APPLICATION OF MULTI-CRITERIA DECISION MAKING APPROACHES IN PRIORITIZING HIGHWAY BRIDGES INVENTORY FOR SEISMIC RETROFITTING

by

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Ali Yousefi
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LIST OF SYMBOLS

V_1	Vulnerability of critical components
V_2	Vulnerability of the noncritical of the structure
G	Acceleration coefficient
S	Site coefficient
A	Pairwise comparison matrix
a_{ij}	Entries of pairwise comparison matrix
λ_{max}	Maximum eigenvalue of pairwise comparison matrix
ω	Eigenvector of pairwise comparison matrix
w_j	Weight of criterion j
B_i	Alternative (Bridge) i
C_j	Criterion j
f	Analysis matrix
f_{ij}	Entries of analysis matrix
f_j^{max}	Largest value of the criterion j
f_j^{min}	Lowest value of the criterion j
r_{ij}	The normalized value of f_{ij}
$L_{p,i}$	L_p-metric
f_j^*	The best values of criteria functions
f_j^-	The worst values of criteria functions
$L_{1,i}$	Concordance
$L_{\infty i}$	Discordance
S_i	Utility measure
R_i	Regret measure

Q_i	VIKOR index
S^-	Min S_i
S^*	Max S_i
R^-	Max R_i
R^*	Min R_i
v	Weight of the strategy
v_{ij}	Weighted normalized value of f_{ij}
v^*	Best value for criterion j
v^-	Worst value for criterion j
B^*	Positive-ideal solution
B^-	Negative-ideal solution

LIST OF ABBREVIATIONS

AR	Alternative Routes
AHP	Analytic Hierarchy Process
SL	Anticipated Service Life
DT	Average Daily Traffic
BI	Bridge Importance
CI	Consistency Index
CR	Consistency Ratio
DM	Decision Maker
FHWA	Federal Highway Administrative
GIS	Geographical Information System
IL	Interface with other Lifelines
MCDM	Multi-Criteria Decision Making
MADM	Multiple Attribute Decision Making
MODM	Multiple Objective Decision Making
PGA	Peak Ground Acceleration
PE	Probability of Exceedance
RI	Random Index
SH	Seismic Hazard
SAW	Simple Additive Weighting
SV	Structural Vulnerability
TOPSIS	Technique for Order Preference by Similarity to an Ideal Solution
VIKOR	VlseKriterijumskaOptimizacija I Kom-promisnoResenje

Penggunaan Kaedah Pembuatan Keputusan Pelbagai Kriteria dalam Pengutamaan Inventori Jambatan Lebuhraya untuk Pemulihan Seismik

ABSTRAK

Terdapat banyak jambatan lama atau telah direkabentuk tanpa pertimbangan reka bentuk seismik di kawasan yang berpotensi mengalami gempa bumi. Jambatan ini terdedah kepada risiko gempa bumi walaupun berskala sederhana dan memerlukan pemulihan dalam beberapa tahap untuk mengurangkan kos sosial dan ekonomi masa depan. Selain itu, proses pemulihan seismik adalah sangat mahal dan terdapat kekangan masa dan sumber untuk pemulihan kesemua jambatan yang sedia secara serentak. Oleh itu, jambatan yang perlu dipulihkan perlu diberi keutamaan dengan mengambil kira pelbagai kriteria termasuk isu teknikal dan sosio-ekonomi.

Kajian ini bertujuan untuk mengenal pasti kriteria utama dan pemberat untuk penilaian jambatan lebuh raya dan menyediakan satu teknik yang berkesan untuk Pengutamaan jambatan. Kriteria yang dicadangkan termasuk kelemahan struktur, risiko seismik, jangkahayat perkhidmatan, purata trafik harian, salingkaitan dengan servis lain, laluan alternatif dan kepentingan jambatan. Untuk menilai kriteria pemberat kaedah Proses Analisis Hierarki (AHP) dijalankan. Masalah akan timbul apabila sebilangan besar alternatif (jambatan) dan kriteria berganda seperti kaedah VIKOR (VlseKriterijumskaOptimizacija I Kom-promisnoResenje) dan TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) digunakan sebagai Kaedah Pembuatan Keputusan Pelbagai Kriteria (MCDM) untuk mengutamakan jambatan. Kaedah ini berupaya mengurangkan pelbagai alternatif ke

dalam satu nilai dan pengutamaan alternatif (jambatan) berdasarkan skor kedudukan mereka.

Satu kajian kes di pusat Iran telah dikaji dan jambatan yang mendapat pengutamaan tertinggi di dalam dua kaedah yang dikenal pasti sebagai senarai teratas untuk pemulihan seismik dan tertakluk kepada penilaian terperinci. Penggunaan kaedah yang dicadangkan membolehkan pembuat keputusan dan pihak berkuasa untuk mengesan jambatan yang paling kritikal dan penting dalam rangkaian untuk peruntukan sumber dan seterusnya untuk mengurangkan impak keseluruhan ke atas ekonomi tempatan dan serantau.

Application of Multi-Criteria Decision Making Approaches in Prioritizing Highway Bridges Inventory for Seismic Retrofitting

ABSTRACT

Many of the bridges are old or were designed without seismic design considerations in areas with potential earthquake hazard. These bridges are vulnerable from even moderate earthquakes and require to be retrofitted in some degree for reducing the future social and economic costs. Besides, the process of seismic retrofitting is extremely costly and time consuming moreover the constraint in resources prevents the retrofitting of all the existing bridges simultaneously. Hence, the bridges must be prioritized with simultaneous consideration of multiple criteria including technical and socioeconomic issues.

This study intends to identify the major criteria and their weight for evaluation of highway bridges and providing an effective technique to prioritize the bridges. Suggested criteria include structural vulnerability, seismic hazard, anticipated service life, average daily traffic, interface with other lifelines, alternative routes and bridge importance. To assess the weight of criteria the Analytic Hierarchy Process (AHP) technique is carried out. Since the problem involving a large number of alternatives (bridges) and multiple criteria, VIKOR (VlseKriterijumskaOptimizacija I Kom-promisnoResenje) and TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) methods as Multi-Criteria Decision-Making (MCDM) model are applied for prioritizing of bridges. These methods reduce multitude alternative performances into a single value and prioritize the alternatives (bridges) based on their ranking score.

The application of the presenting method is illustrated via a case study in central Iran. Bridges getting the highest priority in both methods are identified as the top list for seismic retrofitting and should be subjected to detailed evaluation. Utilization of proposed methods enables decision makers and authorities to detect the most critical and important bridges in the network for resource allocation and consequently to minimize the overall impacts onto the local and regional economy.

CHAPTER 1

INTRODUCTION

1.1 **Highway Bridges**

Disasters such as earthquake are of major global concern and reducing disaster risk is an urgent priority for the countries. These phenomena may produce physical effects on the lifelines and the region. Lifelines are the physical structures and facilities that provide essential services to the public and these are vital for the community especially after an earthquake. Lifeline networks include: transportation systems (road, highway, and railway), water supply systems (potable and industrial water supply), energy supply systems (electric, gasoline and oil supply), telecommunication systems and disposal systems (sewer and garbage disposal). Damage to these networks and their components seriously affects the service and performance (Nielson, 2003).

Past earthquakes have emphasized the importance role of road and highway networks in the emergency response process. Highway networks depend on bridges because these networks are often supported and carried by bridges. Consequently, bridges as a critical component within the highway network, expected to function and remain open immediately following an earthquake (JICA, 2000). Figure 1.1 shows a collapsed bridge impeding traffic to hospital resulting from the 1971 San Fernando earthquake.

Figure 1.1: Collapsed bridge resulting from the 1971 San Fernando earthquake (DesRoches, 2012)

On the other hand, bridges are of the vulnerable component in highway networks and past earthquakes demonstrated the influence of bridges closure on the regional and national economic. For instant, the Kobe earthquake in 1995 caused major damage to about 60% of the bridges in a densely populated area, at a cost of over $3 billion. The magnitude 9.2 Prince William Sound in 1964 caused the loss of about 60% of the region's highway bridges, at a cost of $200 million. During the 1989 Loma Prieta earthquake, the Struve Slough Bridge (a few kilometers from the epicenter), the Cypress Freeway (100 km away from the epicenter) and the San Francisco-Oakland Bay bridge was closed for one month. The 1994 Northridge earthquake caused the damage to 286 highway bridges and collapse of seven ones and the consequences of a large portion of the northwest Los Angeles freeway system (Yashinsky and Karshenas, 2003).

Many of the bridges are old and were designed in elastic philosophy (before modern bridge seismic design codes) or sometimes seismic design considerations were not made for them. Thereby, these bridges are vulnerable from even moderate earthquake and require some retrofitting or rehabilitation to achieve the optimum level of service and safety for future earthquake (Priestley and Seible, 1996; Kim, 1998; Viera, 2000).

Figure 1.1 illustrates the collapse of the Hanshin expressway in the Kobe earthquake in 1995 and the effects that were imposed on the area.

Figure 1.2: The collapse of the Hanshin expressway in the Kobe earthquake (Johansson, 2000)

For seismic vulnerable bridges, there are several courses of action to mitigate possible risks and prevent the consequences of seismic damage in the future earthquakes (FHWA, 2006):

- Bridge retrofit
- Bridge closure
- Bridge replacement
- Acceptance of the damage and its consequences

Bridge closure or replacement by a new one is usually not justified only by seismic deficiency and it will be an option when other deficiencies exist. Therefore, for all practical purposes, a choice is made between improving the bridge by retrofitting and strengthening the deficient component or accepting the risk. This decision often depends on (i) the importance and significance of the bridge in the network and (ii) the cost and effectiveness of retrofit in compare with replacement (FHWA, 2006).

1.2 **Seismic Retrofitting**

Disaster management is a multi-stage process that starts with mitigation and preparedness. It extends to post-disaster response, recovery and reconstruction. A seismic event time-line which illustrates the events that take place before and after a seismic event is shown in Figure 1.3 (Nielson, 2003).

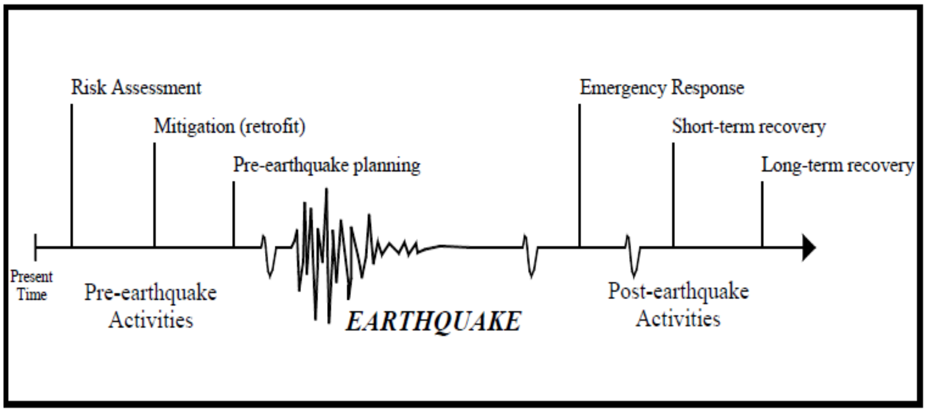


Figure 1.3: Seismic event time-line (Nielson, 2003)

Mitigation and prevention actions refer to measures that eliminate or reduce the extent of earthquake damage. Seismic retrofitting and upgrading of bridges to current seismic design codes is one of the most cost-efficient and effective mitigation methods. Seismic retrofitting is the structural improvement that makes the structures more resistant to seismic activity to prevent or minimize the risk of unacceptable fail during design earthquake. According to the FHWA 2006 the unacceptable damages are defined as follows (FHWA, 2006):

- Serious injury or loss of life
- Collapse of all or part of the bridge
- Loss of use of a vital transportation route

According to the Yashinsky and Karshenas (2003)' work seismic retrofitting of bridges may include the following steps:

1. Preliminary screening of bridge inventory
2. Prioritizing the bridge inventory
3. Detailed evaluation of the chosen bridges
4. Selection of retrofit strategy and design of retrofit measures

The observed performance of the past earthquakes indicates that the seismic retrofit program has been effective and appropriate. All bridges that had been retrofitted adequately had minor damage and remained in service. For example, in the 1994 Northridge earthquake, the highway bridges that had been retrofitted survived the earthquake even though some were within 100 m of collapsed structures (Fan et al., 2010). It implies that most of bridge collapses and major damage could have been prevented if the bridges had been retrofitted adequately. Hence, the problem is the schedule for retrofitting including screening, evaluation and prioritization of bridges. For example, seven of the bridges that collapsed in the Northridge earthquake, five had been scheduled as requiring retrofit and two other bridges had been identified as not requiring retrofit in the first stage (Housner and Thiel Jr, 1995). Thus, the critical issue in retrofitting program is not lack of technical design and standard or practical issues. Instead screening process and prioritization methods are required to be improved (Housner and Thiel Jr, 1995).

It is important that screening is performed to identify seismically deficient bridges and prioritizing bridges in order of need for retrofitting. Bridges found high priority in the final prioritized list are should be subjected to the detailed evaluation before retrofitting is undertaken on them (FHWA, 2006).

1.3 **Prioritization**

Budget constraints and limited resources preclude the simultaneous retrofit of all the seismic vulnerable bridges in the inventory, and the most critical and important bridges should be retrofitted first (Fan et al., 2010). Priority of bridges for seismic retrofitting represents the importance of bridges in the network. Hence, bridges getting the highest priorities are identified as the foremost candidates for seismic retrofitting.

In the prioritizing and selection of bridges for retrofitting in addition to the engineering and technical issues, economic, social, and practical aspects should be considered (FHWA, 2006). Therefore, prioritization and decision to select the preferred bridges can be complicated because it is a challenge to satisfy a multitude of criteria. Moreover, such a process is intended to be rapid, easy to apply and straightforward (Unjoh et al., 2000; Viera, 2000).

1.4 Multi-Criteria Decision Making (MCDM)

When a decision is required, the decision maker (DM) is faced with a set of alternatives or options and the uncertainty about the choice of some of them. The problem lies in determining what the best possible alternatives are. Normally, the best alternatives are defined in terms of a rational decision strategy (Sánchez-Silva, 2005).

MCDM is an important component of decision support system (DSS) that helps managers to decide in conflicting situations. MCDM approaches assist DMs to consider multiple criteria simultaneously and aid DMs in conflict management situations to produce a compromise solution and take better decisions (Amiri et al., 2011). MCDM is a dynamic analytical model that includes managerial and engineering level. The engineering level defines alternatives and performs the multi-criteria analysis of alternatives whiles, the managerial level defines the goals, and chooses the final optimal alternative(s) (Opricovic and Tzeng, 2003).

Alternatives are evaluated in terms of a set of criteria, which represent different dimensions of the alternatives. Criteria may be associated with different units of measure or may conflict with each other. For example, the criterion "structural vulnerability" is cost type, "anticipated service life" is benefit type, and these criteria are measured on different scales. MCDM aims to reduce multiple alternative performances into a single value to facilitate the decision process. MCDM tries to resolve the conflict between various criteria and present a prioritization of alternatives based on their overall performance (Mysiak, 2004; Opricovic, 2009).

The general basic steps of MCDM procedure consists of identifying alternatives, establishing criteria, assessment of criteria weights, and application of the compromise ranking method.

1.5 Problem Statement

Many of the bridges are old or were designed without seismic design considerations in areas with potential earthquake hazard. These bridges are vulnerable from even moderate earthquakes and require to be retrofitted in some degree for reducing the future social and economic costs. Besides, the process of seismic retrofitting is extremely costly and time consuming moreover the constraint in resources (budget, time, and human force) prevents the retrofitting of all the existing bridges simultaneously. Hence, the bridges must be prioritized with simultaneous consideration of multiple criteria including technical and socioeconomic criteria.

1.6 Objectives of Research

The objectives of this research are:

1. To determine the most effective evaluation criteria for prioritization of highway bridges for seismic retrofitting.
2. To assess the weight of considered evaluation criteria using AHP technique.
3. To prioritize and rank the bridges for seismic retrofitting using VIKOR and TOPSIS methods in the highway network of Isfahan city.

1.7 Scope of Research

The research limits its scope in the respective areas:

1. This study considers conventional urban highway bridges that carry vehicular traffic which are longer than 6 meters and with spans not exceeding 150 meters. It can be included single or multiple spans made of steel or concrete.

It is included various type of design construction such as multi-column piers (simply supported), single-column piers (box girders), continuous concrete, continuous steel and concrete rigid frames.

2. For the evaluation of bridges in addition to technical and engineering criteria, some socioeconomic criteria have been considered but it does not include direct and indirect losses.
3. Because most of the bridge damage during an earthquake is caused by ground shaking, only seismic hazard was considered in this study (Yashinsky and Karshenas, 2003).
4. MCDM is a dynamic analytical model that includes managerial and engineering level. The engineering level defines alternatives and performs the multi-criteria analysis of alternatives whiles, the managerial level defines the goals, and chooses the final optimal alternative(s). Hence, DM refers to an individual, organization, or institution having the power to accept or reject the solution proposed by the engineering level.

1.8 Scenario of Case Study

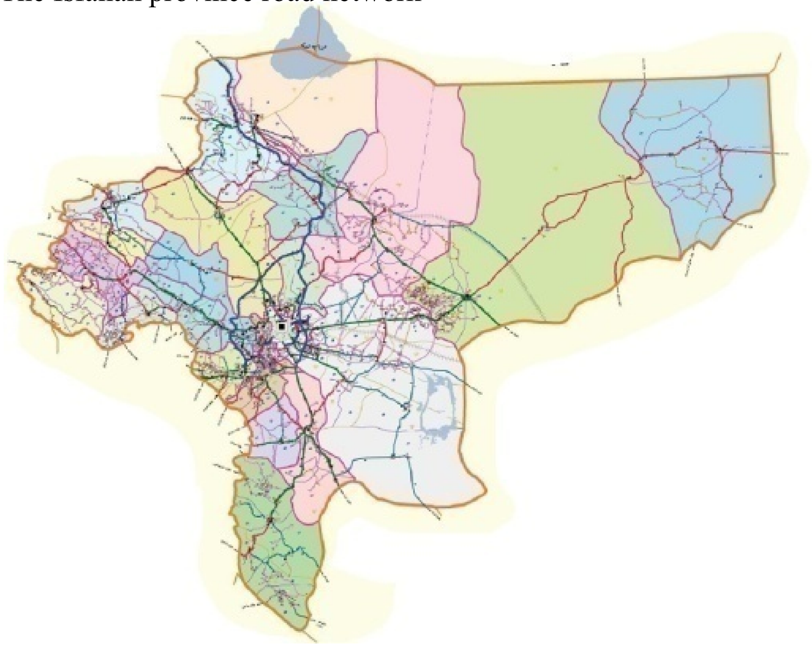
The application of proposed methodology is illustrated via a case study in central Iran. Iran, which is located in the active Alpine-Himalayan seismic belt, is one of the most seismically disastrous countries in the world. This country has experienced more than 130 strong earthquakes with magnitude of 7.5 or more in the past century.

Isfahan city, the capital of Isfahan province, is located in central Iran (at 32º 38´ northern latitude and 51º 38´ eastern longitude) (Figure 1.4) with the area of 482 square kilometers is third largest city of Iran. The Isfahan metropolitan area had a population of 3,430,353 in the 2006 Census, the second most populous metropolitan area in Iran after Tehran. Isfahan's internal highway network is currently under heavy expansion, which began during the last decade. Outside the city, Isfahan is connected by modern highways to Tehran (about 340 km to the north) and to Shiraz (about 200 km to the south). The highways also service satellite cities surrounding the metropolitan area.

(a) The location map of Iran in the world

(b) The location map of Isfahan province in Iran

(c) The Isfahan province road network



(d) The road network of Isfahan city

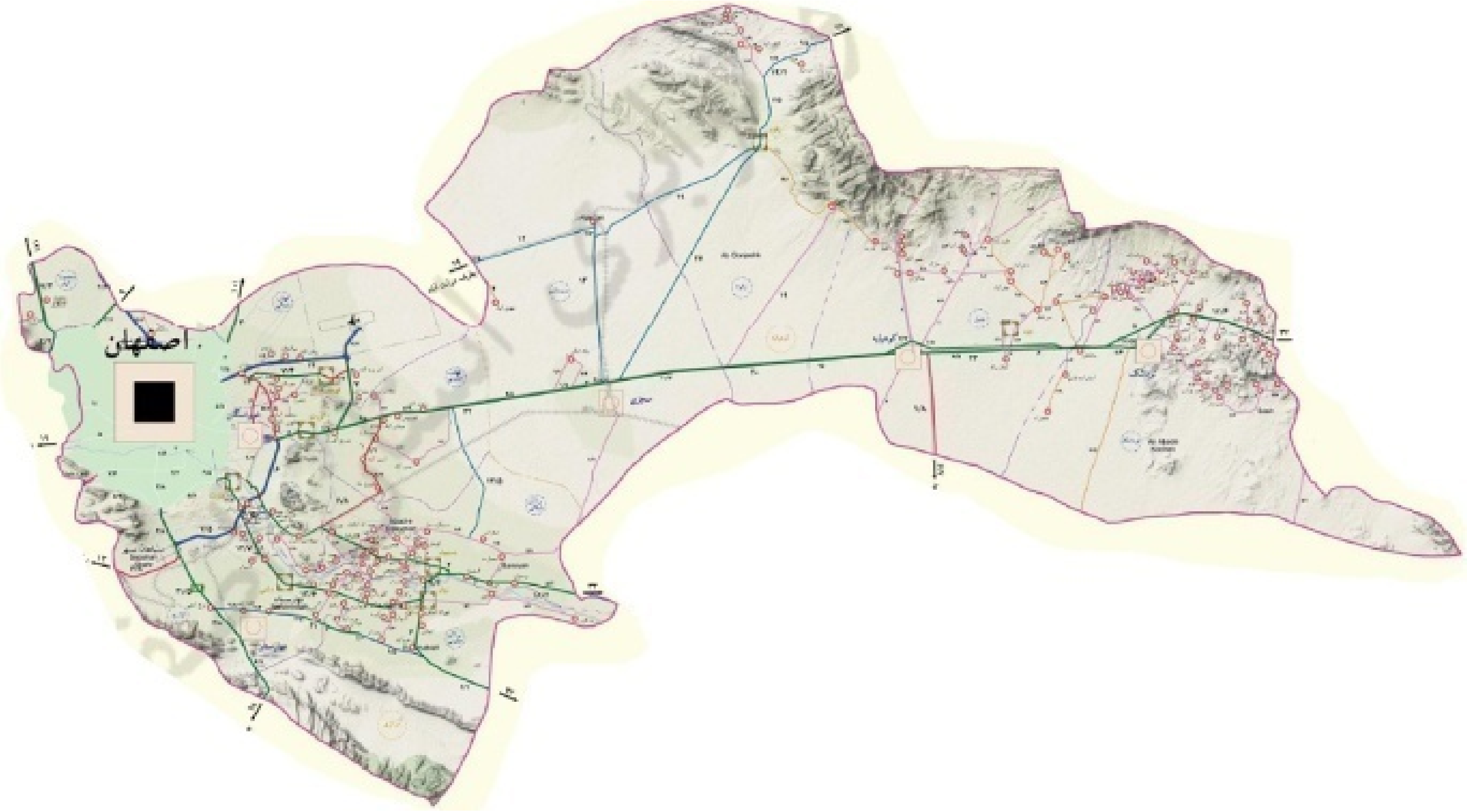


Figure 1.4. (a) The location map of Iran in the world, (b) the location map of Isfahan province in Iran, (c) the Isfahan province road network and (d) the road network of Isfahan city

1.9 Organization of Thesis

This thesis comprises of five chapters where each chapter will focus on the topics as follows:

Chapter 1 covers introduction to the thesis. The problem statement, the research objective and the scope of the research are presented in this chapter as well.

Chapter 2 devotes to related literature and describes briefly the background of the research on screening and evaluation of bridges as well as MCDM approaches.

Chapter 3 includes the concepts, characteristics and computational procedures of the MCDM (VIKOR and TOPSIS) methods adopted for this study. During this chapter, the various steps of these methods are discussed, and the priority functions and criteria weights are defined as well.

Chapter 4 presents a numerical application and illustrates how MCDM (VIKOR and TOPSIS) methods can be used to prioritize the bridge for retrofitting. The results of analysis and overall ranking are summarized and the results will be discussed in this chapter. A consistency test for the weight obtained by the analytic hierarchy process (AHP method) is also presented in this chapter.

The overall conclusion and some recommendation for future research are presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides a background of related literature for this study. Relevant researches previously accomplished can be divided into two fields. The first is in the screening and evaluation of bridges for seismic retrofitting and the second is in the ranking techniques and application of MCDM for prioritizing.

2.2 Screening and Evaluation of Bridges

The seismic retrofitting manuals use different screening techniques for assessing the bridges. Indeed, different preliminary screening methods were developed and there are many such methods available that have been used by various owner agencies (Mander, 1999). Some of them have used a rapid screening approach while some others have used detailed approach. The rapid and detailed screening approaches differ in the extent of data gathering, and time and effort necessary to perform an analysis. The rapid screening approach operates on limited data as it is intended to evaluate a suite of bridges and prioritize them in order but a detailed analysis is intended to be a more exacting assessment of individual bridges and their components. The methods for the screening and evaluation of highway bridges for prioritization, based on considered criteria can be divided into two categories: (i) single-criterion approach, and (ii) multiple criteria approach were reviewed in the next part.

2.2.1 Single Criterion Approach

Many methodologies have been studied and proposed to establish policies for more efficient seismic retrofits. In some cases, the highways bridges are ranked in terms of single technical criterion (e.g. vulnerability, seismicity and traffic counts or travel time) but such approaches do not consider the criteria simultaneously. Briefly, the bridges in the worst condition or performance are given the highest priority for retrofitting (Kim, 1998).

Kawashima and Unjoh (1990) prioritized bridges according to the rate of failure which obtained from a statistical analysis (regression analysis) of bridge damage data with no consideration of failure costs (FIB, 2007).

In 1993, a report entitled “Prioritization of State Bridges for Seismic Retrofit” was released to prioritize bridges for seismic retrofitting. This report provided a ranking of bridges from the most vulnerable to least vulnerable as well as the first estimate of retrofit cost (Hill, 1993).

Reiter (1990) and Kramer (1996) considered the probability of collapse during the bridge’s remaining life. They used probabilistic method to determine probability of collapse and then prioritized bridges. If the collapse probability is high it means the bridge is seismically deficient, then the bridge has given higher priority for seismic retrofitting.

Wakabayashi (1996) carried out importance analysis of highway network according to several scenarios of link closures. The performance criterion was travel time between Osaka and Kobe, but neither structural vulnerability of network components nor their failure probability was considered.

Kim (1998) considered condition level of highway bridges for prioritization. Bridges in the worst physical condition were given the highest priority to receive the budget allocations for retrofitting.

Caltrans (2004) screened bridges using geographical information system (GIS) to identify bridges that might be vulnerable to ground accelerations and risks of them for prioritization.

The level of significance for a bridge can also be ordered by the incurred shipping cost or economic loss from the earthquake shock. An approach was suggested by Kim et al., (2008) to select the bridges for retrofitting. This approach calculated the relative importance of each bridge by the resultant incremental of total system travel time by reducing of the post-earthquake traffic capacity of one bridge and then sorted the bridges by descending order of their contributions, on which the decisions on retrofit prioritization can be made.

Some prioritization schemes have been presented in terms of relative risk without an attempt on quantification of cost or benefit. Although some schemes such as Maffei and Park (1995) have attempted to establish a cost-benefit analysis to support the decision of retrofit. Maffei and Park (1995) separated benefits from costs and proposed the new methodological using a benefit-cost ratio for prioritization. They did not use any multi-criteria analysis in the benefit component of their ratio.

Svirsky (2012) ranked the bridge based on the sufficiency rating which is an overall rating of a bridge's fitness for the duty that it performs based on criteria that describe its structural evaluation, functional obsolescence and its essentiality to the public. A low sufficiency rating may be due to structural defects, narrow lanes, low vertical clearance, or any of many possible issues.

2.2.2 Multiple Criterion Approach

For evaluating of the highway bridges in addition to single criterion approaches, many approaches have been proposed according to multiple criteria. In these studies in addition to engineering and seismic issues, other important aspects such as socioeconomic criteria have been considered in the prioritization of bridges. In other words, prioritization and decision for choosing the bridges has been prepared based on multiple criteria which includes technical standards (e.g. Seismic hazard, vulnerability and expected damage) and socioeconomic criteria (e.g. Bridge importance, interface with other lifelines and other qualitative criteria) (Liu and Frangopol, 2005). The following are some of the proposed methods of prioritization and ranking of bridges.

Federal Highway Administration (FHWA) has issued three editions of retrofit manual for highway bridges (FHWA, 1983, 1995, 2006). In 1983, the FHWA published general guidelines for preliminary screening and prioritizing of highway bridges for retrofitting under seismic effects. Seismic ranking of bridges established under these guidelines considered three main criteria including, vulnerability, seismicity and importance. The seismic bridge ranking is a combination of these individuals ranking with weighing criteria (FHWA, 1983). The 1983 retrofit guidelines (FHWA, 1983) were updated in a new manual titled the "Seismic Retrofitting Manual for Highway Bridges" (FHWA-1995) which described procedures for preliminary screening of bridges and two approaches for detailed evaluation. FHWA (1995) was conceptually similar to FHWA (1983). "Seismic Retrofitting Manual for Highway Bridges: Part 1-Bridges" (FHWA-2006), which is a replacement for FHWA-1995, contains preliminary screening process, identifying and prioritization procedures for bridges that need to be evaluated for seismic retrofitting. FHWA (1995 and 2006) take into account quantitative criteria such as seismic hazards and structural vulnerability to prioritize the bridges for retrofitting. The authors suggest to further take into account "socioeconomic" issues by subjectively increasing the priority.

Babaei and Hawkins (1991) proposed method which was conceptually similar to FHWA (1983). In this method, the priority of a bridge was determined based on the hazard and resistance of bridge that is computed with the FHWA (1983) provisions, and the cost of failure was computed considering network behavior.

Basoz and Kiremidjian (1996) proposed a ranking-based prioritization methodology for bridge retrofitting. This method was conceptually similar to Babaei and Hawkins (1991)' work but it was an improved conceptual model. Two main areas of concern were considered for prioritizing: seismic vulnerability and strategic importance. The appraisal of the level of strategic importance of each bridge should take into consideration four criteria: emergency response (immediately after an earthquake), public safety, interference with other lifelines and local economic impacts.

Transit New Zealand (1998) developed a screening procedure for evaluating bridges within New Zealand. The process considered the bridge's vulnerability, its probability of experiencing high magnitude earthquakes, and the impact to the economy if the bridge becomes unusable (Seville and Metcalfe, 2005).

In a study that developed retrofit program for the City of Los Angeles, California, prioritization of the bridge for retrofit program was carried out based on replacement cost, overall rating and condition of the bridge, traffic flow, and the year of construction (Kuprenas et al., 1998).

In the study presented by Unjoh et al., (2000) priority of bridges was determined based on properties derived from hazard, resistance and cost. The method was based on regression on bridge damage data, with consideration of the single bridge failure costs. Weights were derived from observation of damages from past earthquakes.

Bana e Costa et al., (2008) presented a multiple criteria additive model (MACBETH model) to evaluate the strategic importance of bridges for prioritizing in Lisbon, Portugal. Five criteria including (i) emergency response, (ii) vulnerability, (iii) public safety, (iv) interference with other lifelines, and (v) long term economic impacts. Then the overall strategic importance values of bridges were aggregated in an additive model with scaling factors for the five criteria.

Valenzuela et al., (2010) employed the needs-based framework for developing an Integrated Bridge Index (IBI) as an aid for prioritization and decisions made on maintenance of bridges. The criteria considered for the index were the structure distresses, hydraulic vulnerability, seismic risk, and strategic importance of the bridge. Kiremidjian et al., (2007) proposed a method for risk assessment that considers the direct cost of damage and costs due to time delays in the damaged network.

Some approaches evaluate the performance or serviceability of a highway network. Analysis of the highway network is performed for a given hazard level and the resulting damage states used to estimate the effect on system performance as measured by traffic flow (e.g., increased travel times). The sensitivity of this performance to bridge condition is subsequently used to determine bridge retrofit needs and priorities. Economic losses include direct and indirect losses. Direct losses are due to structural and non-structural damage and it is the cost of repair or replacement of a damaged bridge. Indirect costs are due to long-term economic effects which resulting from a variety of causes such as deaths and injuries, business disruption, restricted or denied access for emergency response and recovery, traffic congestion, and loss of utility lines. Quantification of expected damage and economic losses is a complex and critical process and cannot be done without considering each bridge in its functional and societal context (Werner et al., 2000).

In the study accomplished by Basoz and Kiremidjian (1994) they found critical set of bridges that compose minimal cuts in the highway network, and then ranked individual bridges within the sets. The system functionality was defined as connectivity between critical destinations in cases of emergency.

Basoz and Kiremidjian (1996) and Werner et al., (2000) used risk assessment method to evaluate the overall system performance. In both of these publications, the risk to the network was calculated from the direct damage to bridges and the connectivity between a predefined origin-destination (O-D) set. Basoz and Kiremidjian (1996) considered the time delay and used the information primarily for retrofitting prioritization strategies. Basoz and Kiremidjian (1998) and Basöz and Mander (1999) estimated direct losses with some degree of confidence using the repair cost ratios. These ratios express repair costs as a proportion of bridge replacement costs.

Nojima (1998) used Montecarlo simulation of the bridge network behaviour which is a probabilistic and performance-based method. This technique approximates the reliability of network subjected to failure in terms of the system flow capacity as a criterion. A road network was modeled in a simplified way and subjected to failure. The prioritization order then was determined by flow capacity. It signifies that the bridges that maximized the network flow were given higher priority and chosen for retrofitting.

Chang et al., (2010) proposed a simple risk measure for transportation systems by considering the difference in costs associated with travel times before and after retrofitting. By comparing the results between with/without retrofit of a specific bridge, a prioritization was made.

2.3 **Ranking and Prioritization**

Ranking techniques lead to a prioritization of bridges in the inventory and aid DM in order to detect the most critical and important bridges for resource allocation in retrofitting program. Hence, bridges with higher-ranking value deserve higher priority in the seismic retrofitting program. Many seismic ranking methods have been proposed for prioritization of bridges in the past. Each method often implies a considerable degree of subjectivity.

In multiple criteria approaches, most of ranking schemes have considered similar contributory criteria for prioritizing but the means for combining these criteria differ. Therefore, a variety of methods, from simple ranking method to complex approach, have been employed to obtain prioritization of bridges. In the following, some proposed methods depending on the combination of criteria will be presented and reviewed.

Most of the methods developed a seismic rating system first, and then used the results of this rating to rank the inventory. The result of the bridge ranking is modified using socioeconomic criteria (bridge importance and network redundancy) to prioritize the inventory in a subjective way. Criteria considered in the ranking usually include “structural vulnerabilities” and “seismic or Geotechnical hazards”.

But some methods use these criteria only when prioritizing the list of deficient bridges (FHWA, 2006). Otherwise, these seismic ratings are used to guide decision-making but common sense and engineering judgment are the final word.

The different ranking method may be employed based on engineering judgment that often implies a considerable degree of subjectivity, in the form of engineering judgment (e.g. Predefined criteria multiplied by subjective weights). In these cases, seismic ratings are used to guide decision-making but common sense and engineering judgment are the final word in ranking of bridges.

2.3.1 Indices Method

Some of the seismic retrofitting manuals have used an indexing method as seismic rating system. This simple and conservative method is based on semi-empirical rules (Mander, 1999). This method is the best-known and most popular decision methods that are widely used. This methodology provides a simple procedure for computing a score for each bridge in order to assign a corresponding ranking. The total score for each bridge is computed by multiplying the rating for each criterion (obtained from bridge checklists) by the importance weight assigned to the criterion and then summing these products over all the criteria (Malczewski, 2000; Lamelas et al., 2006). It uses the additive aggregation of the criteria outcomes. After listing bridges in numerical order, this ranking order is modified according to socioeconomic criteria (bridge importance, network redundancy, non-seismic deficiencies, anticipated service life, and similar criteria) in a subjective way. The seismic rating or score assigning to each bridge is obtained from Equation 2.1:

$$\mathrm{F}\,(\mathrm{x}) = \sum_{i=1}^{n} \mathrm{w_i f_i(x)} \qquad (2.1)$$

where w is weight of the criterion and f(x) is rating of the criterion for the bridge.

This method also presents some drawbacks to the methodology. Because of the simple addition calculation, alternatives which score well on the highest rated criteria while being very poor in other areas can dominate. Others that score less on the most important criteria but are beneficial to all can be seen as inferior when in actuality these alternatives are the most preferable. In addition, without a normalization of the values, the comparison amongst alternatives affecting different criteria will be deficient.

FHWA (1983) issued general guidelines for the empirical and subjective determination of a bridge ranking index. Based on these guidelines ranking and priority of bridge was computed as the sum of seismicity, vulnerability and importance according to Equation 2.2. in the proposed procedure, criterion weight is assigned via engineering judgment.

$$R=I.w_1+S.w_2+V.w_3 \tag{2.2}$$

where R is ranking index and I, S, V and w_i are importance, seismicity, vulnerability and relevant weights respectively.

Maroney (1988), Buckle (1990), Gates and Maroney (1990), Roberts (1991) and Babaei and Hawkins (1991) accomplished conceptually similar method to FHWA (1983) and used weight criteria in their methods except of the approach proposed by Babaei and Hawkins (1991). The weights of criteria are multiplied by the respective rating index and then summed up to obtain the overall ranking. In the procedure proposed by Babaei and Hawkins (1991), the worth of the bridge is incorporated in the final ranking as a separate criterion, while Buckle (1990) incorporates it as part of the criterion of importance. During these procedures, the higher the numerical value of the overall ranking index for a particular bridge results the higher the priority for seismic retrofitting (Ramirez et al., 1996). Table 2.1 summarizes all methods discussed in the previous section briefly.

Table 2.1: Comparison of the different ranking methods

Rank	Weight	Range	Reference
$R=I.w_1+S.w_2+V.w_3$ Criteria (0-10)	w_1, w_2, w_3 (sum=10.0)	0-100	(FHWA, 1983)
$R= I^*+S+V^*$ Criteria (0-1)	*criterion included	0-0.1	(Maroney, 1988; Gates and Maroney, 1990; Roberts, 1991)
$R= (I+w). S^*. V$	No criteria	0-950	(Babaei and Hawkins, 1991)
Same form as FHWA, but I includes worth criterion	w_1, w_2, w_3 (sum=10.0)	0-100	(Buckle, 1990)

Note: I = importance, S = seismicity, V= vulnerability and w = worth

In a study that developed retrofit program for the city of Los Angeles, California, prioritization and selection of the bridge was carried out with a weighted seismic risk value score as express in Equation 2.3 (Kuprenas et al., 1998):

$$Rs = 0.5\ F_C + 0.2\ F_O + 0.15\ F_T + 0.15\ F_A \tag{2.3}$$

where F_C, F_O, F_T and F_A are replacement cost, overall rating and condition of the bridge, traffic flow and the year of construction, respectively.

In the proposed method in FHWA (1995), priority was a function of bridge rank and some socioeconomic criteria. The bridge ranking was obtained based on rate of "structural vulnerability" and "seismic hazard", then the ranking was found by multiplying these two ratings together. Therefore, the bridges with the highest score were given higher priority for retrofitting. The final prioritized list was determined