise solution should be determined to assist the decision makers to make a best decision.

Hwang and Yoon in 1981 developed the TOPSIS technique based on the concept that "the chosen alternative should have the shortest distance from the positive–ideal solution and the longest distance from the negative-ideal solution". The ideal solution is the collection of ideal scores (or ratings) in all criteria considered. The TOPSIS technique defines a "similarity index" by combining the proximity to the positive-ideal solution and the remoteness of the negative-ideal solution (Azar 2000). The TOPSIS method works based on an aggregating function that measures the closeness to the reference points. In order to apply the methodology the analysis was carried out via a case study. The Isfahan highway network consisting 15 bridges was chosen. It is located in central Iran. The bridge seismic inventory data in this study were obtained from the Ministry of Roads and Urban Development of Iran, Iranian Seismological Center, and International Institute of Earthquake Engineering and Seismology.

3.1. Criteria and Evaluation of the Alternatives

Criteria are qualitative or quantitative properties by which the performance of the alternatives are measured and evaluated. The criteria can be distinguished as "benefit" type, when the decision maker (DM) is interested in maximizing the evaluation of alternatives according to them, and "cost" type, when the DM wants to minimize them. Hence, the criteria are generally conflicting with each other. In most cases, there is no definite solution satisfies all criteria simultaneously (Caterino et al. 2009). The determination of bridge priority depends on several basic factors such as Structural Vulnerability (V), Seismic Hazard (H) and Importance Classification (I) (Buckle et al. 2006, Ramirez et al. 1996).

3.1.1. Structural Vulnerability (V)

Vulnerability is a function of bridge structural properties and explains the conditions of the whole bridge (Viera 2000). It is estimated by the means of visual inspection. The lowest value of V is 1 and the highest is 10 (Blakelock et al. 1999).

3.1.2. Seismic Hazard (H)

The seismic hazard of a bridge site is ascertained from a probabilistic process. The hazard is determined from the geology, topography, and seismology of the region as well as the historical records of previous events (Yashinsky and Karshenas 2003). Seismic hazard is reflected in the acceleration coefficient (A) representing the Peak Ground Acceleration (PGA) that will likely occur due to an earthquake sometime within a 475-year period. This acceleration has 10 percent probability of being exceed within a 50-year period. Another factor that modifies PGA is site coefficient (S). Therefore, seismic hazard is defined as shown in Eqn. 3.1 (Buckle Ian and Freidland Ian 1995).

$$E = 12.5 \times A \times S \tag{3.1}$$

where A is acceleration coefficient as given in Table 3.1 from relative earthquake hazard map (IISEE 2012) and S is the site coefficient as given in Table 3.2.

Table 3.1. Seismic region and design base acceleration

Region	Description	Acceleration Coefficient
1	Very High seismic relative hazard	0.35
2	Intermediate seismic relative hazard	0.25
3	Low seismic relative hazard	0.20

Table 3.2. Site Coefficient

Soil Profile Type	Site Coefficient
I	1.0
II	1.2
III	1.5
IV	2.0

3.1.3. Importance Classification (I)

The Importance Classification (I) reflects the importance of the bridge in the road network. The determination of the importance of a bridge is subjective and consideration should be given to social, survival, financial, and defense requirements (Valenzuela et al. 2010). Three important classifications (I) are specified in this study:

I. Strategic: bridges which their loss would create a major economic impact or bridges that are formally defined as strategic by a local plane (this category also includes those bridges that cross routes which are defined as strategic).

II. Critical: those bridges that must continue to function immediately following an earthquake and are required to prevent secondary life safety.

III. Standard: all other bridges are classified as standard.

3.2. Decision Matrix and Weights

In order to applying MCDM methods, all the alternatives have to be evaluated according to each criterion using decision matrix. The decision matrix is a matrix of m×n (m alternatives and n criteria) in which the element x_{ij} indicates the performance of the alternative A_i with respect to criterion C_j (Mysiak). This requires the qualitative variables to be converted into crisp numbers and the relative importance (weight) of each criterion to be determined (Caterino et al. 2009). However, usually it is not easy to determine the values of such weights; therefore, rationalizing and using expert experience and judgment help the decision maker to express the preference (Opricovic and Tzeng 2004). According to the data collected in this study, the alternatives are listed down on the left side of the matrix, and the criteria are listed across the top of the matrix along with related weights. Table 3.3 shows the decision matrix and criteria weight.

Table 3.3. Decision matrix and criteria weight

Alternatives	Criteria		
	V 0.39	H 0.37	I 0.24
A_1	1	4.5	2
A_2	5	4.5	1
A_3	2	3.6	3
A_4	6	4.5	2
A_5	7	4.5	3
A_6	3	6	1
A_7	3	3.6	2
A_8	5	4.5	3
A_9	4	5	1
A_{10}	6	4.5	3
A_{11}	1	3.6	3
A_{12}	2	4.5	2
A_{13}	8	4.5	2
A_{14}	4	6	3
A_{15}	7	3.6	2

3.3. Procedural Basis of TOPSIS

TOPSIS stands for the Technique for Order Preference by Similarity to an Ideal Solution. Yoon and Hwang (1981) introduced the TOPSIS method based on the idea that the best alternative should be as close to the ideal solution as possible and as far from the negative-ideal solution as possible. They assumed that if each criterion takes a monotonically increasing or decreasing variation, then it is easy to define an ideal solution. Such solution is composed of all the best performance values exhibited (in the decision matrix) by any alternative for each criterion, while the worst solution is composed of all the worst performance values. The goal is to propose the alternatives that have the shortest distance from the ideal solution in the Euclidean distance. However, it has been argued that such solution may need to have the farthest distance from a negative-ideal solution simultaneously. Proximity to each of these performance poles is measured in Euclidean distances (Shanian and Savadogo 2009). The TOPSIS procedure consists of the following steps:

1) Calculate the normalized decision matrix. All the elements in the original matrix should be normalized. The normalized value r_{ij} is calculated by Eqn. 3.2:

$$r_{ij} = x_{ij} \Big/ \sqrt{\sum_{i=1}^{m} x_{ij}^2} \tag{3.2}$$

where i and j are the indexes related to the alternatives and criteria, respectively.

2) Calculate weighted normalized decision matrix. The weighted normalized value v_{ij} is calculated as Eqn. 3.3:

$$v_{ij} = w_j \times r_{ij} \tag{3.3}$$

where ω_j is the weight of the j^{th} criteria.

3) Identify Positive-Ideal and Negative-Ideal Solutions. The positive-ideal solution is the composite of all the best criterion ratings attainable and is denoted as Eqn. 3.4:

$$A^{*} = \{v_1^{*}, v_2^{*}, \ldots, v_i^{*}, \ldots v_n^{*}\} \tag{3.4}$$

where v^{*} is the best value for j^{th} criterion among all alternatives.
The negative-ideal solution is the composite of all worst criterion ratings attainable, and is denoted as Eqn.3.5:

$$A^{-} = \{v_1^{-}, v_2^{-}, \ldots, v_i^{-}, \ldots v_n^{-}\} \tag{3.5}$$

where v^{-} is the worst value for the j^{th} criterion among all alternatives.
The weighted normalized decision matrix with positive-ideal (A^{*}) and negative-ideal solutions (A^{-}) is shown in Table 3.4.

Table 3.4. Weighted normalized decision matrix

Alternatives	V	H	I
A_1	0.0210	0.0952	0.0533
A_2	0.1051	0.0952	0.0267
A_3	0.0420	0.0761	0.0800
A_4	0.1262	0.0952	0.0533
A_5	0.1472	0.0952	0.0800
A_6	0.0631	0.1269	0.0267
A_7	0.0631	0.0761	0.0533
A_8	0.1051	0.0952	0.0800
A_9	0.0841	0.1057	0.0267
A_{10}	0.1262	0.0952	0.0800
A_{11}	0.0210	0.0761	0.0800
A_{12}	0.0420	0.0952	0.0533
A_{13}	0.1682	0.0952	0.0533
A_{14}	0.0841	0.1269	0.0800
A_{15}	0.1472	0.0761	0.0533
A^{-}	0.1682	0.1269	0.0267
A^{*}	0.0210	0.0761	0.0800

4) Calculate separation measures using the n-dimensional Euclidean distance. The separation of each alternative from the ideal solution (S^{*}) is given by Eqn. 3.6:

$$S_i^{*} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^{*}\right)^2} \tag{3.6}$$

Similarly, the separation from the negative-ideal solution (S^{-}) is given as Eqn.3.7:

$$S_i^{-} = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^{-}\right)^2} \tag{3.7}$$

5) Calculate similarity indexes (C^{*}). Calculate the relative closeness to the ideal solution. The relative closeness of the alternative A_i with respect to A* is defined as Eqn. 3.8:

$$C_i^{*} = \frac{S_i^{-}}{S_i^{*} + S_i^{-}} \tag{3.8}$$

6) Rank the preference order.

3.4. Analysis Results

The bridges are ranked according to their Euclidean distances. Although, the ideal solution is usually unachievable TOPSIS defines an index called similarity to the positive-ideal solutions (proximity to positive and remoteness to negative values). The results are proposed to the decision maker as the set of compromise solutions.
As shown in Table 4.1 Bridge A_{13} has the highest priority which means it should be retrofitted first, and followed by A_{15} as a second one, A_4 as a third one, and so on.

Table 4.1. Multi criteria ranking results

Alternative	S^*	S^-	C^*	Ranking
A_1	0.0328	0.1529	0.8234	13
A_2	0.1014	0.0706	0.4106	5
A_3	0.0210	0.1461	0.8743	14
A_4	0.1102	0.0590	0.3485	3
A_5	0.1069	0.0655	0.3798	4
A_6	0.0848	0.1051	0.5534	10
A_7	0.0499	0.1197	0.7060	11
A_8	0.0862	0.0885	0.5064	8
A_9	0.0877	0.0867	0.4971	7
A_{10}	0.1069	0.0749	0.4119	6
A_{11}	0.0000	0.1646	1.0000	15
A_{12}	0.0390	0.1328	0.7731	12
A_{13}	0.1508	0.0414	0.2153	1
A_{14}	0.0810	0.0996	0.5514	9
A_{15}	0.1290	0.0611	0.3213	2

4. CONLUSION

In summary, a bridge retrofitting prioritization has been conducted to illustrate how TOPSIS approach can be used. TOPSIS model for bridge prioritization problems was shown to be a suitable and efficient tool in this study. It is particularly suited to large-scale problems. The decision matrix is introduced for the evaluation of all the bridges according to each criterion including structural vulnerability, seismic hazard and importance classification. Then the weighted coefficients are obtained for the criteria, using the expert knowledge. The decision matrix and weighted coefficients are taken as the input for the TOPSIS model. TOPSIS presented the ranking score of the bridges take into account the distances to the positive-ideal and negative-ideal solutions.
TOPSIS is a helpful method in MCDM, particularly when the decision maker is not able to express preference at the beginning of system design. TOPSIS seems to be more appropriate for ranking and selecting the alternative among all MCDM methods because of its capability to deal with each kind of judgment criteria and the clarity of its results.

AKCNOWLEDGEMENT
Authors would like to acknowledge and extend their gratitude to USM Graduate Assistance scheme for the financial support during completion of this paper. A great appreciation is also addressed to Dr. Ahmad Goli Khorasgani from the Ministry of Roads and Urban Development of Iran.

REFERENCES

Administration, U. S. F. H., T.-F. H. R. Center & A. T. Council. 1983. *Seismic Retrofitting Guidelines for Highway Bridges: Earthquake Protection of Transportation Structures*. US Department of Transportation, Federal Highway Administration.

Azar, F. S. (2000) Multiattribute decision-making: use of three scoring methods to compare the performance of imaging techniques for breast cancer detection.

Bana e Costa, C. A., C. S. Oliveira & V. Vieira (2008) Prioritization of bridges and tunnels in earthquake risk mitigation using multicriteria decision analysis: Application to Lisbon. *Omega,* **36:3**, 442-450.

Blakelock, R., W. Day & R. Chadwick (1999) Bridge condition index. *Management of highway structures***:** 130.

Buckle, I., I. Friedland, J. Mander, G. Martin, R. Nutt & M. Power. 2006. Seismic retrofitting manual for highway structures: Part 1-bridges.

Buckle Ian, G. & M. Freidland Ian. 1995. Seismic Retrofitting Manual for Highway Bridges. Federal Highway Administration, US Department of Transportation. Publication No. FHWA-RD-94-052, McLean, Virginia.

Buckle, I. G. 1991. Screening procedures for the retrofit of bridges. 156-165. ASCE.

Caterino, N., I. Iervolino, G. Manfredi & E. Cosenza (2008) Multi-Criteria Decision Making for Seismic Retrofitting of RC Structures. *Journal of Earthquake Engineering,* **12:4**, 555-583.

Caterino, N., I. Iervolino, G. Manfredi & E. Cosenza (2009) Comparative Analysis of Multi-Criteria Decision-Making Methods for Seismic Structural Retrofitting. *Computer-Aided Civil and Infrastructure Engineering,* **24:6**, 432-445.

Ehrgott, M. & M. Burjony. 2001. Radiation therapy planning by multicriteria optimization. 244-253.

Encinas, M. P., M. Fernández, M. Martín, M. Calvo, A. Gómez-Alonso, A. Dominguez-Gil & F. Lozano (1998) Multicriteria decision analysis for determining drug therapy for intermittent claudication. *Methods and findings in experimental and clinical pharmacology,* **20:5**, 425-438.

Hwang, C. L. & K. Yoon. 1981. *Multiple attribute decision making: methods and applications: a state-of-the-art survey*. Springer-Verlag New York.

IISEE. 2012. International Institute of Seismology and Earthquake Engineering Ibaraki: Building Research Institute (BRI).

lodzimierz Ogryczak, W. (2007) Multicriteria models for fair resource allocation1. *Control and Cybernetics,* **36:2**.

Mysiak, J. (2004) mDSS Decision methods.

Opricovic, S. (2009) A Compromise Solution in Water Resources Planning. *Water Resources Management,* **23:8**, 1549-1561.

Opricovic, S. & G.-H. Tzeng (2004) Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research,* **156:2**, 445-455.

Queiruga, D., G. Walther, J. González-Benito & T. Spengler (2008) Evaluation of sites for the location of WEEE recycling plants in Spain. *Waste management,* **28:1**, 181-190.

Ramirez, J., A. D. Pan & F. T. Mwakasisi (1996) Seismic Evaluation of Highway Bridges-Phase 1.

Shanian, A. & O. Savadogo (2009) A material selection of highly sensitive components based on multiple criteria decision analysis. *Expert Systems with Applications,* **36:2, Part 1**, 1362-1370.

Valenzuela, S., H. d. Solminihac & T. Echaveguren (2010) Proposal of an Integrated Index for Prioritization of Bridge Maintenance. *Journal of Bridge Engineering,* **15:3**, 337-343.

Viera, V., Oliveira, C. S., and Costa, C. B. (2000) A methodology to evaluate strategic importance of bridges and tunnels considering seismic vulnerability: Application to Lisbon. *Proc., 2nd EuroConf. on Global Change and Catastrophe Risk Management: Earthquake Risks in Europe*.

Yashinsky, M. & M. J. Karshenas. 2003. *Fundamentals of seismic protection for bridges*. Oakland, CA: Earthquake Engineering Research Institute.

Yoon, K. & C. Hwang. 1981. TOPSIS (technique for order preference by similarity to ideal solution)–a multiple attribute decision making, w: Multiple attribute decision making–methods and applications, a state-of-the-art survey. Berlin: Springer Verlag.