A DECISION SUPPORT METHODOLOGY FOR REHABILITATION MANAGEMENT OF CONCRETE BRIDGES

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A Thesis
In
The Department
of
Building Civil and Environmental Engineering

Presented in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy at
Concordia University
Montreal, Quebec, Canada

August 2008

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Your file Votre référence
ISBN: 978-0-494-45645-3
Our file Notre référence
ISBN: 978-0-494-45645-3

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ABSTRACT

A DECISION SUPPORT METHODOLOGY FOR REHABILITATION MANAGEMENT OF CONCRETE BRIDGES

Saleh Abu Dabous, Ph. D.

Concordia University, 2008

Managing the existing bridge infrastructure has become a major social and economic concern in North America. This is due to the critical conditions of the deteriorated bridges and the limited funds available to repair their deficiencies. Most transportation agencies make bridge investment decisions based on a combination of some form of quantitative data analysis and the subjective judgments of decision and policy makers. The subjective nature of the decision making process easily raises questions about whether the investment decisions are being developed in a fair, equitable and systematic manner. This dissertation presents a decision support methodology developed for the rehabilitation management of concrete bridges in general, and for bridge decks in particular. A probabilistic bridge condition assessment method is developed. This method is consistent with the current practice in bridge inspection and the Markovian approach to model deterioration. A means to rank bridge projects is presented, which makes use of a hierarchy structure to represent the problem and rank the different bridge projects using the Multi Attribute Utility Theory (MAUT). A method to evaluate the available rehabilitation strategies is discussed. This method uses a modified Analytic Hierarchy Process (AHP) and the Monte Carlo simulation technique to evaluate the weights for the different rehabilitation strategies

available for each project. A decision making technique to select a recommended work program that maximizes benefits to the network and to the users is developed. The developed methodology has the potential to be extended to other bridge components and to be the foundation for a comprehensive bridge management system. The significant features of this methodology can be summarized as follows:

1) It is consistent with the current practice in bridge management condition assessment and deterioration modeling.
2) It employs a multiple-criteria decision making process;
3) It has the flexibility to allow engineers to utilize their experience and judgment in the decision making process; and
4) It combines the network and the project levels of the bridge management process and performs effectively within a limited budget.

Acknowledgments

I would like to express my deepest gratitude and my sincere appreciation to my supervisor, Dr. Sabah Alkass, for his solid support and guidance throughout all of the stages of my Ph. D. Program. I am indebted to him for the rest of my life for helping me to achieve my dream. I would like to acknowledge the significant input from Mr. Adel Zaki towards completing this research. I appreciate the time and the effort that he has spent to share his knowledge and experience.

The invaluable feedback from Dr. Osama Moselhi on my work is highly appreciated. Also, I wish to thank Dr. Ashutosh Bagchi and Dr. Amin Hammad for their continuous encouragement throughout my program.

I would like to acknowledge Mr. Guy Richard from the Ministry of Transportation of Quebec, Mr. Bala Tharmabala from the Ministry of Transportation of Ontario and Mr. Guy Mailhot from Jacques Cartier & Champlain Bridges Inc. for providing the necessary data and facilitating the interviews. The financial support from the Natural Sciences and Engineering Research Council of Canada and the Faculty of Engineering and Computer Science (SRT), Concordia University, are genuinely appreciated.

I dedicate my thesis to the soul of my mother. Very special thanks to my father, brothers and sisters for their continuous love and support.

Last but not least, I would like to express to my wife Hiba and my son Ahmad my deepest appreciation for their continuous love, support and sacrifice.

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CHAPTER 1: INTRODUCTION

1.1 OVERVIEW

Aging civil infrastructure has become a major social and economic concern. Satisfactory performance of existing civil infrastructure is essential to maintain the economic growth and social development of a modern society.

The Canadian Society of Civil Engineers (CSCE) estimated the municipal infrastructure maintenance debt at CDN$ 57 billion in 2003 and potentially CDN$110 billion in 25 years. In the same vein, a report submitted to the International Public Works Congress has provided the following significant conclusions (Vanier 2000):

- The extent of the asset management market in Canada is very large, upwards of CDN$ 5.5 trillion; while in the USA it could be six-times larger.
- Maintenance and repair expenditures in Canada are in the order of CDN$110.0 billion per year, whereas capital renewal expenses are close to CDN$ 86.5 billion per year. The sum of these two figures is close to double the value of new construction in Canada each year.

Infrastructure deterioration is due to aging and excessive usage, scarcity of financial resources, and a lack of rational infrastructure management programs. Managers of municipal infrastructure are realizing the need for effective tools to manage this vast asset base, and are now demanding decision-support tools to help them in their work (Vanier 2000).

Infrastructure management is the decision-making process for selecting and prioritizing actions necessary to maintain a facility or a system within an acceptable limit of serviceability and safety, while taking budget constraints into consideration.

Decision support systems have been used successfully in the construction industry. They could be used as tools to help engineers and practitioners make efficient decisions through: (1) improved identification of and information about the infrastructure assets; (2) methodologies for needs assessment; and (3) analytical tools for the evaluation of possible solutions.

1.2 BACKGROUND OF THE STUDY

The highway transportation system is a major component of most civil infrastructure systems and can be considered one of modern society's critical foundations. In particular, bridges are an important item of the transportation system; because of their distinct function of joining highways as the crucial nodes, they are the most vulnerable element. In addition, bridges are exposed to aggressive environmental conditions and increasing traffic volumes and truck loads (Frangopol and Liu 2005).

Not surprisingly, in many countries around the world, a movement to develop and use bridge management systems has begun. The main objective of a bridge management system is to optimize and select the actions necessary to maintain the bridge network within acceptable limits of safety and serviceability. In the United States, the most widely known computerized bridge management systems are Pontis and BRIDGIT. Pontis is an advanced bridge management program and has been extensively used across the United States. Khan (2000) reported that Pontis was already in use in 38 states.

Pontis includes functions for bridge inspection and inventory data collection and analysis, recommending preservation policy, predicting needs and performance measures, and developing projects to include in an agency's capital plan. The optimum policies are developed on a network level and are based on the minimum expected life-cycle cost over an infinite planning horizon (Thompson et al. 1998).

BRIDGIT is ideal for smaller departments of transportation, and it can run in parallel with Pontis, as may be required by larger departments. BRIDGIT aids in the development of bridge maintenance, rehabilitation and replacement programs based on life cycle costing and incremental benefit cost analysis (Hawk and Small 1998)

Several countries have followed the trend and developed bridge management systems. In general, these systems have adopted concepts and approaches similar to those used in Pontis and BRIDGIT. These general concepts and approaches include defining inspection methodologies, performing economic evaluations and integrating optimization models to select the alternative with the lowest global cost.

Among the European bridge management systems are Danbro in Denmark and Finish in Finland. Other country-specific bridge management systems include those in the Netherlands, Germany, France, UK, Norway, Spain, Finland, Poland,

and Japan. A final report by the European commission (www.trl.co.uk/brime) discusses a few of these packages.

Despite the investments already made to develop bridge management systems all over the world, there remains much room for improving the performance of bridge management decision making. Evidence from the literature can be used as a guide for potential research work, including:

- Additional characteristics required by a bridge management system so that it can be flexible enough to retain the engineering judgment of the bridge manager responsible for individual structures as a key element in the decision-making process (Darby et al. 1996, Brooman and Wootton 2000).
- Only a few management systems can be defined as knowledge-based systems that can simultaneously include the complete process for managing bridges, from inspection to replacement (Branco and de Brito 2004). The bridge management system developed by the Highway Engineering Division of the Ontario Ministry of Transportation comes closest to this concept (Reel and Conte 1989).
- Enhancements to specific systems have been proposed in the literature. For instance, Marshal et al. (1999) reported that a number of items should be enhanced in Pontis, including:
    - The program simulation should be modified to allow users to specify a set of rules to satisfy all maintenance needs on the structure, not just the needs identified by Pontis.

- Project recommendations are associated with one particular program scenario. However, it is essential to be able to move from one scenario to another in order to build a program that represents the agency's actual plan.

1.3 PROBLEM STATEMENT

The deterioration of existing bridges is a major problem in the operation of the nation's highway bridges. The number of bridges in Canada is not known exactly but is estimated to be approximately 80,000, with a total replacement value of CDN$ 35 billion (TAC 1999). The Federation of Canadian Municipalities reported that 83% of Canadian bridges need some sort of repair (Mirza and Haider 2003). Maintaining the existing bridge infrastructure has become a major social and economic concern since bridges must be kept within acceptable limits of safety and serviceability. At the same time, maintenance, repair and replacement (MR&R) of bridges are very expensive items that involve large investments which are not always available to the transportation agencies.

Bridge management decision making is a complex, two-level problem. The first level deals with the selection of the most effective improvement strategy for each bridge project. Analyzing each bridge project individually to select the appropriate MR&R strategy is normally referred to as the project level decision making. The second level of the decision making problem is the network level. This level involves analyzing a network or a sub-network of bridges to select and prioritize projects for intervention. This is a complex task since networks contain large numbers of bridges that must be evaluated. In addition, the limited fund availability is a major challenge for the decision makers, since that limited fund must be deployed effectively to maximize the benefits to the network and its users.

Although transportation agencies have implemented bridge management systems, managers and decision makers do not always follow these systems' recommendations. Kulkarni et al. (2004) reported that most transportation agencies make bridge management decisions based on a combination of analyzing available quantitative data and using subjective judgments of the decision and policy makers. This subjective nature of the decision making process can raise questions about whether the investment decisions are being developed in a fair, equitable and systematic manner or if they more often reflect the intuitive judgments of the decision makers (and perhaps their more 'powerful' constituents).

Rational decision support systems which meet the decision makers' requirements and include the experts' knowledge and judgment in the decision making process should improve this process.

1.4 RESEARCH OBJECTIVES

The main objective of this research is to develop a methodology for bridge deck rehabilitation management. The methodology can assist practitioners and decision makers in monitoring bridge deck conditions and in selecting optimal rehabilitation and maintenance strategies while taking into consideration limited budgets.

The following sub-objectives are developed in order to achieve the main objective of the present research:

1) Propose a unified bridge deck condition index that is consistent with the current practice in bridge condition assessment.

2) Adopt and integrate one of the available deterioration models into the developed framework.

3) Develop quantitative and rational decision methods to evaluate the various bridge projects and the available bridge improvement strategies.

4) Utilize a technique to develop a recommended work program. The work program specifies which projects to improve and what improvement action to undertake within the available budget.

5) Incorporate these methods into an integrated methodology to assist in the evaluation and selection of bridge improvement strategies and the development of a recommended work program. Develop a prototype computer system as a proof of concept and as a validation of the methodology.

1.5 RESEARCH METHODOLOGY

The objective of this research is to develop a decision support methodology for bridge deck rehabilitation management. In order to achieve this objective, the following methodology is followed.

1) Conduct intensive literature review on the current practice for bridge deck condition assessment, rehabilitation and maintenance methods. Review available concrete deterioration models and life cycle analysis techniques.

2) Collect bridge inspection and condition assessment data from transportation agencies in Canada and collect data reports on major bridge deck rehabilitation projects in Canada.

3) Conduct interviews and discussions with decision makers and bridge experts from Canadian transportation agencies and private companies to solicit knowledge from their experience and to understand the bridge management decision making process followed in their agencies.

4) Review current practice in bridge condition assessment and deterioration modeling and propose a unified bridge condition rating and forecasting method.

5) Analyze the available quantitative decision making techniques and develop methods based on these techniques to evaluate alternatives. Identify a set of decision objectives and criteria to evaluate projects and rehabilitation strategies.

6) Develop methods to evaluate bridge projects and rehabilitation strategies and to formulate a recommended work program that meets the overall goal of maximizing benefits to the users and the network while staying within budget limitations.

7) Incorporate the developed methods into a prototype computerized decision support system.

1.6 THESIS ORGANIZATION

Chapter 2 introduces fundamental knowledge related to bridge management and presents a literature review that includes the main bridge management system components, with a particular focus on bridge decks. Chapter 3 presents the conceptual design of the proposed bridge deck decision support system and explains the methodology proposed to develop the system.

Chapter 4 develops a probabilistic condition rating methodology for bridge elements and discusses combining the ratings of the different elements into an overall bridge condition rating. Chapter 5 discusses the development of a network ranking method and Chapter 6 presents a decision support method for selecting a bridge rehabilitation strategy.

Chapter 7 explains a recommended work program which specifies the bridge projects and the rehabilitation actions to be performed on each bridge within a limited budget. Chapter 8 summarizes the main conclusions and research contribution. This last chapter also presents the system limitations and highlights recommendation for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Infrastructure management is the decision-making process for selecting and prioritizing the operations required to maintain the reliability of an infrastructure facility or system within acceptable limits (Aktan et al. 1996). A Bridge Management System (BMS) is a rational and systematic approach to organizing and carrying out the activities related to planning, designing, constructing, maintaining, rehabilitating, and replacing bridges vital to transportation infrastructure (Hudson et al. 1987). Implementing an effective BMS can achieve an agency's long term goal of providing a safe and acceptable level of service within budgetary constraints.

This chapter discusses the main components of bridge management systems and reviews the bridge management decision making process for selecting the operations necessary to maintain bridge infrastructure.

2.2 BRIDGE INFORMATION MANAGEMENT

Information support and management is a critical step for the effective and successful operation of any infrastructure-management system (Hudson et al. 1998). A decision support system refers to the use of state-of-the-art computers to store, analyze, and display information so that it can contribute to making rational decisions.

Bridge data must be managed, since it can be both in-depth and dispersed, and it is constantly changing. The bridge data provides critical information for the decision making process. Therefore, a central database capable of capturing, retrieving and updating the stored data is an essential element of any BMS. However, a BMS is more than a data processing and storing tool. It includes complex analysis models to process and deliver the information required for the decision making process.

Input data and analysis routines stream into the BMS from the administrative, programming and implementation functions of a transportation agency. The BMS updates the database and analyzes the input raw data. The analysis results are then reported to the decision maker. One example of a conceptual framework for a BMS is presented in Figure 2.1 (Hudson et al. 1987).

In addition to aiding in the process of making rational decisions, a BMS automates the preparation of annual and multiannual work programs for the maintenance, repair and replacement of bridges.

2.3 NETWORK AND PROJECT LEVEL BMS

Bridge management deals with both levels of decision making: the project-level and the network-level. Project-level bridge management focuses on individual bridges and is mainly concerned with alternative actions for each bridge. Project-level bridge management treats each bridge on an individual basis for inspection, maintenance, repair, and rehabilitation needs.

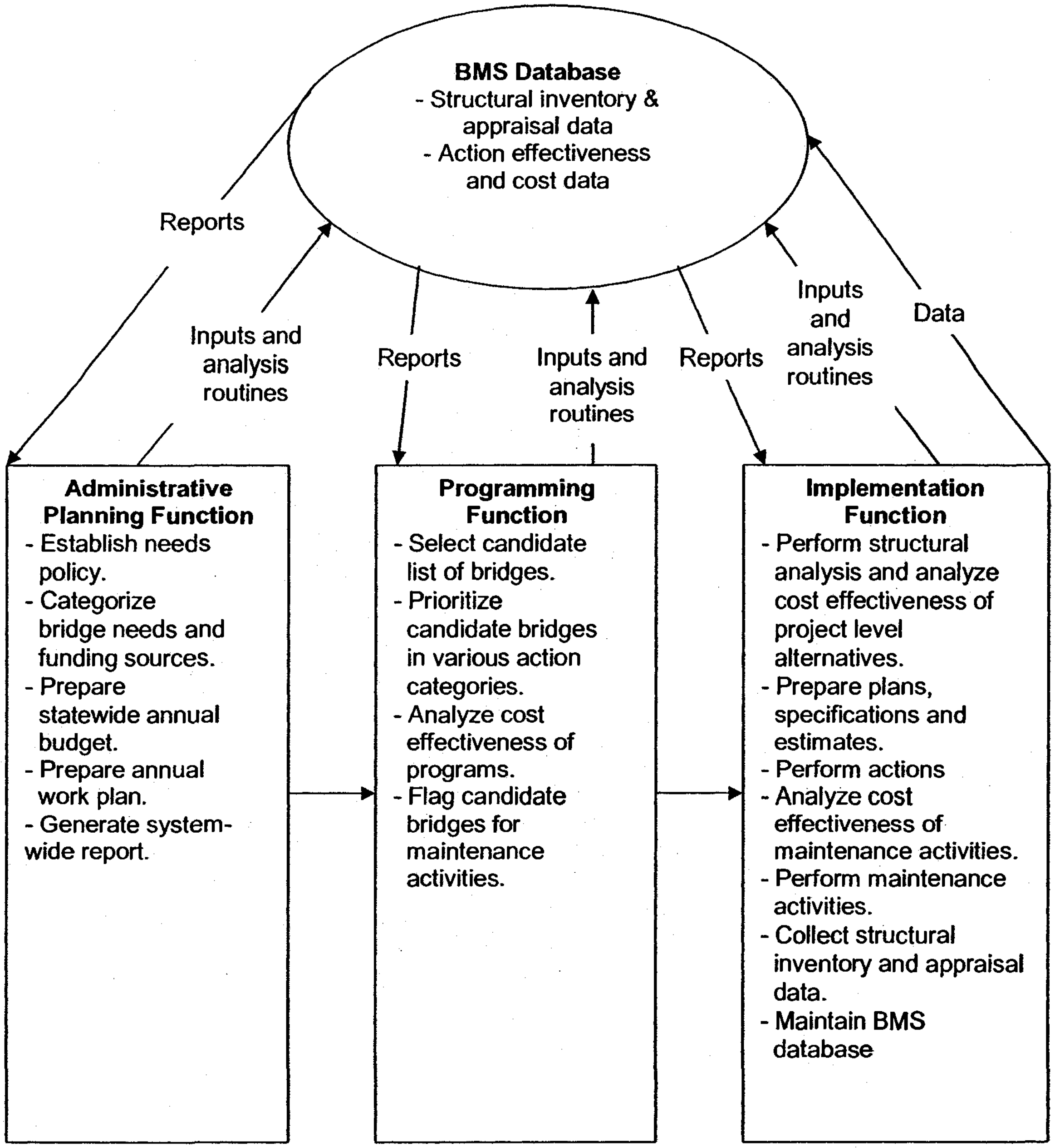


Figure 2.1 Conceptual Framework of a BMS

Network-level bridge management is concerned with bridges inventory and performs multiannual network analysis. The purpose of network-level management is to maintain the performance of all of the bridges in a network at a pre-determined level. This special capability allows a BMS to perform analyses of all of the bridges in an agency's inventory and to determine the impacts of implementing, modifying or deferring action plans.

Recognizing both the project-level and the network-level, bridge management can take either a top-down or a bottom-up approach. The top-down approach first determines the desired goals for the entire network, then selects the individual bridge projects based on those goals. The Pontis bridge management system has adopted the top-down approach. Pontis performs analyses to develop purely network level policies. Then it uses these results to guide the project-level decision making (Thompson et al. 1998).

The bottom-up approach determines the optimal action for each bridge and then selects which projects will be completed first, based on network optimization. The bottom-up approach yields better results for smaller bridge networks. The BRIDGIT bridge management system uses the bottom-up approach (Hawk and Small 1998).

2.4 BRIDGE MANAGEMENT ACTIVITIES

The main activities of a bridge management system are: (1) Condition assessment; (2) Deterioration modeling; and (3) Decision making and optimization.

Condition assessment is based on data from periodic field inspections. The purpose of condition assessment is to estimate the degree and extent of deterioration and defects. A bridge is divided into individual elements, or components, and the condition of each element or component is reported using a condition state. The condition states are defined using numbers or linguistic variables as measures for the degree and extent of deterioration. For example, a scale of 1 to 5 can represent the condition states of bridge elements with 1 representing excellent and 5 representing poor.

A deterioration model is required to predict the future condition of bridge elements under different maintenance and repair scenarios or under the do-nothing option. In general, deterioration models predict the future conditions in a deterministic or probabilistic nature. Deterministic models assume that the future deterioration rate is known and can specify bridge conditions with time. Probabilistic models assume that the actual deterioration rate is unknown and provide a probability that the bridge will be in a certain condition in the future.

Information about alternative actions, such as useful lifetimes, effectiveness and cost can be retrieved from the bridge management database. Using deterioration information combined with cost and effectiveness information for different strategies, an optimization model determines optimal maintenance, repair and rehabilitation strategies for bridge elements.

The following is a detailed discussion of BMS activities and a review of the literature available on bridge management.

2.5 BRIDGE CONDITION ASSESSMENT

Bridge conditions are assessed through an inspection process which involves the use of specific techniques to assess the physical condition of bridges. A detailed visual inspection is conducted on a routine or scheduled basis in order to discover serious defects and to evaluate the degree of the deterioration of bridge elements. In addition, ad hoc inspections should be carried out after natural calamities such as earthquakes and emergency inspections can be carried out after accidents due to a specific defect.

If a serious defect is identified during the visual inspection, a detailed condition survey is required. The detailed condition survey uses nondestructive testing (NDT) methods to determine the extent of the defect in a bridge element. Based on the condition survey, an appropriate corrective action such as strengthening the bridge can be recommended.

Post-maintenance inspection should be conducted to insure that the defect has been rectified, and then the bridge will be scheduled for routine inspection and maintenance. Figure 2.2 presents a schematic of a bridge inspection schedule.

Bridge inspection procedures and guidelines are documented in well-developed bridge inspection manuals such as the Ontario Structure Inspection Manual (OSIM 1989) published by the Ontario Ministry of Transportation, and the Bridge Inspector's Training Manual 90 (FHWA 1991) published by the U.S. Department of Transportation. These manuals provide the basic guidelines for bridge inspection and condition evaluation. These manuals are commonly used to perform the inspection. Sections 2.5.1 and 2.5.3 describe certain aspects of these manuals.

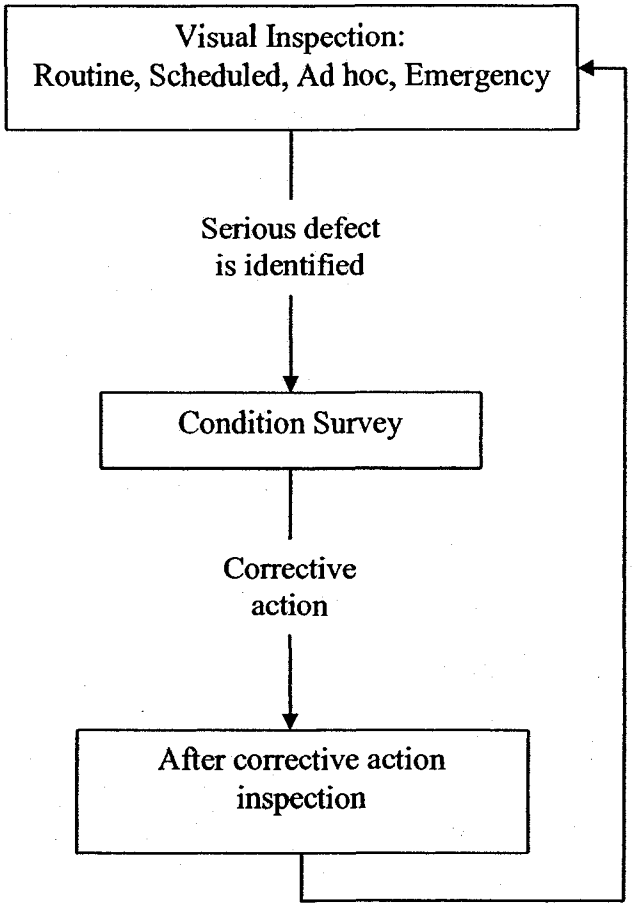


Figure 2.2 Bridge Inspection Schedule

2.5.1 The Ontario Structure Inspection Manual (OSIM)

The OSIM provides detailed standards for inspecting and rating structures and their components. These standards apply to bridges, culverts, tunnels with spans over 3 meters, and retaining walls. The OSIM is divided into three parts. Part 1 presents technical information such as inspection procedures, bridge components and material defects. Part 2 discusses the requirements of detailed inspections and condition rating and Part 3 develops programming guidelines for repair and rehabilitation.

The OSIM divides inspections into general inspection, detailed inspection, and condition surveys. The general inspection is a direct visual inspection and can be carried out on a routine or a non-routine basis. Detailed inspections are also performed biennially or on a non-routine basis. Light and simple to operate equipment is used during the detailed inspection, such as measuring tapes, chalk, camera, flashlights, and screwdrivers. Inspection forms are filled out to document some general inspection data such as the inspection team, date and weather conditions. Inspection forms for each component are filled out based on the conditions of the inspected elment.

The conditions surveys precisely measure and document the extent and location of deterioration on a structure. As a result, additional tools and equipment such as mobile platforms, bucket trucks, scaffolding and equipment for NDT are required. Condition surveys are conducted on selected structures every five years. The detailed condition surveys include load carrying capacity assessment and deck assessment by radar and thermograph.

The OSIM recommends an element-level inspection and defines four material condition states to categorize the condition of each bridge element. These states are Excellent, Good, Fair and Poor. At inspection time, quantities within a bridge element may be in any one of these different condition states. The inspector estimates and records the quantities (area, length, or unit) of the bridge elements in each condition state.

The OSIM includes tables to describe the four condition states for different types of materials such as steel and concrete. In addition, it provides descriptions of defects and the associated condition states for special elements such as bearings and expansion joint seals. As a general rule of thumb, the OSIM provides a philosophy to identify the four condition states for any element or material type. The general description of the four condition states is shown in Table 2.1.

Table 2.1 Condition States Description (OSIM 1989)

Condition State	Description	Examples
Excellent	- Refers to a part of an element that is in 'as constructed' condition	-"Bug holes" in concrete barrier walls
Good	- Refers to a part of an element where the first sign of minor defects are visible.	-Light corrosion -Light scaling -Narrow cracks in concrete
Fair	-Refers to a part of an element where medium defects are visible.	-Medium corrosion (up to 10% section loss)
Poor	-Refers to a part of an element where severe and very obvious defects are visible.	-Severe corrosion (greater than 10% section loss) -Spalling, delamination, etc.

2.5.2 Bridge Inspection in the United State

In the United States, the National Bridge Inspection Standards require periodic inspections of the nation's bridges and the reporting of bridge conditions in a standardized format. Condition ratings are assigned for each of the three main bridge components: deck, superstructure, and substructure. To facilitate the inspection process, the Bridge Inspector's Training Manual further divides these three major components into 13, 16, and 20 elements, respectively, as shown in

Table 2.2. In addition, this manual provides the basic guidelines for bridge inspection, the different types of bridge deterioration and their common causes, and procedures for rating the condition of the different bridge elements.

Table 2.2 Bridge Elements (FHWA 1991)

Deck	Superstructure	Substructure
1. Wearing surface	1. Bearing devices	1. Bridge seats
2. Deck condition	2. Stringers	2. Wings
3. Curbs	3. Girders	3. Back wall
4. Median	4. Floor beams	4. Footings
5. Sidewalks	5. Trusses	5. Piles
6. Parapets	6. Paint	6. Erosion
7. Railings	7. Machinery	7. Settlement
8. Paint	8. Rivets-Bolts	8. Pier-cap
9. Drains	9. Vibrations	9. Pier-column
10. Lighting	10. Welds	10. Pier-footing
11. Utilities	11. Rust	11. Pier-piles
12. Joint leakage	12. Timber decay	12. Pier-scour
13. Expansion joints	13. Concrete cracks	13. Pier-settlement
	14. Collision damage	14. Pier-bents
	15. Deflection	15. Concrete cracks
	16. Alignment of members	16. Steel corrosion
		17. Timber decay
		18. Debris seats
		19. Paint
		20. Collision damage

The Federal Highway Administration keeps records for every bridge with a length greater than 6.1 meters. The condition ratings for bridge elements are assigned biannually and these ratings are aggregated to estimate condition ratings for the superstructure, the substructure and the deck. Ratings range from 0 to 9, where

0 is the lowest possible condition and 9 is the best. A bridge with a condition rating of 4 or less is considered structurally deficient.

The Pontis bridge management system relies on biennial visual inspection of every bridge in the inventory. In Pontis, each element is assigned one of five condition states. The condition state is assigned by a trained inspector after visually inspecting an element. Some elements have fewer condition states.

2.5.3 Reliability of Visual Inspection

The reliability of visual inspections and the accuracy of the developed ratings are essential issues since the results of the inspection are the basis used to identify bridges that need maintenance and repair.

The Nondestructive Evaluation Validation Center (NDEVC) at the FHWA completed a research report on reliability of visual inspection process for highway bridges (FHWA-RD-01-020) in June 2001. This report provides overall measures of the reliability and accuracy of inspections and identifies factors that may influence the results. The study concluded that the definitions of particular condition states may not be refined enough to facilitate accurate and reliable ratings. The study is available online at (www.tfhrc.gov/hnr20/nde/01020).

Nevertheless, visual inspection is an essential initial step in bridge management. The visual inspection provides an assessment of the conditions of bridges in a network. The results of the visual inspection can be used to prioritize bridges for action or can reflect the need for further in depth inspections and condition evaluation.

2.5.4 Nondestructive Testing

NDT is a set of techniques to evaluate the internal condition of an element without destroying it. Although destructive testing reveals more reliable assessment of an element's conditions, it is not always possible to destroy portions or the entire tested element because of the high cost of this type of test. The Handbook on nondestructive testing of concrete (Malhotra and Carino 2004) provides a complete description of NDT techniques including procedures, applicability, advantages and drawbacks.

The NDT techniques associated with bridge deck condition assessment are discussed in the following section.

2.5.5 Bridge Deck Inspection

The bridge deck has the highest deterioration rate among the bridge elements. This is due to the direct impact from loading and the reaction with chlorides from deicing salt. Bridge deck condition assessment starts with visual inspection by an experienced inspector to evaluate the conditions of the top and bottom surfaces of the deck. Visual inspection reveals defects such as cracking, scaling, spaling, delaminations and reinforcement corrosion. NDT of a bridge deck can be conducted to quantify the extent of defects observed in the visual inspection.

For concrete bridge decks without wearing courses or asphalt overlays, chain drag and hammer sounding are the most common NDT techniques since these techniques are easy to carry and are not expensive. The purpose of the chain drag and the hammer sounding is to identify areas with delamination. The basic principle of chain drag is to identify the change in sound being emitted while moving a heavy chain (2.2 Kg/m with 50 mm links) in a swinging motion (OSIM 1989). The delaminated areas are recognized and marked since these areas have hollow echo sounds. High-technology sonic devices have also been developed to locate areas with delaminated concrete.

A concrete bridge deck with wearing course overlay can be evaluated using ground penetrating radar (GPR). The GPR is used to collect information by recording the reflections of a single energy pulse from the interfaces of the different material layers and reinforcement within the deck over time. The GPR can present a viable option for bridge management by estimating deterioration quantities with improved accuracy and less variability than provided by traditional visual estimation methods (Barnes et al. 2000).

If the results obtained from NDT reveal extensive deterioration in a bridge deck, concrete cores should be extracted and tested. Cores are taken randomly from different locations of the deck. However, locations with probable chloride contamination, such as the concrete beside expansion joints and near drains, should be chosen for coring. The number of cores to be extracted depends on bridge deck conditions and the extent of deterioration. Holes in the deck from coring should be visually inspected to spot delamination and also to estimate deck thickness and to locate reinforcement if such information is not available. Extracted cores are tested in a laboratory for compressive strength and chloride contamination.

Nondestructive testing has been a major factor in the bridge deck decision making process. Findings based on NDT were the basis for the complete bridge deck replacement for Jacques Cartier Bridge in Montreal (Zaki and Mailhot 2003). Another major deck rehabilitation project was completed in 2004 for the Peace River Bridge. During rehabilitation it was found that the locations of the deteriorated deck concrete were accurately predicted by the ground penetrating radar results (Ramsay 2006).

2.5.6 Bridge Deck Condition Rating

In Pontis, bridge deck inspection results are obtained from assessing the percentage of spalling and delaminations in the deck and measuring the width and spacing of cracks (Estes and Frangopol 2003). Colorado Department of Transportation (1995) suggested condition rating according to the extent of these defects. These values are presented in table 2.3 and 2.4. In Bridgit, four condition states are defined for the bridge deck. Table 2.5 presents the condition state descriptions for concrete decks (Hawk and Small 1998).

Table 2.3 Suggested Condition State Ratings for Deck Cracking (CDOT 1995)

	Condition states for cracks in concrete deck Spacings of cracks (m)			
Crack width (mm)	**>3**	**2-3**	**1-2**	**<1**
<1	1	1	2	3
1-2	1	2	3	4
2-3	2	3	4	4
>3	3	4	4	4

Table 2.4 Suggested Condition States for Bare Concrete Deck (CDOT 1995)

Condition state	Description
1	No repaired areas, no spall/delaminations exist
2	Repaired areas/spalling/delamination area is 2% or less of deck surface
3	Repaired areas/spalling/delamination area is 10% or less of deck surface
4	Repaired areas/spalling/delamination area is more than 10% but less than 25% of deck surface
5	Repaired areas/spalling/delamination area is more than 25% of deck surface

Table 2.5 Condition State Descriptions for Bridgit Element 200 (Concrete Deck)

Condition state	Description
1	Surface areas of slabs show no sign of spall/delamination or important cracking, including repaired areas.
2	Minor deterioration to concrete surface. Spalls or delaminations are less than 2.5 cm in depth or 15 cm wide in any directions
3	Medium deterioration exists. Spalls or delaminations are between 2.5 and 5 cm in depth and/or are between 15 and 60 cm in width. Corrosion of rebar may be present but loss of section may be incidental. Wide cracks may be present but do not significantly affect the strength and performance of either the element or bridge.
4	Advanced deterioration to concrete surfaces. Spalls or delaminations are greater than 5 cm in depth and/or greater than 60 cm wide in any direction. Cracking, corrosion of reinforcement and/or loss of concrete section are sufficient to warrant analysis of impact on strength and/or performance of either the element or the bridge.

Purvis et al. (1994) suggested in SHRP-S-377 report that three quantities are indicators bridge deck concrete condition. These quantities are:

1. Percent of bar-level concrete samples with chloride content higher than the corrosion threshold value (CL).
2. Percent of concrete area that is delaminated (DELAM), not including spalling.
3. Percent of concrete area that is spalled (SPALL).

In terms of assessing treatment options at a given time, spalling is the most important factor, delamination is second, and chloride contamination at the level of the reinforcing steel is the third most important. The SHRP-S-377 report assigned the following weights for these factors:

- Spalling is three times more important than delamination.
- Delamination is 2.5 times more important than bar-level chloride contamination.

The report proposed the following equation to quantify the concrete condition index (S) at the time of the condition survey.

$$S = [CL + 2.5\,(DELAM) + 7.5\,(SPALL)] / 8.5 \qquad (2.1)$$

where CL is the amount of choride present in bar-level concrete samples above the corrosion threshold value; DELAM is percent of concrete area that is delaminated, but not including spalling; SPALL is the percent of concrete area that is spalled.

2.6 DETERIORATION MODELING

In general, infrastructure management involves defining the current facility conditions and predicting future conditions. Current conditions are defined using a condition assessment methodology and future conditions are predicted using a deterioration model. Deterioration involves the gradual decrease in both condition and performance of an element or structure under normal operating conditions.

Deterioration of concrete bridges is a major problem in the operation of a nation's highway. Bridge deterioration is due to natural aging, increasing load spectra, and is due to environmental conditions including freezing and thawing cycles, shrinkage and temperature gradient. In addition, the deterioration rate is directly related to design and construction practices and techniques, maintenance practices, materials properties and the operating environment (Madanat et al. 1995, Hudson et al. 1998).

The physical and functional deterioration modeling of bridges is a complex process due to the interaction, at different levels, of the above mentioned factors and mechanisms. For instance, rapid deterioration in a bridge deck can be caused by a deficiency in the structural system. This deficiency can lead to excess stresses in certain locations causing the concrete to crack. De-icing salt can penetrate the cracks and cause degradation of the concrete and corrosion of the reinforcing steel.

It is essential for any BMS to include an integral deterioration model to forecast the future condition of bridge elements. Actions including maintenance, rehabilitation or replacement of bridge elements are based on current and future element conditions . In addition, introducing a life cycle cost analysis technique as a decision making approach requires accurate deterioration modeling in order to produce a financial analysis of different maintenance strategies.

The following sub-sections review the available models for bridge deterioration modeling. The literature available on bridge deterioration can be categorized into deterministic, stochastic, and artificial intelligence models (Morcous et al. 2002).

2.6.1 Deterministic Deterioration Models

Deterministic models use a single, defined value to describe bridge element conditions at a certain given time, and they use historical data to estimate the deterioration rate. This rate is calculated using the available statistical techniques such as regression analysis and curve fitting techniques. Assuming that the deterioration rate will continue, future conditions can be predicted.

A deterministic model yields the same exact output if the model is repeated several times using the same input data. As a result, a deterioration model developed based on the historical data of a structural element will propose a similar performance for any element of the same type under the same conditions. This is based on the assumption that systems are ideal and interact with each other in a constant, standard fashion. This assumption indicates that the environmental system, the structural system, the material properties, and the boundary conditions always exhibit the same behaviour and are not affected by any random or unknown process.

The actual deterioration process has proven that this assumption is not accurate. The deterioration rate of one element cannot be generalized to all similar elements. As a result, deterministic models cannot be used for a network of projects. To a certain extent, deterministic deterioration models can be developed to predict the behavior of particular systems where major repair and maintenance actions are not expected until the end of the useful life of the system. For example, Zayed et al. (2002) developed a deterministic performance function for steel bridge paint using regression analysis performed on some available data.

The previous discussion leads to the conclusion that the deterioration behavior of bridge elements is stochastic. The complexity and interaction of several mechanisms make it unrealistic to model the deterioration process using a deterministic approach. The next section presents the stochastic deterioration modeling approach.

2.6.2 Stochastic Deterioration Models

As discussed in the previous section, the deterioration process has a stochastic rather than a deterministic nature since several complex mechanisms characterize the variability of a deteriorated element. Probabilistic models are often used to characterize deterioration. In general, stochastic models can be categorized into Probability Distribution, Simulation Techniques, and Markovian Models.

2.6.2.1 Probability Distribution

A probability distribution describes the probabilities associated with all of the values of a random variable. Mauch and Madanat (2001) reported that time-based deterioration models can predict the probability distribution of the time taken by an infrastructure facility to change its condition state. For example, given a set of condition state transition probabilities, the probability distribution of the time to condition state change can be derived. The use of probability distribution requires knowledge of the distribution law for the variables being predicted, which limits the usefulness of this technique for individual distress prediction.

2.6.2.2 Simulation Techniques

Simulation techniques can be used to model deterioration when adequate analytical models are not available. This technique requires distribution functions for the variables. For instance, the deterioration can be simulated if enough statistics on the transition times required for an element to change its condition are available. The output of the simulation will be a probabilistic deterioration profile in terms of the time taken by the element to change from one condition rating to another.

Roelfstra et al. (2004) modeled chloride-induced corrosion mathematically and performed numerical simulations of the condition evolution for different values of model parameters. The simulation results were used to calibrate the Markov transition matrices adopted by the Swiss bridge management system (KUBA-MS).

2.6.2.3 Markovian Models

Deterioration is usually assumed to be a Markov process (Frangopol et al. 2004, Barlow and Proschan 1965). In general, a Markov process is a stochastic process that holds the following property: For a given value of $S(t_1)$, any future value of $S(t_2)$, where $t_2 > t_1$ is independent of the values of $S(t)$, where $t < t_1$. In other words, the conditional distribution of the future is independent of the past conditions.

This property in Markov models is known in the literature as the state dependence assumption, which implies that the future state or condition depends on the present condition and not on the past conditions. The state dependence assumption was made for simplicity and to facilitate computations. However, this assumption is not supported by mechanistic knowledge of material behaviours. Empirical research has confirmed that age is a significant factor in the deterioration process (Madanat et al. 1997, Jiang et al. 1988).

Despite the state dependence assumption, Markov models have proven to be effective and practical representations of the deterioration process. Several advantages for Markov chain models are discussed in the literature (Morcous and Lounis 2006). Chief among these are that Markov models: (1) are able to represent uncertainty from different sources such as uncertainty in initial condition, uncertainty in applied stresses, presence of condition assessment errors, and inherent uncertainty of the deterioration process (Lounis 2000); (2) are incremental models that account for the present condition in predicting the future condition (Madanat et al. 1995); and (3) can be adopted effectively at the network level and can manipulate a large number of facilities because of their computational efficiency and simplicity (Morcous and Lounis 2006).

A Markov chain is a special type of Markov stochastic process that is based on the concept of probabilistic cumulative damage, which predicts changes in component conditions over multiple transition periods (Bogdanoff 1978). Most bridge management systems, such as Pontis (Golabi and Shepard 1997), BRIDGIT (Hawk and Small 1998) and the Ontario Bridge Management System (Thompson et al. 1999), have adopted Markov chain models as a stochastic approach for predicting the performance of bridge components and networks. A Markov chain is adopted in this research to represent the deterioration process of the bridge deck. A full discussion of Markov chains is included in Chapter 4.

2.6.3 Artificial Intelligence Deterioration Models

Artificial Intelligence (AI) is a branch of computer science that deals with intelligent behaviour, learning and adaptation in machines. Research in AI is focussed on producing machines to automate tasks that require intelligent behaviour. Two branches of artificial intelligence have been used in deterioration modeling, namely, neural networks and case-based reasoning.

Artificial neural networks (ANN) are non-linear statistical data modeling tools that can be used to model complex relationships between inputs and outputs or to find patterns in data. Sobanjo (1997) proposed the use of ANN to model bridge deterioration. The input was the age of bridge in years, mapped to an output of a corresponding condition rating. In general, ANN have been criticized for being black boxes in which the mathematical mapping between inputs and outputs and the learning process cannot be explained. In addition, despite the fact that ANN have automated the process of finding the polynomial that best fits a set of data points, they still have the problems of deterministic models (Morcous et al. 2002). A more detailed discussion on artificial intelligence in bridge management is presented in section 2.8.

Case-based reasoning (CBR) is the process of solving new problems based on the solutions of similar past problems. This technique was proposed by Morcous (2000) for modeling the deterioration of concrete bridge decks using data obtained from the Quebec Ministry of Transportation. The system was developed based on the assumption that two bridges that have similar features and operate under similar conditions will have the same performance. A library of cases with known parameters and performance was compiled. The performance of a new case can be predicted by retrieving a similar case from the library.

Although Morcous (2000) presented the CBR as a robust model to predict deterioration, he mentioned the following drawbacks: 1) CBR may not be able to retrieve any matching cases when the size of the case library is inadequate; 2) the determination of attribute weights and degrees of similarity requires engineering judgment, which suffers from subjectivity; and 3) the acquisition of domain-specific knowledge for case adaptation is not a simple task.

2.7 DECISION MAKING AND OPTIMIZATION

Strategic decision making for bridge maintenance, repair and rehabilitation has become a major issue for transportation agencies for the following reasons: 1) many bridges are old; 2) older bridge design features do not accommodate the current traffic volume, vehicle sizes and vehicle loads; 3) only limited and constrained budgets are available. Most of the existing decision making methodologies attempt to optimize the long term maintenance, repair and rehabilitation actions in order to minimize the total cost and to maintain bridges at an acceptable level of serviceability and safety. These conflicting objectives have made the bridge management decision process very complex. The following is a review of the techniques available for bridge management decision making.

2.7.1 Life Cycle Cost Analysis

Cost is a major factor in the decision making process, especially within tight budgets considerations. The cost concept has evolved over the years into life cycle cost, which implies that the preferred alternative is an alternative that would cost less in the long run. The escalating costs of energy and materials, inflation, and rising interest rates have contributed to the appeal of the life cycle cost approach.

The life cycle approach is the preferred concept when decision makers are not only concerned with safety, but also with costs (Frangopol et al. 2004). Life cycle cost (LCC) for bridge engineering is defined by the Federal Highway Administration as: "the evaluation of agency, user, and other relevant costs over the life of investment alternatives. Evaluating the total cost of an alternative is essential if improvements that minimize long-term costs are to be identified. Improvements with the lowest initial costs are often more costly in the long run than alternatives with higher initial costs, especially if costs of traffic delay during maintenance and rehabilitation activities in congested areas are considered".

LCC analysis is used to evaluate the long-term economic efficiency of competing alternatives and maintenance options. The objective of LCC optimization is to minimize life-cycle maintenance costs while enforcing limits on relevant performance measures in order to keep bridges safe and serviceable

The NCHRP Project (12-43) developed a methodology for bridge life-cycle cost analysis (BLCCA) to be used by transportation agencies. The proposed methodology is described in a guidance manual and implemented in a software package for the LCC analysis of bridges. The purpose of the analysis is to aid bridge professionals in selecting bridge improvement alternatives. In addition, it identifies various modular elements required in a bridge LCC analysis. Hawk (2003) reported that additional information such as work-zone user costs, loads, condition deterioration models, and prediction of future needs is required to fully implement the software.

Ehlen (1999) compared new and conventional construction materials by using LCC analysis. The concept was used to examine the effectiveness of three fibre-reinforced polymer bridge decks. Purvis et al. (1994) applied LCC analysis on a hypothetical test case with assumed bridge parameters and rehabilitation costs.

The research focus was on sensitivity analysis due to the impact of uncertainty on average daily traffic.

2.7.2 Monte Carlo methods

Monte Carlo methods are computational algorithms for simulating the behaviour of physical and mathematical systems. Monte Carlo methods utilize computer simulation because of the repetition of algorithms and the large number of calculations involved. Monte Carlo simulation has been used to optimize the life cycle cost of bridge improvement alternatives.

Huang et al. (2004) developed a project-level decision support tool to rank maintenance scenarios for deteriorated concrete bridge decks based on probabilistic LCC analysis. The analysis included agency and user costs of alternative maintenance scenarios and considered uncertainties in the agency cost and the corrosion rate in the deterioration model. Monte Carlo simulation was used to analyze the risk impact of uncertain and random variables on the results of life cycle cost analysis.

Kong and Frangopol (2003) studied uncertainties in reliability-based life-cycle maintenance cost optimization of deteriorating bridges. Monte Carlo simulation was carried out to compute sample mean values of a system reliability index and LCC. In a different study, Frangopol and Neves (2003) investigated uncertainty effects on the evaluation of condition and safety indices as well as on the LCC of deteriorating bridges under different maintenance strategies using Monte Carlo simulation. These studies indicate that large dispersions exist for the computed performance indices. Therefore, it is important to take the uncertainty effects into account in order to make rational decisions when selecting optimal maintenance solutions.

2.7.3 Decision Tree Analysis

The decision tree model provides a systematic means of structuring and evaluating action possibilities related to an uncertain inspection/repair environment (Frangopol et al. 1997).

Maintenance actions can be visualized by a decision tree such as the one presented in Figure 2.3 (Thoft-Christensen and Soerensen 1987). After inspection, maintenance actions M will have the probability P_M to be carried out; this maintenance action is represented by the branch label 1. The probability that M will not be carried out is $(1 - P_M)$; this action is represented by branch label 0. The probability of performing maintenance action M will be based on the condition assessment of a bridge element or group of elements.

Morcous (2005) used decision tree algorithms to model bridge deck deterioration. Chung et al. (2003) applied the decision tree approach to the inspection of metal fatigue in steel bridges. Bonyuet et al. (2002) presented optimization procedures for bridge replacement decision making using decision trees. Local optima were obtained at each branch of the search tree to estimate the lower confidence limit of the user cost.

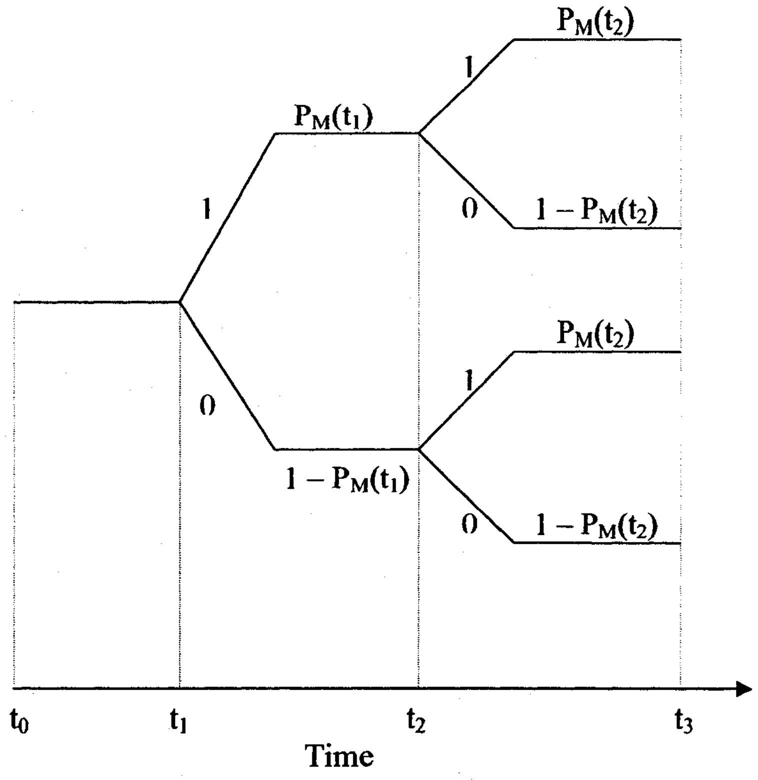


Figure 2.3 Decision Tree Representation

2.7.4 Markov Decision Process

Many state-of-the-art infrastructure management systems utilize the Markov Decision Process (MDP) for decision making (Abraham and Wirahadikusumah 1999, Madanat and Ben-Akiva 1994, Gopal and Majidzadeh 1991). The MDP provides a mathematical framework for modeling decision making in situations where outcomes are partly random and partly under the control of the decision maker. Markov decision processes are an extension of Markov chains; the difference is the addition of actions that lead to improvements.

The state dependence assumption in Markov models means that the transition probability is independent of the history. When the process is currently in state i and an action A is taken, the process moves into state j with probability P_{ij}

$$P_{ij}(A) = P(X_{n+1} = j \mid X_n = i) \qquad (2.2)$$

Optimization of maintenance policies using the Markov decision process can be performed using the following procedure (Frangopol et al. 2004). When the system is in state i, the expected discounted costs over an unbounded horizon are given by the following recurrent relation:

$$V_\alpha(i) = C(i, A) + \alpha \sum_{j=1}^{N} P_{ij}(A) V_\alpha(j) \qquad (2.3)$$

where α is the discount factor for one year, estimated by $\alpha = (1 + r/100)-1$, where r is the yearly discount rate; V_α is the value function using α.; and C (i , A) is the costs that are incurred when the process is in state i and action A is taken.

Starting from state i, $V_\alpha(i)$ is the cost of performing action A, given by C (i , A), in addition to the expected discounted costs of moving to state j after one year with probability P_{ij} . Applying the equation again, $V_\alpha(j)$ is the discounted costs starting in state j. This equation can be applied recursively for all maintenance actions. The choice of a maintenance action is determined by the maintenance policy.

A cost-optimal decision can now be found by minimizing the previous cost equation with respect to the action under consideration. One approach to formulating the minimization or maximization problem is by using mathematical programming. For instance, a linear programming formulation or one of its variations can be used to maximize certain conditions under a budget constraint or to minimize the maintenance cost under a minimum safety constraint.

2.8 ARTIFICIAL INTELLIGENCE IN BRIDGE MANAGEMENT

As discussed earlier, AI is a branch of computer science that deals with intelligent behaviour, learning, and adaptation in machines. Research in AI is concerned with producing machines to automate tasks requiring intelligent behaviour. AI methods are increasingly used in infrastructure management to handle data obtained from inspection or measurements obtained from the field and the laboratory.

Several systems have been proposed that profit from the AI in bridge management. These systems include knowledge-based systems (experts' rules), fuzzy set theory (knowledge representation via fuzzy IF – THEN rules), genetic algorithms (search and selection), and neural networks (learning and adaptation).

2.8.1 Knowledge-Based Decision Support Systems

Knowledge-based decision support systems are flexible approaches to facilitate the decision making process. These systems employ decision criteria similar to that used by experienced practitioners, since the systems are developed based on a set of rules derived from experts' knowledge. In addition, mathematical programming techniques are adopted in some of these systems to the optimize decisions associated with varying costs.

Knowledge-based decision support systems are relatively easy to develop and focus on solving problems that appear in the application area rather than problems under any possible condition (Chassiakos, 2005). Knowledge-based systems are not as effective as fully developed bridge management systems and offer limited decision support.

Based on bridge management practice in Greece, Chassiakos (2005) developed a knowledge-based system for planning the maintenance of highway concrete bridges. This system includes functions for maintenance priority setting among bridges, feasible treatment assessment for each case, and maintenance planning for bridge stock. The system is based on knowledge elicitation from experienced maintenance engineers, and attempts to model their decisions for maintaining highway concrete bridges.

Brito et al. (1997) developed a prototype for an expert system for bridge management, using two modules. At the inspection site, the BRIDGE-1 module helps to standardize the inspection techniques and acts as a useful tool for bridge inspectors. The extracted information is then used by the BRIDGE-2 module, in which the decision system for the optimal non-periodic inspection, maintenance and repair strategies is implemented. Thus far, its application has been limited to defects related to reinforced concrete corrosion.

Zuk (1991) developed an expert system to make recommendations regarding the appropriate actions to relieve problems in older highway bridges. Five options are considered: rehabilitation, improvement, replacement, abandonment, and routine maintenance. Rules, criteria and procedures solicited from expert knowledge were built into a computerized system to reduce the evaluation time and to provide a consistent basis for decision making.

A knowledge-based approach has been adopted in certain agency's bridge management systems. The Ontario BMS features a knowledge-based approach to treatment selection. Based on element condition, a knowledge-based model identifies feasible treatment alternatives (Thompson et al. 1999).

Alberta Transportation developed an expert system to support their bridge management functions. The system's primary objectives are to facilitate consistent and accurate decisions to optimize the allocation of bridge funds, evaluate system performance, and plan and manage bridge construction, rehabilitation, and maintenance actions. Their Bridge Expert Analysis and Decision Support system was intended to be a major component of a larger department-wide, integrated Transportation Infrastructure Management System (Loo et al. 2003).

2.8.2 Fuzzy Set Theory

Fuzzy logic was introduced to model the uncertainty of natural language in the famous article of Dr. Zadeh (1965). Fuzzy logic was later developed to handle the concept of partial truth, that is, the truth value between completely true and completely false.

The concept of fuzzy sets is an extension of conventional set theory. Similar to the strong relationship between boolean logic and the concept of a subset, there is a strong relationship between fuzzy logic and fuzzy subset theory. In conventional set theory, a membership function μ can be used to decide if an element x belongs to a set A.

$$\mu = \begin{cases} 1 \text{ if } x \in A \\ 0 \text{ if } x \notin A \end{cases}$$

When the membership function can have values in the real interval [0,1] to represent the degree to which the element x belongs to A, then the set A is a fuzzy set (Zadeh 1965).

Fuzzy set theory was used in bridge management to represent the subjectivity and uncertainty in qualitative terms used by bridge inspectors, such as good, poor and fair (Yao 1980, Hadlpriono 1988, Tee et. al 1989). The concept was also used to evaluate the damage grade of existing bridges (Liang et al. 2002). Zhao and Chen (2002) developed a fuzzy rule-based inference system for bridge damage diagnosis and prediction, with the goal of providing bridge designers with information about the impact of design factors on bridge deterioration.

Sasmal et al. (2006) reported that the existing literature contains extensive studies to evaluate the condition of different structures using fuzzy logic, but the methods are either too simplistic (Liang et al. 2001), which would not reflect the proper condition of the structure, or very complex (Kawamura and Miyamoto 2003), requiring a thorough understanding of the methodology and considerable computation time to solve the problem. Furthermore, some key issues, such as the determination of membership functions, priority vector, final mapping, and processing of non-convex fuzzy sets, which are vital for condition evaluation and rating of bridges using fuzzy logic, did not receive much attention.

Sasmal et al. (2006) proposed a procedure and formulations for the condition rating of existing bridges using fuzzy mathematics combined with an eigenvector-based priority-setting technique. They propose a scale of 0 to 9 for rating bridge elements. An element with a rating value of 9 signifies the best possible condition without distress, and the descending rating numbers represent increased degrees of distress. The membership functions for 0 and 1 ratings were initially assumed and the membership functions for other rating values were evaluated using a consecutive fuzzy addition rule. This procedure, however shares the previously mentioned drawback of cumbersome and complex calculations.

2.8.3 Genetic Algorithms

Genetic algorithms (GA) are a computing search technique used to find true or approximate solutions to optimization and search problems. GA are based on the mechanics of natural selection and natural genetics. They combine survival of the fittest among string structures with a structured yet randomized information exchange to form a search algorithm. GA are implemented as a computer simulation in which a population of abstract representations (chromosomes) of candidate solutions (individuals, or creatures) to an optimization problem evolves towards better solutions.

Typically, solutions are presented as binary strings of 0s and 1s, but other encodings are also possible. The evolution usually starts from a population of randomly generated individuals and happens in generations. In each generation, the fitness of every individual in the population is evaluated. Multiple individuals are stochastically selected from the current population based on their fitness, and then modified to form a new population. The new population is used in the next iteration of the algorithm.

Fwa et al. (1994) introduced the use of genetic algorithms in maintenance optimization. The proposed methodology was used to develop a computer software known as PAVENT for maintenance planning of pavement networks. PAVENT was further updated to resolve the complexity of multi-objective maintenance and rehabilitation problems (Fwa et al. 1996, Fwa et al. 2000).

Liu et al. (1997) and Miyamoto et al. (2000) also developed GA-based models for the determination of optimal long-term maintenance strategies for bridge deck networks. Liu and Frangopol (2004) developed a genetic algorithm-based procedure for optimal life-cycle maintenance planning of deteriorating bridges.

Morcous and Lounis (2005a) criticized the above models for using deterministic future condition predictions, since such models neglect the stochastic nature of infrastructure deterioration. They proposed a maintenance optimization model using genetic algorithms and a Markov chain for deterioration prediction.

However, the main drawback of optimizations using genetic algorithms is that the solution is not necessary an optimum. The algorithm may find a near-optimal group of solutions. Frangopol and Liu (2005) discussed a numerical example to optimize an existing bridge network consists of 13 highway bridges. A total of 30 optimized solutions were obtained, representing the wide spread between conflicting multiple objectives.

2.8.4 Artificial Neural Networks

Artificial Neural Networks (ANN) are a system of interconnecting neurons in a network working together to produce an output function. In engineering, neural networks refer to a branch of computational science that uses neural networks as models to simulate or analyze complex problems. ANN address problems similar to the other branches of artificial intelligence. The main difference is that other branches of artificial intelligence use traditional computational algorithms to solve problems, whereas ANN use software or hardware entities linked together as the problem-solving computational architecture.

The purpose of neural networks is to derive comprehensible meaning from complicated or imprecise data. Neural networks can be used to extract patterns and detect trends that are too complex to be observed either by humans or other computer techniques. Well-designed ANN are trainable systems that can learn to solve complex problems. The acquired knowledge from training examples is accumulated and generalized to solve unforeseen problems. In other words, the developed networks are planned to become self-adaptive systems. It is essential to test a developed network with an independent set of data to examine the accuracy and the consistency of the results.

The use of the ANN technique in predicting bridge deterioration was first proposed by Sobanjo (1997). In this developed model, the input was the age of bridge in years mapped to the output of a corresponding condition rating. Tokdemir et al. (2000) developed a more elaborate model that incorporated additional governing factors, such as highway class, design type, material type, and traffic volume. A time-series-based ANN model was developed by Lou et al. (2001) to predict the future condition of pavements for given past condition records. Morcous and Lounis (2005b) developed a back-propagation neural network model to approximate the relationship between the corrosion initiation time of the top layer of reinforcing steel in concrete bridge decks.

Although ANN were proposed as a powerful machine learning tool, they have a major drawback: the individual relations between the input variables and the output variables are not developed by engineering judgment or based on analytical basis, so that the model tends to be a black box. Once the inference process of a neural network becomes a black box, the representation of knowledge in the form of rules is impossible.

Much research effort has been expended to overcome the black box problem. For instance, Kawamura et al. (2003) developed a performance evaluation system of existing bridges slabs under deterioration on the basis of expert knowledge and neural networks. Their proposed approach attempted to prevent the knowledge base from becoming a black box after the machine learning phase by performing inference in the network based on expert knowledge. However, the approach can be complicated and unpractical since it creates a large number of inference rules.

2.9 SUMMARY

The vastness of the existing bridge infrastructure has made maintaining the existing bridge infrastructure rather than designing and building new bridges the major issue for transportation agencies. The literature survey outlines the current status of research in the area of bridge management. The main components of a bridge management system are discussed and current bridge management decision making techniques are presented. Chapter 3 presents a conceptual design for the developed decision support system and explains its components.

CHAPTER 3: PROPOSED SYSTEM METHODOLOGY

3.1 INTRODUCTION

The available reports on the status of highway infrastructure demonstrate that the existing bridge infrastructure is deteriorating and requires immediate attention. Bridge managers need decision support systems to help them to manage the existing deteriorating bridge infrastructure (Mirza and Haider 2003, Vanier 2000, TAC 1999). This situation reflects the urgent need for research in the field of bridge management to develop tools which can help bridge managers and decision makers with the complex problem of bridge management.

The research here was initiated to develop a decision support methodology for bridge deck rehabilitation management. Since bridge management data can be scares and not available, the system methodology is developed based on information collected during interviews with bridge engineers and experts, some conducted at two Canadian Ministries of Transportation. In total, eleven interviews were performed with bridge engineers from both ministries and three interviews with department managers. The interviews have many objectives including: 1) collecting data and information; 2) reviewing the current practices in bridge management; and 3) investigating the features of an ideal decision support system. Information and conclusions obtained from the interviews are used through out the research. The conclusions specific to the features of a desired decision support system are summarized as follows:

- Decision support systems are warranted to improve performance of the bridge network and to reduce maintenance costs.

- The decision support system should be consistent with current practices in bridge management, which represents several years of accumulated experience and knowledge.
- An effective decision support system allows engineers to incorporate their experience and judgment in the decision making process. In addition, the tool should be interactive and allow for the refinement of results and the modification of constraints.

This chapter presents the methodology and the conceptual design of the developed decision support system. The details of the system components' development and the underlying methods shall be discussed throughout the thesis.

3.2 LIMITATION OF AVAILABLE SYSTEMS

Many of the available bridge management systems base their decision-making process on optimizing life cycle cost while enforcing relevant performance constraints. Pontis and Bridgit, among the most widely used bridge management systems in the United States, have adopted this methodology (Thompson et al. 1998, Hawk and Small 1998). For instance, Pontis utilizes dynamic programming to find the optimal long-term policy that minimizes expected life cycle costs while keeping the element out of the risk of failure (Thompson et al. 1998).

Frangopol and Liu, (2007) discussed that the optimized life cycle cost methodology creates practical difficulties, especially when the available budget is larger or lower than the computed minimum life cycle cost. If the available budget is larger than the computed minimum life cycle cost, bridge performance can be improved to a higher level than what could be achieved via the minimum life cycle cost solution. On the other hand, if the available budget is less than the computed minimum life cycle cost, an alternative solution is needed since the minimum life cycle cost solution cannot be implemented.

It is also essential to include additional subjective criteria, besides the agency's cost, in the decision making process -- such as the indirect impact of the bridge improvements on users and society. Sound decision making should take into account indirect cost components such as user delays, and the economic, social and environmental impacts associated with bridge MR&R projects.

The methodology developed in the present research is oriented to overcome the limitations of the current bridge management system by incorporating quantitative and qualitative data in the decision making process. An important aspect is of this work is to extract and incorporate experts' knowledge and judgment in a robust manner.

3.3 SYSTEM METHODOLOGY

As defined in the literature review, bridge management is the decision-making process for selecting and prioritizing the actions necessary to maintain a bridge network. This is a complex task which requires processing a large amount of data and information in order to formulate decisions and recommendations. The primary functions of a decision support system are:

- Condition Rating: This is performed by processing the inspection data collected via bridge inspection programs and transforming the collected data into a rating for the condition of the bridge. The condition rating helps the decision maker to identify bridges that require intervention and to select the appropriate action.
- Deterioration Modeling: This function forecasts the future conditions of a bridge structure. Deterioration modeling can help to identify bridges that will require intervention in the future, for planning and budgeting purposes. In addition, deterioration modeling can be used to optimize the MR&R actions to be performed on a bridge throughout its life cycle.
- Decision Making: The decision support system facilitates the decision making process by analyzing the available MR&R strategies and recommending appropriate options for the various bridge projects.

The system methodology developed here prioritizes projects for intervention and selects appropriate MR&R action for each project while incorporating quantitative and qualitative data in the decision making process. The flow chart in Figure 3.1 depicts this system methodology.

The developed methodology starts with determining the bridge condition rating. Data collected through inspection is input into the decision support system using forms designed for this purpose. The system processes the inspection data and produces condition rating for each bridge in the network. The system then uses a deterioration model to forecast the future condition of all of the bridges in the network. Chapter 4 discusses the condition rating method.

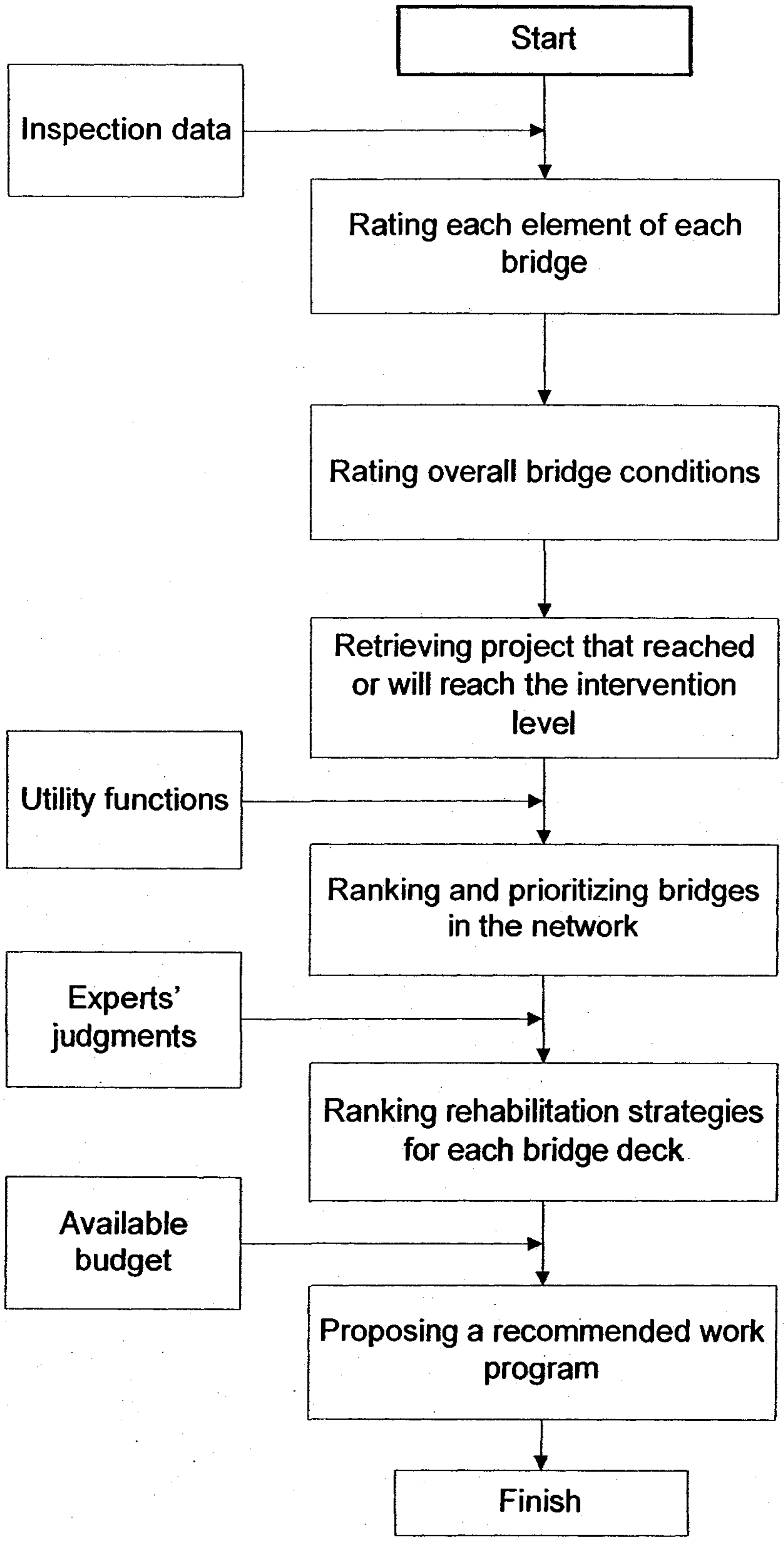


Figure 3.1 Flow Chart for the System Methodology

The various bridge projects have different priorities in terms of the urgency for intervention. These projects can be ranked to define the priority of each project, using a defined set of objectives and criteria. Chapter 5 presents a multi-objective ranking method to perform the ranking and prioritizing task for projects in a bridge network.

The rehabilitation strategies that are available to improve the condition of bridges are maintenance, repair or replacement. Selecting the appropriate rehabilitation strategy is a complex task since the decision making process is governed by multiple and conflicting criteria. Chapter 6 discusses a decision support method for the multi-criteria selection of bridge rehabilitation strategy. This support method evaluates each strategy and assigns it a weight that reflects the priority of the rehabilitation strategy. The strategy with the highest weight must be selected if the funds are available. If the available funds are not sufficient to implement the strategy with the highest weight, the second-highest weight strategy can be considered.

The available budget for transportation agencies is normally somewhat limited. Therefore, that limited budget must be allocated to the most deserving projects, in order to maximize the benefits to users and society. Chapter 7 presents a method for allocating the available limited budget to various projects. The recommended work program is developed using the outputs obtained from the condition assessment and the ranking and prioritizing methods developed in Chapters 4, 5 and 6.

3.4 SYSTEM COMPONENTS

The developed methodology can be considered as a decision support system consisting of four modules: 1) Condition Assessment; 2) Deterioration Modeling; 3) Ranking Projects; 4) Decision Module. These modules interact together and with a database which holds the bridges' attributes. The system conceptual design is presented in Figure 3.2. A prototype decision support system is presented in Chapter 7. The prototype is a proof of the presented concept and is a validation for the functionality of the decision support system. The following four sections discuss the database and the modules of the developed decision support system in more detail.

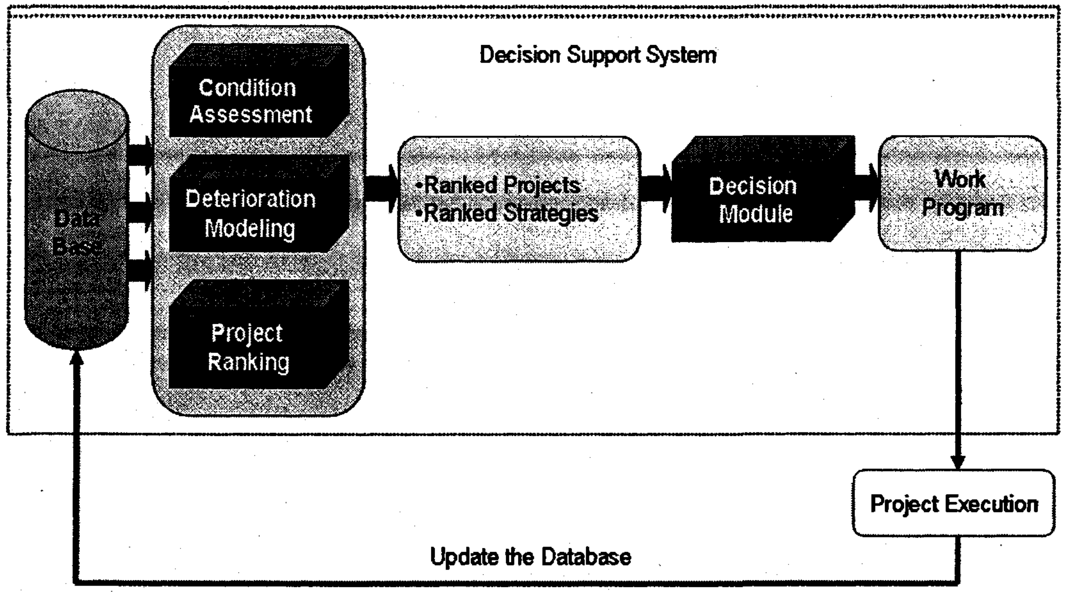


Figure 3.2 Conceptual Design of the Decision Support System

3.4.1 System Database

Bridge networks have a large amount of data and information associated with them. The data can be general to any bridge in the network or specific to individual bridge structures. The broad and dispersed bridge data provides critical information for the decision making process. Therefore, a central database capable of capturing, retrieving and updating stored data is an essential element of any bridge decision support system.

A database management system can be used to perform data processing tasks which include adding new data, deleting data or updating existing data. In addition, the management system facilitates data retrieval and reporting. The decision support system uses built-in procedures and algorithms to process the available data and information in order to transform it into quantitative measures of the available alternatives and to develop decision recommendations.

Some information requires updating, such as new inspection data as it becomes available or updating the cost data as it increases or decreases. Updating the data does not mean deleting the old data, for it is important to keep track of the history of the structures. Historical data contains important information that can be used to understand the behaviour of the bridge structure and to develop trends which can be very useful in the decision making process. El Marasy (1990) classified the information to be entered and stored in bridge databases according to its variation with time into constant data and variable information. Branco and de Brito (2004) further classified bridge information into static, semi-static and updatable information.

- Static information is comprised of reference files and forms that do not require any changes once created, such as: 1) Inspection forms and the classification system; 2) Inspection manuals; 3) Correlation matrices which relate two variables, such as relating each defect to its cause or relating each defect to the appropriate repair technique; 4) Computer programs and mathematical models; and 5) Necessary administrative data such as the bridge authority and the responsible department.
- Semi-static information includes files and forms which do not change under normal circumstances. These files include: 1) Cost and rate files such as discount and inflation rates and cost data files; 2) Cost files for individual bridges such as the initial cost and repair and the maintenance cost of projects performed on the bridge; 3) Annual budget data; and 4) Load capacity and load factors for each bridge.
- Updateable information is composed of files and forms which are continuously being changed throughout the service life of the bridge, including: 1) Inspection files to hold the collected information during the inspection; 2) Rating files that hold the ratings of the various bridges; and 3) Maintenance and repair recommendations proposed by the decision support system.

A number of data models are available. Database designers are responsible for selecting the data model which most appropriately suits the data structure. Elmasri and Navathe (2000) mentioned that the most widely used commercial database management systems use relational, network, or hierarchical data models. The relational database model is commonly used in engineering applications (Johnston 1997). In this model, the data is structured in tables. The Pontis bridge management system is designed around a relational database which stores data about the agency's physical bridge inventory and its projects, including data related to performing program simulations, various data definitions, and system parameters (AASHTO 2005a).

The database developed for the decision support system is relational, since this model is the most suitable to store bridge data. In addition, relational databases use standard query language (SQL) which facilitates transferring the database to other relational database management systems if needed.

The design of a relational database is usually represented using entity relationship (ER) diagrams. An entity is an object with a physical or conceptual existence and has a number of attributes to describe it. For example, a bridge is a physical entity which is defined with a set of attributes such as the bridge name, location and traffic volume. Each bridge has a set of values for the different attribues. The design of the database developed for the prototype decision support system is presented in Chapter 7.

3.4.2 Condition Assessment

Condition assessment is an essential step in bridge management. It provides the datum from which bridge management decisions are developed. Bridge condition data is extracted during inspection, which involves the use of techniques to assess the condition of the bridge elements and the extent of defects.

Bridge inspections are required periodically. A detailed visual inspection is normally performed every two years. The inspector estimates the quantities (area, length, or unit) of each bridge element that is in each condition state. For example, the inspector is required to estimate the total physical areas of the bridge deck that are in the Excellent, Good, Fair or Poor condition states.

Using the data collected during the detailed visual inspection, the condition assessment module conducts a condition rating for each bridge element. Each bridge element contributes differently to the overall structural integrity of the bridge. It is essential to define the structural importance of each bridge element. The condition ratings for the various elements can be combined using the structural importance factors into an overall bridge condition rating.

The condition rating for each bridge in the network is stored in the database. The condition rating for each bridge includes the elements' ratings, the elements' structural importance and the overall bridge condition rating. The decision maker can specify an intervention level and the subset of the network that requires intervention can be identified. In addition, the decision maker can retrieve bridges or elements that have a specific condition rating from the database.

3.4.3 Deterioration Modeling

The bridge element condition rating developed using the condition assessment module represents that element's current conditions. A deterioration modeling module is required in order to forecast future conditions. The inputs for the deterioration modeling module are the current condition vectors for the bridge element. Transition probability matrices that correspond to the different improvement projects are implemented within the module. After a specific number of periods, the module develops the condition vector for the element.

In addition, deterioration modeling can be used to estimate the current condition if recent inspection data is not available, using the previous inspection data as the input into the deterioration module.

The deterioration modeling module can identify elements that are expected to be in a certain condition in a given year. The decision maker can use the deterioration modeling module to retrieve elements that will reach the intervention level after a specific number of years.

The deterioration model is useful for planning and allocating budgets since the model can be used to quantify the overall improvement attained from a specific work program. This task is crucial in order to compare different recommended work programs by evaluating the network condition at a specific time in the future after implementing different recommended work programs. The work program that provides the maximum improvement to the network can then be selected for implementation.

3.4.4 Ranking Projects

The ranking module evaluates the bridge projects in the network or in a subset of the network under multiple criteria. The overall objective of the ranking exercise is to achieve efficient use of the available funds. The inputs for project ranking are the measured attributes of the bridges. Project ranking develops a weight for each bridge project which represents the degree to which the project satisfies the selection criteria. These weights are used to rank the bridge network or a subset of the bridge network.

At the project level, the ranking module evaluates the different alternative maintenance and rehabilitation strategies. The inputs for the project level ranking module are the experts' judgments regarding the relative importance between the various maintenance alternatives with respect to each criterion. The output is a weight associated with each strategy that represents the degree that the strategy satisfies the multiple criteria selected for evaluating the alternatives. This module represents the major contribution of the current research.

3.4.5 Decision Module

Normally bridge managers have a limited budget for bridge improvement projects. Developing a work program is one of the most difficult tasks for bridge managers and decision makers. The recommended work program for infrastructure management answers the following questions (Hudson et al., 1998):

1) Which project should receive action?
2) What action (MR&R) should be applied?
3) When should the work be done?

The decision module develops such a work program under the constraint of limited funds by allocating the available fund to the most deserving projects. The decision module utilizes the weights developed from the ranking module to evaluate the different combinations developed for each project and for the rehabilitation strategies, in order to develop a work program. The recommended work program specifies the bridge projects that need actions and what type of action to be performed in order to meet the multiple criteria defined by the decision maker. The cost of the various MR&R strategies is used to develop an overall cost estimate for the recommended work program in order to ensure that the total cost will not exceed the available budget. In addition, sensitivity analyses can be performed to account for the uncertainty associated with the cost estimates for the MR&R strategies and to provide the decision maker(s) with a more reliable assessment for the cost of the recommended work program. The recommended work program represents the optimum intervention strategy during the planning period, within the available funds.

CHAPTER 4: CONDITION RATING AND DETERIORATION MODELING

4.1 INTRODUCTION

As discussed in the literature review, problems associated with bridges have recently become a focus of interest globally and particularly in North America. It has become clear that highway agencies are faced with an increasing number of deficient bridges that will require intervention in the years to come. MR&R of deteriorating bridges are among the most expensive items for these agencies. Such a high cost commitment can be much easier to rationalize by deploying a systematic method to assess current conditions and forecast future conditions of existing bridges.

The current conditions are defined using a condition rating methodology. A bridge condition rating provides the datum from which bridge management decisions are developed. As a result, the accuracy of decisions developed by any bridge management system relies on the accuracy of the condition rating reflecting the actual condition of each bridge in a network. Future conditions are predicted using a deterioration model. It is essential for the condition rating and the deterioration model to be coherent in defining current and future conditions of bridge structures if the results are to be consistent and reliable.

This chapter discusses a probabilistic bridge condition rating method that is consistent with the stochastic Markov chain approach to model deterioration.

4.2 BRIDGE CONDITION ASSESSMENT

Bridge condition assessment begins with visual inspection by an experienced inspector to estimate and record the extent of defects and distress. The bridge inspection involves the use of various evaluation techniques to assess the physical condition of bridges and reveals defects such as cracking, scaling, spalling, delamination and reinforcement corrosion. Traditional NDT techniques such as hammer sounding and chain drag are performed to quantify the extent of defects observed by the visual inspection.

Data collected through inspection is used to rate the bridge condition. The purpose of the condition rating is to evaluate the serviceability and the structural strength of the existing bridges. Therefore, the condition rating must combine the physical conditions of the bridge elements and the structural conditions of these elements.

4.3 BRIDGE CONDITION ASSESSMENT PRACTICE IN CANADA

Four Canadian Ministries of Transportation were contacted and two were visited to review the current practice in bridge condition assessment and management. There are wide discrepancies between provinces at the bridge condition assessment level. Few provinces have sufficiently well-developed inspection and condition assessment methodologies, while others have not implemented a bridge condition index. The following is a discussion of the current practice of the Ministries of Transportation that responded.

The Ministry of Transportation of Ontario has developed a bridge management system. The ministry's bridge office led a task force to develop a new performance measure for bridges. The Regional Structural Sections and the Program Management Branch provided valuable input in the development of a bridge condition index. The index is a single-number assessment of the bridge condition based on the remaining economic worth. It is based on the assumption that a bridge has an initial value and as it deteriorates to a lower condition, its value decreases. The ministry is using the condition index for ranking, prioritizing and budgeting purposes.

The Alberta Department of transportation performs condition assessment on existing bridge structures to determine the optimum long-term solution for maintenance, repair or replacement. The objective is to maximize the service life of the structure at a minimum life cycle cost. The objective of this assessment is to develop a strategy that deals with the vital issues of "what, when and how much". The Department identifies bridge structures that are likely to require maintenance, repair or replacement in a short-term programming period. Structures may be identified for an assessment based on condition and functional deficiencies or by planned highway improvements. An overall bridge index is developed, combining the average of the sub-structure and the super-structure indexes. The agency uses a functional rating similar to the sufficiency rating adopted in the United States.

In Quebec, the ministry of transportation uses a rating from 1 to 9 for each bridge element. This system is similar to the one used by the national bridge inventory in the United States. The Ministry of transportation of Quebec has worked with Stantec Consulting to review its bridge asset management methodology to create or adopt a software system similar to the Ontario Bridge Management System.

Prince Edward Island's Transportation and Public Work's department have a total of 200 bridges in their inventory. Visual bridge inspection is completed every three years. Bridges are given an overall rating as a whole. This rating uses 1, 2, and 3 to indicate significant work is required, minor work is required, or no work is required, respectively.

The Nova Scotia Department of Transportation and Public Works is responsible for the management of approximately 4,000 bridges in the provincial highway system of Nova Scotia. They use a condition rating from 1 to 9 similar to the National Bridge Inventory in the United States. Nova Scotia Transportation and Public Works retained Stantec Consulting to implement a customized version of the Ontario Bridge Management System for their province.

The review of the current practices in bridge condition assessment reflects the need for a unified condition assessment and rating method. A standard or unified method is required in order to use the available data collected during the detailed condition inspection and to account for uncertainty issues associated with the detailed visual inspection process. Abu Dabous (2008) proposed a unified condition index for existing concrete bridges. The following section describes the concept of the condition index.

4.4 DEVELOPMENT OF A UNIFIED BRIDGE ELEMENT CONDITION INDEX

Roberts and Shepard (2000) discussed a new performance measure for bridges which has been developed for the California Department of Transportation (Caltrans). This measure is known as the health index (HI) and determines the remaining bridge asset value. The HI measures the structural condition of a single bridge or a network of bridges by using quantitative condition data collected as part of the bridge inspection program.

Abu Dabous et al. (2008) criticized the HI for being an overall representation of a bridge or a network condition which does not accurately reflect the conditions of specific bridge elements since the HI is an average of the conditions of the bridge elements. For instance, if the condition of the girders is poor and the other components' conditions are good, the HI will be relatively high and will not reflect the poor condition of the girders. Alternatively, they proposed an element-level condition index which represents the condition of each element precisely and they discussed a probabilistic method to account for uncertainty in bridge inspection data.

The element-level condition index is based on the remaining value of the deteriorated quantities of a bridge element. An element that is completely in excellent condition has 100% remaining value. Once the element starts deteriorating, its remaining value decreases. The remaining value of the element depends on the deteriorated quantities and the degree of distress for each quantity of the element.

In order to meet the requirement of being consistent with current bridge inspection practice, the methodology recommends using the four condition states defined in the Ontario Structure Inspection Manual (OSIM 1989). These states are Excellent, Good, Fair and Poor. The OSIM provides a general philosophy to identify these four condition states for any element or material type. The general description of the four condition states is presented in Table 4.1.

Table 4.1 Condition States General Description (OSIM 1989)

Condition State	Description	Examples
Excellent	Part of an element that is in 'as constructed' condition	-"Bug holes" in concrete barrier walls
Good	Part of an element where the first sign of minor defects are visible	-Light corrosion -Light scaling -Narrow cracks in concrete
Fair	Part of an element where medium defects are visible	-Medium corrosion (up to 10% section loss)
Poor	Part of an element where severe defects are visible	-Severe corrosion (greater than 10% section loss) -Spalling, delamination

At the time of inspection, quantities within a bridge element may be in any one of these different condition states. The inspector estimates and records the quantities (area, length, or unit) of the bridge elements in each condition state. Based on discussions with bridge engineers, this research develops percentages that represent the remaining value of the bridge elements in each condition state.

The remaining value of element's quantities that are in Excellent, Good, Fair and Poor condition state are 90%, 70%, 45%, or 15%, respectively.

At any given time, certain quantities within each bridge element may be in any of these different condition states. The inspector estimates and records these quantities (area, length, or unit) for each of the bridge elements. For example, if inspection of the deck reveals that 50% of the surface area is in Good condition and 50% is in Poor condition, then 50% of the deck has 70% remaining value and 50% of the deck has 40% remaining value.

Using the principle of remaining values, a bridge element condition index (BECI) is developed. The BECI is a number from 0 to 100 where 100 signifies the best possible condition with no deterioration, and descending values represent increased degree of deterioration. The BECI is calculated by taking the ratio of the current or deteriorated bridge element value to the initial value as follows:

$$\text{BECI} = (\text{current element value}/\text{initial element value}) \times 100 \qquad (4.1)$$

where the current element value is the total sum of the quantities in each state multiplied by the remaining value of the element in that state. The initial element value is the value of the element at brand new condition and equals the total quantity of the element multiplied by 100%.

The bridge element condition index is an average of the weights and the quantities that are in the different condition states. Using the average may not reflect the poor condition of specific portions of the bridge element. However, this index is an improvement over the HI which may not reflect the poor condition of the whole element.

The BECI is estimated for each bridge element independently. An example follows which demonstrates the BECI concept. The data used in this example is extracted from a bridge inspection report provided by the Ministry of Transportation of Ontario. A bridge inspection team inspected 800 m^2 of bridge deck (total area) and reported their results, shown in Table 4.2.

Table 4.2 Bridge Deck Condition Inspection Results

Condition state	Deck area (m^2)
Excellent	310
Good	120
Fair	210
Poor	160

Current deck value = $(310 \times 0.9) + (120 \times 0.70) + (210 \times 0.45) + (160 \times 0.15) =$ 481.50

The bridge deck condition index can be estimated as the current value divided by the initial value of the bridge deck as given in Equation 4.1.

$BECI_{DECK} = (481.50 / 800) \times 100 = 60.20$

The proposed BECI and the HI use deterministic values as an approximation for the element value at each of the four condition states. However, this approximation may not be accurate since data collected through inspection procedures is normally associated with subjectivity and uncertainty.

Modeling uncertainty is usually done via the fuzzy set theory, which captures the subjectivity of human behaviour, or by using the probability theory, that represents the stochastic nature of decision analysis. In order to effectively deal with the uncertainties and imprecision associated with the bridge inspection process, these two approaches are analyzed in order to decide which is most appropriate.

4.5 FUZZY LOGIC APPLICATION FOR MODELING UNCERTAINTY

As discussed in the literature review, fuzzy logic was introduced by Zadeh (1965) to model the uncertainty of natural language. This logic was proposed as a means to handle the definition of partial truth which is the true value between completely true and completely false. The concept of a fuzzy set is an extension of the conventional set theory. A fuzzy set, R, is defined as a set of pairs (t, $\mu R(t)$), where t is an object or an element in the universe of discourse, and $\mu R(t)$ is the degree of membership associated with the element t. If t is a continuous variable, the degree of membership can be defined using a membership function. Tee et al. (1988) proposed a fuzzy mathematical approach to account for subjectivity, imprecision and personal bias associated with bridge inspection and the condition rating process. They presented algorithms for fuzzy weighted average (FWA) computation. Since then, many of the proposed methodologies to perform bridge condition rating have adopted approaches similar to FWA (Sasmal et al. 2006, Yadav and Barai 2004).

A weighted average technique is normally used to combine pieces of information with unequal weights. The FWA extends the traditional weighted average technique by applying it to fuzzy quantities. The FWA is given by the following equation:

$$FWA = \frac{\sum_{i}^{n} W_i R_i}{\sum_{i}^{n} W_i} \qquad (4.2)$$

where W_i denotes the fuzzy importance factor of the ith element and R_i denotes the fuzzy condition ratting of the same element. Fuzzy addition, fuzzy multiplication, and fuzzy division operations proposed by the extension principle (Zadeh 1965) are used to perform the mathematical operations and the resultant average is the FWA. The FWA computation algorithm for bridge condition consists of the following steps:

1) Develop the membership functions for both the element condition rating and the structural importance of the various elements. The membership function for the element condition rating is a mathematical representation of the natural language rating expressions used by inspectors such as Good, Fair or Poor.

2) Translate the inspector rating variables and the structural importance of the various bridge elements to fuzzy sets by using the membership functions developed in Step 1.

3) Combine the fuzzy condition ratings and their structural importance using Equation 4.2 to obtain a fuzzy set representing the entire system.

4) Map the resultant fuzzy set obtained in the previous step to one of the natural language rating expressions. The overall natural language bridge rating is the variable that has the shortest distance from the resultant fuzzy set.

The initial effort of this research targeted the use of the FWA approach to develop a bridge condition rating. However, while analyzing the approach, a number of practical difficulties have been encountered. These difficulties can affect the robustness and reliability of any condition assessment methodology that uses the FWA approach.

The major drawback of using the FWA approach is that the resultant fuzzy set might not be convex. The convexity indicates that the membership function has only one distinct peak. Enforcing convexity facilitates the task of finding a natural language expression to describe a computed fuzzy set. Therefore, an adjustment must be made to the resultant fuzzy set to achieve the desired convexity by replacing multiple peaks with a single peak. Another adjustment that is often made to the resultant fuzzy set is normalization. Normalization ensures that at least one element in the set has a degree of membership equal to one.

There is no apparent mathematical rationale supporting the use of convexity and normalization operations on the fuzzy set (Tee et al. 1988). However, empirical tests have shown that enforcing convexity and normalization produced more reliable and accurate final translated results (Mullarky and Fenves 1985). No standard guidelines or procedures are available to enforce the use of these two constraints and employing the process(es) is optional. The resultant membership function must be inspected to perform the necessary adjustments to enforce convexity and normality, which may not be practical in developing a condition rating process for a large network of bridges.

One more problem associated with the FWA technique is the final mapping between the resultant fuzzy set and the rating variables. The shortest-distance approach is normally used to map the resultant fuzzy set of the entire system back to a rating variable. The rating variable with a membership function that has the shortest distance from the resultant fuzzy set is the one used for the overall bridge condition rating. This approach does not take into account how much shorter the distance is between one rating variable and another. In certain cases, the distance can be the same between the fuzzy set and the membership function of two rating variables or the distances are very similar. It is not clear in such cases as to which rating variable will be used in order to rate the bridge condition.

Alternatively, probabilistic analysis using the Monte Carlo simulation technique would contribute to avoiding these issues. The following section discusses applying probabilistic analysis to develop bridge element condition rating.

4.6 BRIDGE ELEMENT CONDITION RATING USING SIMULATION

An effective way to deal with uncertainties is through simulation, which can provide more accurate estimates using a large number of "what if" scenarios. The Monte Carlo simulation is a stochastic technique that randomly generates values for uncertain variables, over and over, to simulate a model. This technique can be used to evaluate the BECI by using random numbers for the element's remaining value in each condition state. A range is defined to represent the remaining element value in each condition state and a probability distribution can be assigned for each range to represent the variable frequency. For each iteration, the simulation selects random values from the defined ranges and calculates the BECI. After running several iterations, the simulation will develop a distribution for the estimated values of the BECI.

To facilitate the representation of the stochastic deterioration process, a bridge element is assumed to gradually depart from one condition state to the next lower one. For instance, a bridge deck deteriorates gradually from a Good to a Fair condition state and then from Fair to Poor. Linear membership functions are developed as an approximate representation of the element deterioration process, shown in Figure 4.1.

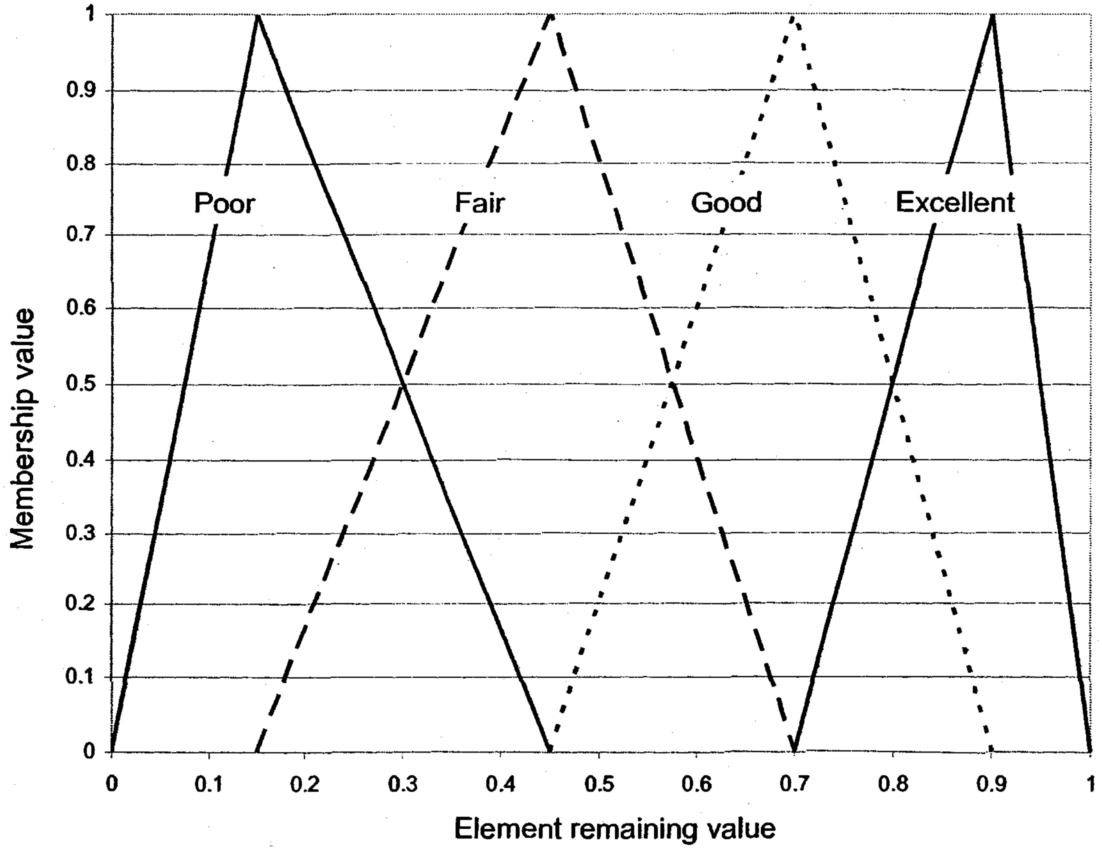


Figure 4.1 Membership Functions for the Remaining Value of a Bridge Element

The purpose of these membership functions is to relate the four linguistic variables with the remaining value of the bridge element. During the transition from one condition state to the lower one, the membership value associated with the first condition state decreases and the membership with the lower condition increases. This departure from one condition state to the lower one is associated with a decrease in the remaining value of the bridge element. For example, if a portion of the deck is in Good condition, the remaining value of that portion is 70% and once that portion starts deteriorating, the membership value with Good will decrease and the membership value with Fair will increase. This gradual departure from Good to Fair is associated with a decrease in the remaining value of the element from 70% to 45%.

Abu Dabous et al. (2008) used the α-cut concept to define ranges of the remaining values for each condition state. The α-cut is the crisp set of all elements that belong to the membership function at least to the degree of α where $\alpha \in [0,1]$. The α-cut of a membership function A is defined as:

$$A_\alpha = \left(x \text{ ¸ } X \mid \mu(x) \text{¡Ý} \alpha \right) \qquad (4.3)$$

The bridge element is deemed to be in a condition state as long as the membership value with that condition state is higher than 50%. Applying an α-cut equal to 50% on the membership functions in Figure 4.1 can define the crisp set associated with each condition state. The lower and upper value of each set represents the pessimistic and optimistic remaining values for each condition state as shown in Table 4.3. Triangular probability distributions are used to define the distribution of each variable within each interval.

Kawamura et al. (2003) identified ranges of a condition index to represent the following four linguistic condition states: “severe deterioration”, “moderate deterioration", "mild deterioration", and "safe". Following a similar approach and benefiting from the remaining values for each condition state in Table 4.3, ranges for the BECI which represent the Poor, Fair, Good and Excellent condition states are defined in Table 4.4.

Table 4.3 Remaining Value of the Bridge Element

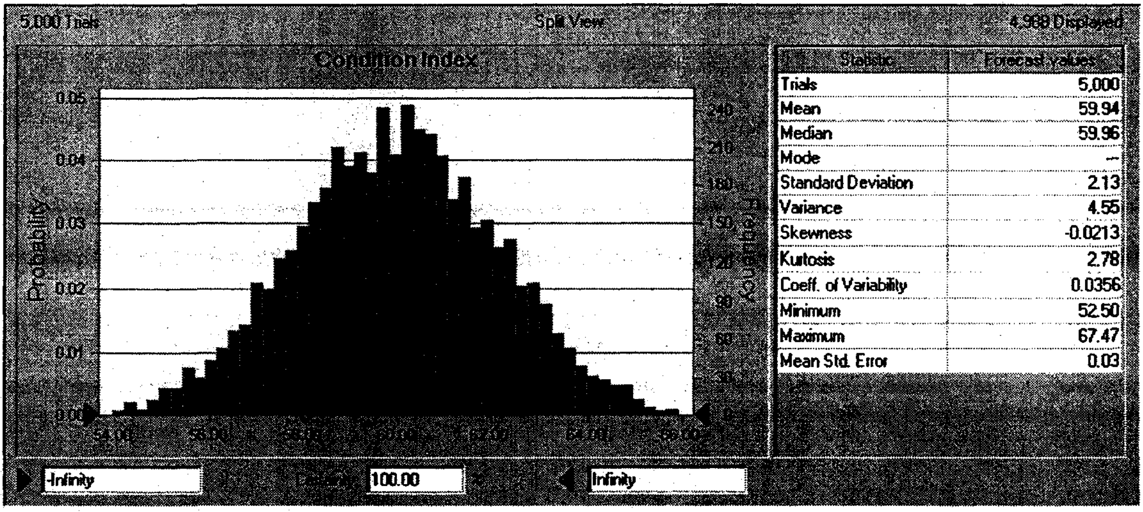
Condition State	Pessimistic	Most likely	Optimistic
Excellent	0.81	0.90	0.95
Good	0.576	0.70	0.80
Fair	0.31	0.45	0.575
Poor	0.075	0.15	0.30

Table 4.4 Values of the Condition Index for the Four Condition States

Condition State	Condition Index
Excellent	81–100
Good	57.60–80.90
Fair	31–57.50
Poor	0-30

Crystal Ball software developed by ORACLE is used to perform Monte Carlo simulation and to identify the probability associated with each condition state. Each simulation uses a random value for each condition state, determined from the ranges of values defined in Table 4.3, to evaluate the BECI. The frequencies of having the BECI in the range of Excellent, Good, Fair and Poor condition states are estimated. For example, if the simulation runs for 1000 iterations and for 700 iterations the BECI is estimated to be between 57.6 and 80, then the probability that the element is in a Good condition state is 70%.

The previous example presented to demonstrate the bridge element condition index calculations is analyzed again using the Monte Carlo simulation. The data is taken from Table 4.2. Five thousand iterations are performed to evaluate the probability associated with each condition state. The result of the simulation is shown in Figure 4.2. The BECI for the deck ranges from 52.50 to 67.47 with a mean value of 59.94.



Statistic	Forecast values
Trials	5,000
Mean	59.94
Median	59.96
Mode	---
Standard Deviation	2.13
Variance	4.55
Skewness	-0.0213
Kurtosis	2.78
Coeff. of Variability	0.0356
Minimum	52.50
Maximum	67.47
Mean Std. Error	0.03

Figure 4.2 Simulation Result for the BECI of the deck

The probability of the bridge deck to be in a Good condition state with BECI values between 57.60 and 80.90 is 85.88% and the probability of the bridge deck to be in a Fair condition state with a BECI values between 31 and 57.50 is 14.12%, as shown in Figure 4.3. The final condition vector which contains the probability of the bridge deck to be in Excellent, Good, Fair or Poor condition, respectively, is: [0 85.88% 14.12% 0].

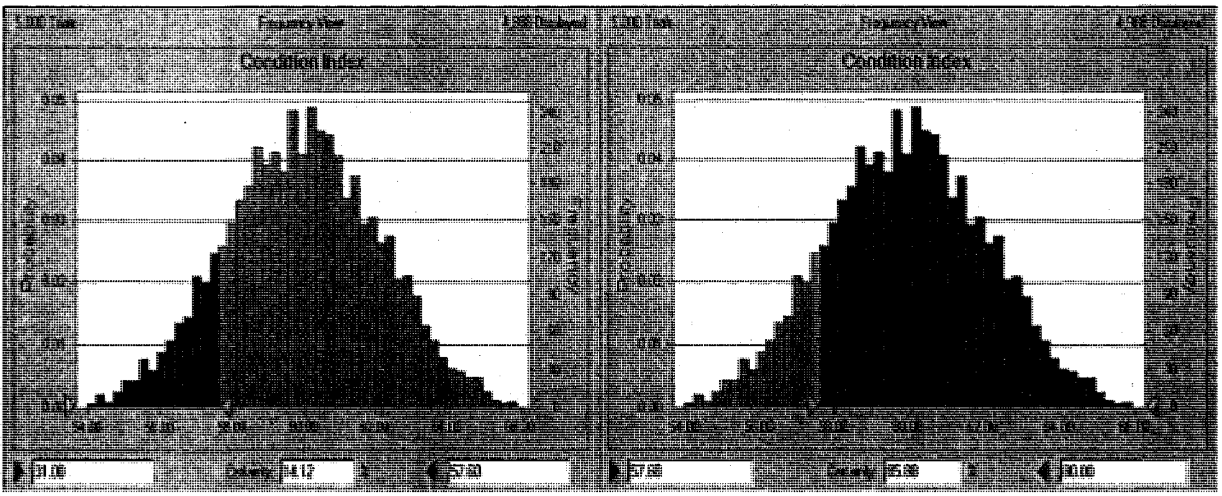


Figure 4.3 Probability of BECI to be in Good and Fair Condition States

Table 4.5 summarizes the results of a bridge inspection extracted from a bridge inspection report. The report was provided by the Ministry of Transportation of Ontario.

Table 4.5 Bridge Element Inspection Results

Element	Quantity (m^2)	Excellent (m^2)	Good (m^2)	Fair (m^2)	Poor (m^2)
Deck	800	310	120	210	160
Beams	600			300	300
Abutments	100		50	50	
Piers	100		90	70	
Barrier	200		120	80	

Following the methodology presented above, the condition vector for the different bridge elements can be developed. The condition vectors for the bridge elements are presented in Table 4.6.

Table 4.6 Bridge Element Condition Vectors

Element	Condition Vector [Excellent Good Fair Poor]
Deck	[0% 86% 14% 0%]
Beams	[0% 0% 53% 47%]
Abutments	[0% 41% 59% 0%]
Piers	[0% 58% 42% 0%]
Barrier	[0% 68% 32% 0%]

4.7 OVERALL BRIDGE CONDITION RATING

The condition ratings for the various bridge elements must be combined to form an overall bridge condition rating. The combined rating is the Bridge Condition Index (BCI), which represents the overall material and structural condition of the bridge.

The developed condition vectors quantify the material condition for the different bridge elements. However, the material condition rating does not influence the element's structural condition rating in a similar degree. In addition, the cause of the defect can have various implications. For example, cracks in concrete are normally rated based on their characteristics, such as the width of the crack. If two different concrete girders have cracks with the same width, both defects are rated using the same linguistic variable such as 'minor'. However, one crack can be a flexural crack flagging an initial structural failure while the other may be due to creep and shrinkage of concrete, which has limited structural importance.

In conclusion, the determination of structural importance for various bridge elements is a difficult task. A complete non-destructive testing program associated with structural analysis can evaluate the structural reliability of a damaged element. However, the detailed non-destructive testing program is expensive to perform and visual inspection results are normally available. In this case, it is essential to benefit from bridge experts' knowledge and bridge inspectors' experience to evaluate the structural importance of the different bridge elements.

Tee et al. (1988) employed a statistical approach to investigate the structural importance of various bridge elements. The approach involved conducting an opinion survey to extract and organize experts' knowledge and experience. A total of 46 inspectors and bridge engineers in Indiana and its neighbouring states responded to the survey. The results were used to construct membership functions for the structural importance of bridge elements at different condition states. Others have utilized the results of this survey to develop bridge condition rating methodologies (Melhem and Autraliya 1996, Sasmal et al. 2006).

The survey results quantified the structural importance of the different bridge elements at different condition ratings. The results of the survey were generalized for any bridge, assuming that the structural importance corresponding to the different ratings is not bridge specific. However, the stochastic behaviour of deteriorated bridge elements makes this generalization inaccurate in several cases.

Alternatively, bridge experts and bridge inspectors can use their experience and knowledge to analyze and evaluate the defect's type and the causes in order to develop structural importance values specific to the bridge under consideration. To accomplish this, a systematic and consistent methodology is required where the Analytic Hierarchy Process (AHP) is used. The developed methodology is presented in the following section.

4.7.1 Structural Importance Factors for Bridge Elements

There is no precise definition of the structural importance of the different bridge elements in the literature. Tee et al. (1988) referred to the structural importance as the structural role of the element. The research here defines the structural importance of a bridge element as the degree the element contributes to the overall structural integrity and safety of the bridge.

The Analytic Hierarchy Process (AHP) is used to extract the bridge inspector's and expert's judgment and to evaluate the structural importance of the different bridge elements. Two fundamental steps are required: The first step is the task of simplifying the problem where the complex system is broken into a hierarchy structure, and the second step is the task of performing pairwise comparisons to measure the relative impact of different elements in the hierarchy and to establish relations within the structure. A fundamental scale of absolute values representing the strength of judgments has been developed and validated (Saaty 1980). In this approach the decision maker expresses his/her opinion about the value of one single pairwise comparison at a time. Usually, the decision maker has to choose an answer among discrete choices. Table 4.7 presents the scale of relative importance.

Table 4.7 Scale of Relative Importance

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favour one activity over another
7	Demonstrated importance	An activity is strongly favoured and its dominance demonstrated in practice
9	Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

For the purpose of evaluating the structural importance of bridge elements, a two-level hierarchy structure is developed, as presented in Figure 4.4. The bridge inspector and the expert are required to compare two elements with respect to the overall bridge structural criticality and to specify the intensity of the relative importance. If one element jeopardizes the bridge safety and integrity while another has a limited effect on safety and integrity, then the first element has absolute importance over the second. The bridge elements are compared in pairs and the intensities of the relative importance are specified.

Defects and the extent of distress of the various elements determine their structural importance. The detailed visual inspection should capture these defects and evaluate the extent of distress of the various elements. The effect of these defects and distress extents on the structural performance of the elements should be analyzed and included in the judgment.

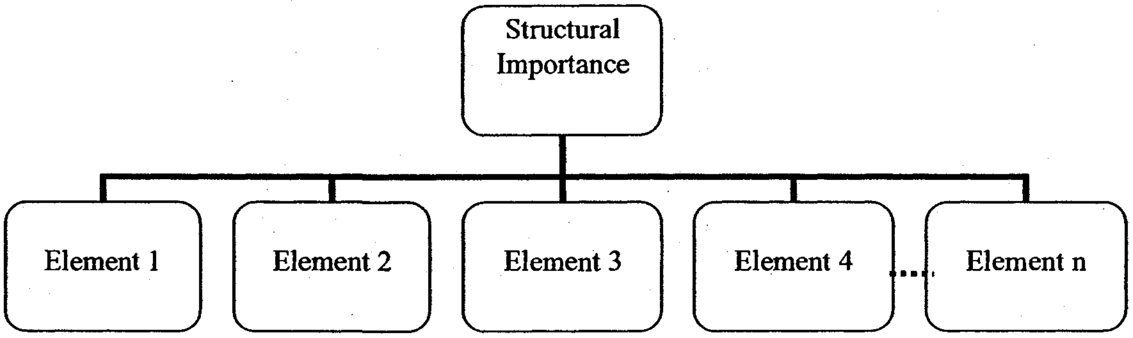


Figure 4.4 Hierarchical Structure for the Elements' Structural Importance

The results of the pairwise comparison are laid out in a reciprocal comparison matrix as shown in Table 4.8. In this matrix, a_{ij} is the relative structural importance of element i with respect to j. The matrix is reciprocal once it satisfies the following two conditions: $a_{ij} = 1/a_{ji}$ and $a_{ii} = 1$ for all i and j.

The structural importance of the various elements is developed as a vector of priorities which is a normalized eigenvector and estimated in two steps. First is to normalize the comparison matrix by computing the sum of each column, and then dividing each element in each column by the sum of that column. Second is to compute the average of each row which represents the priority weight of the corresponding element. The first row corresponds to the first element and the second row corresponds to the second element and so on. The structural importance factors are presented in Table 4.8 as S_1 to S_n.

Table 4.8 Pairwise Comparison for Elements Structural Importance

	Element 1	Element 2	Element 3	Element 4	… …	Element n	Structural Importance
Element 1	1	a_{12}	a_{13}	a_{14}	… …	a_{1n}	S_1
Element 2	a_{21}	1	a_{23}	a_{24}	… …	a_{2n}	S_2
Element 3	a_{31}	a_{32}	1	a_{34}	… …	a_{3n}	S_3
Element 4	a_{41}	a_{42}	a_{43}	1	… …	a_{4n}	S_4
:	:	:	:	:	:	:	:
Element n	a_{n1}	a_{n2}	a_{n3}	a_{n4}	…	1	S_n

An important feature of the AHP methodology is the ability to check for consistency. The process does allow inconsistency in the pairwise comparisons to a certain extent. If all the comparisons are perfectly consistent, then $a_{ij} = a_{ik} \times a_{kj}$ should always be true for any combination of comparisons taken from the comparison matrix. A consistency index (CI) can be determined for this purpose where a small value of the CI represents a small deviation from consistency, which reflects an acceptably consistent judgment.

$$CI = \frac{\lambda_{max} - N}{N - 1} \tag{4.4}$$

where λ_{max} is an approximation of the maximum eigenvalue and N is the number of elements compared in the reciprocal matrix. A simple way to obtain λ_{max} is by adding the elements in each column in the comparison matrix and multiplying the resulting vector by the priorities vector (i.e. the approximated eigenvector) obtained earlier.

In AHP, the pairwise comparisons are considered to be adequately consistent if the corresponding consistency ratio (CR) is less than 10% (Saaty, 1980). CR is calculated as CI/RI where RI is a random consistency index derived from a large sample of randomly generated reciprocal matrices. Table 4.9 presents the values of the RI for different matrix sizes. A consistency ratio less than 10% reflects an informed judgment that could be attributed to expert knowledge about the problem under study. If this limit is not achieved, the expert is required to revise the pairwise comparisons to improve consistency.

Table 4.9 Random Indexes (RI) for the Various Matrix Sizes (Saaty, 2001)

Number of elements	RI
3	0.52
4	0.89
5	1.11
6	1.25
7	1.35
8	1.40
9	1.45
10	1.49
11	1.51
12	1.54
13	1.56
14	1.57
15	1.58

The previous bridge example used to develop the element condition rating is further analyzed here to develop the structural importance factors. To perform this task, a bridge expert was required to perform pairwise comparisons between the different elements. The expert compared the bridge elements in pairs with respect to the degree that these elements affect the structural integrity and safety of the bridge. The intensities of the relative importance between the different bridge elements and the expert judgment are listed in Table 4.10. The structural importance weights of the elements are developed using the eigenvector approach. These weights represent the structural importance for the elements of the bridge under consideration.

Table 4.10 Pairwise Comparison of Elements Structural Importance

	Deck	Beams	Abutments	Piers	Barrier	Structural Importance
Deck	1	1/7	1	3	2	0.127
Beams	7	1	7	9	7	0.630
Abutments	1	1/7	1	3	1	0.110
Piers	1/3	1/9	1/3	1	1	0.056
Barrier	1/2	1/7	1	1	1	0.076

The check for consistency can now be performed. The $\lambda_{max} = 5.22$, $CI = 0.06$ and $CR = 0.051$. Since the CR is less than 10%, the judgments used to develop the matrix of relative importance were consistent. It is therefore clear that the deteriorated beams have the highest structural importance value and can be a critical component for the structural integrity and safety of the bridge.

The various elements' condition ratings and structural importance must be aggregated into one value representing the overall bridge condition index, as the next section presents, using a model.

4.7.2 Overall Bridge Condition Rating

To obtain an overall bridge condition rating, the condition rating and the structural importance of the various bridge elements must be combined. Clemen and Winkler (1999) discussed the combination of probability distributions in risk analysis, where they reported that early work on the mathematical aggregation of probabilities focused on axiom-based aggregation formulas. An appealing approach to the aggregation of probability distributions is the linear opinion pool, which can be given as:

$$E(\theta) = \sum_{i=1}^{n} E_i(\theta)\, W_i \qquad (4.5)$$

where n is the number of experts, $E_i(\theta)$ represents expert i's probability distribution for unknown θ, $E(\theta)$ represents the combined probability distribution, and W_i are non-negative and sum to one.

This linear combination of the probabilities is easily understood and calculated. Further, this approach is the only combination scheme that satisfies the marginalization property, which states that the combined probability is the same whether one combines marginal distributions or joint distributions (Clemen and

Winkler 1999). For example, if θ is a vector of uncertain quantities, the decision maker can evaluate one element of the vector θ_i.

Adopting this approach, an overall Bridge Condition Index (BCI) can be estimated by combining the condition vectors of the various bridge elements and the structural importance values. The BCI can be given using the following equation:

$$BCI = \sum_{i=1}^{n} BECI_i \times S_i \tag{4.6}$$

where BCI is the bridge condition index, $BECI_i$ is the condition index of element i, S_i is the structural importance of the same element, and n is the number of bridge elements. The structural importance of the various elements is obtained as presented in the previous section. Equation 4.6 requires that: $S_1 + S_2 + \ldots + S_n = 1$. This condition is satisfied since the eigenvector approach develops weights with a total sum equal to 1.

The condition vectors of the various elements in Table 4.6 and the structural importance factors in Table 4.10 are aggregated using this approach, as follows:

$$\begin{aligned} BCI &= [0\%\ \ 86\%\ \ 14\%\ \ 0\%] \times 0.127 + [0\%\ \ 0\%\ \ 53\%\ \ 47\%] \times 0.630 + \\ &\quad [0\%\ \ 41\%\ \ 59\%\ \ 0\%] \times 0.110 + [0\%\ \ 58\%\ \ 42\%\ \ 0\%] \times 0.056 + \\ &\quad [0\%\ \ 68\%\ \ 32\%\ \ 0\%] \times 0.076 \\ &= [0\%\ \ 10.92\%\ \ 1.78\%\ \ 0\%] + [0\%\ \ 0\%\ \ 33.39\%\ \ 29.61\%] + \\ &\quad [0\%\ \ 4.51\%\ \ 6.49\%\ \ 0\%] + [0\%\ \ 3.25\%\ \ 2.35\%\ \ 0\%] + \\ &\quad [0\%\ \ 5.17\%\ \ 2.43\%\ \ 0\%] \\ &= [0\%\ \ 24\%\ \ 46\%\ \ 30\%] \end{aligned}$$

This vector represents the overall bridge condition rating. The values in this condition vector represent the probability of the bridge to be in an Excellent, Good, Fair or Poor condition state, respectively. The overall condition rating of the bridge has a 46% chance to be in Fair condition and a 30% chance to be in Poor condition.

4.8 DETERIORATION MODELING

Most bridge management systems, such as Pontis (Golabi and Shepard 1997), BRIDGIT (Hawk and Small 1998) and the Ontario Bridge Management System (Thompson et al. 1999), have adopted Markov chain models as a stochastic approach for predicting the performance of bridge components and networks.

A Markov chain is based on two assumptions, the first is that the future condition depends on the present condition and not on the past conditions. This property in Markov models is known in the literature as the state dependence assumption. Secondly, the condition of an element can be described in terms of discrete condition states. These are finite and countable states forming what is called Markov chains. The term transition refers to a condition change from state i in one period to state j in the next period. The probability P_{ij} represents the chance that this transition will take place and is termed the transition probability. The transition probabilities between the different condition states are assembled in one matrix called the transition probability matrix (P). The dimension of this matrix is (n x n), where n is number of possible condition states.

If the initial condition vector P(0) that describes the present condition of a bridge component is known, the future condition vector P(t) at any number of transition periods t can be predicted. Condition predictions for any future year can be made simply by multiplying the initial condition vector by the transition probability matrix (Jiang and Sinha 1990, Jiang et al. 1988).

$$P(t)= P(0) \times P^t \qquad (4.7)$$

The initial condition vector is based on the condition assessment and represents the probability of the bridge element to be in each condition state.

4.8.1 Transition Probability Matrix

Transition probabilities are obtained from accumulated condition data. If condition data is not available, transition probabilities can be obtained using experts' judgment. The transition probabilities can then be updated using bridge condition data as it becomes available.

Two methods are commonly used to generate transition probability matrices from the available condition data. These methods are regression-based optimization and the percentage prediction method. Regression-based optimization estimates transition probabilities by minimizing the sum of absolute differences between the regression curve that best fits the condition data and the conditions predicted using the Markov chain model. The percentage prediction method proposed by (Jiang et al. 1988) is a more commonly used technique. In this method the probability P_{ij} is estimated using the following equation:

$$P_{ij} = e_{ij} / e_i \qquad (4.8)$$

where e_{ij} is the number of transitions from state i to state j within a given time period, and e_i is the total number of elements in state i before the transition.

A transition probability matrix can be developed for each bridge element. The element condition vector developed in the previous section can then be multiplied by the transition probability matrix to forecast an elements condition after one transition period.

The Ministry of Transportation of Ontario provided condition data for twenty bridge projects managed by the ministry. The data is specific for the bridges' decks and includes the condition assessment of each deck based on detailed visual inspection performed every two years.

By analyzing the condition data for the different bridge decks, the transition probability matrices are developed using the percentage prediction method. In addition, experts' judgment is requested to supplement missing or unavailable data and to validate the developed matrices. Figure 4.5 presents the developed matrices which correspond to four groups of MR&R actions available to improve the bridge deck condition. These MR&R actions are: 1) routine maintenance; 2) minor repair; 3) major repair; and 4) replacement.

These matrices are implemented in the developed bridge deck decision support system as an initial representation of the transition probabilities for the bridge deck associated with performing any of the four MR&R actions. The transition probabilities can then be updated using the condition data input into the system as it becomes available.

$$\begin{pmatrix} 0.72 & 0.28 & 0 & 0 \\ 0 & 0.79 & 0.21 & 0 \\ 0 & 0 & 0.84 & 0.16 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Do Nothing

$$\begin{pmatrix} 0.87 & 0.13 & 0 & 0 \\ 0 & 0.86 & 0.14 & 0 \\ 0 & 0 & 0.85 & 0.15 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Maintenance

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0.83 & 0.17 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}$$

Major Repair

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix}$$

Replacement

Figure 4.5 Transition Probabilities for the Different MR&R Actions

Since the condition data was collected every two years, the transition period in these matrices is two years. As a result, each matrix contains the probabilities of the bridge deck to stay in the same condition, to degrade to the lower condition or to upgrade to the higher condition state after one transition period while the corresponding action to the matrix is implemented during this period.

The current condition vector for the bridge deck provided in Table 4.6 is:

[0% 86% 14% 0%]

Multiplying this vector by the transition probability matrix for maintenance forecasts the condition vector for the deck after one transition period under routine maintenance as follows:

[0% 74% 24% 2%]

and after two periods:

[0% 63% 31% 6%]

Once the transition probability matrices for the various bridge elements are developed, the elements' current condition vectors in Table 4.6 can be used to forecast their future conditions by multiplying each element condition vector by the transition matrix for that particular element. The future condition vectors developed for the various elements can be aggregated using Equation 4.6 to develop a forecast for the overall bridge condition rating.

4.9 SUMMARY

A review of the current practice for bridge condition assessment followed by a number of Ministries of Transportation in Canada provided the impetus for this research. The fuzzy logic approach to rate bridge conditions was evaluated and its practical difficulties were discussed. Alternatively, a probabilistic methodology to perform bridge condition rating was developed. An element-level bridge condition index based on the remaining value of the deteriorating quantities was also developed. The Monte Carlo simulation technique was used to evaluate the probability of a bridge deck to be in one of the four condition states: namely, Excellent, Good, Fair or Poor. The Analytic Hierarchy Process (AHP) was adopted to evaluate the structural importance of the bridge elements. A technique to aggregate the condition ratings and the structural importance of the bridge elements into an overall bridge condition rating was proposed. Once the methodology is implemented, it enables the decision maker to retrieve those bridges or elements that require intervention from a bridge network. Once bridges which reached or will reach the intervention level during the planning horizon are identified, these projects can be ranked and prioritized. Chapter 5 discusses a ranking method for bridge projects.

CHAPTER 5: A RANKING METHOD FOR BRIDGE PROJECTS

5.1 INTRODUCTION

Chapter 4 discussed condition rating and deterioration modeling methods for existing concrete bridges. These methods identify bridges which have reached or will reach the intervention level, based on their material and structural conditions. It is impossible to perform actions on all of these bridges immediately due to limitations of the available resources. Therefore, the bridges must be ranked and certain bridges need to be prioritized for action while others must be delayed till next year or the year after. The issues that need to be addressed at this stage are: which of these bridges require attention most urgently, and what technique can be used to prioritize bridges in terms of their need for repairs or actions.

This chapter discusses the ranking and prioritizing procedures that are currently used and presents an enhanced method to perform the ranking and prioritizing tasks. The developed method is based on the Multi-Attribute Utility Theory (MAUT), to include multiple and conflicting criteria and to incorporate qualitative and quantitative measurements in the ranking process. In addition, this method provides the decision maker with the necessary flexibility to calibrate the decision criteria according to the agency's policy and objectives. Finally, the developed method is applied to a case study to demonstrate and validate its practicality and applicability.

5.2 RANKING AND PRIORITIZING

Bridge networks are major capital assets which require continuing investment in order to maintain the bridges within acceptable limits of safety and serviceability. If an unlimited budget is available, all the maintenance and rehabilitation needs are addressed as they arise and the bridge infrastructure can be maintained in an excellent condition. However, as discussed in the literature review, municipalities and transportation agencies must cope with limited funds. Therefore, priorities have to be set for the distribution of available funds among the different projects in a network. Normally, priorities are defined based on ranking all of the available bridge projects in a network. The ranking is done according to an overall score developed using a pre-defined set of criteria identified by the decision maker.

Ranking and prioritizing projects provide the insight needed for the decision making process. Ranking and prioritizing procedures have been widely used by several departments of transportation to evaluate and select bridge projects. Capital budgeting decisions at the network level are commonly based on ranking procedures (Kulkarni et al. 2004).

Bridge management systems are required to produce the ranking of various projects in a network. Pontis, the most widely used bridge management system in the United States, provides this functionality and can rank projects according to a benefit-to-cost ratio, the average health index or the sufficiency rating for each project (AASHTO 2005b). The following is a discussion of these procedures, including an overview of their major drawbacks.

5.2.1 Benefit-to-Cost Ratio Analysis

The benefit-to-cost ratio analysis evaluates all of the benefits and costs associated with a project, including both direct agency cost and indirect user cost using the same unit -- the dollar. Priority is given to projects that provide more benefits and incur less cost.

The direct agency cost can be estimated from the available cost data. On the other hand, the indirect user costs or benefits are difficult to quantify and are usually estimated using certain parameters or simplifying assumptions. The length of detour that users must take as an alternative route during the bridge improvement project can reflect the user cost and the reduction in accidents can represent the user benefit.

Kulkarni et al. 2004 reported that concerns arise when the benefit concept is applied to evaluate a large number of diverse projects at many different locations, as opposed to a small number of projects. These concerns include fairness in selecting projects, since the approach may select a project with a lower need ahead of another project with a higher need because of the lower cost for the first project. Also, an excessive amount of effort is needed to apply the concept to a large number of projects.

5.2.2 Health Index

As discussed in Chapter 4, the HI is a performance measure for bridges which has been developed for the California Department of Transportation (Roberts and Shepard 2000). The HI measures the structural condition of a single bridge or a network of bridges by using quantitative condition data collected as a part of the bridge inspection program. This index determines the remaining bridge asset value and is based on the assumption that the asset value decreases as the element deteriorates over time. The equations to compute the HI are as follows:

$$HI = (\Sigma CEV / \Sigma TEV) \times 100 \tag{5.1}$$

where CEV is the current element value and TEV is the total element value.

$$TEV = \text{total element quantity} \times \text{failure cost of element} \tag{5.2}$$

$$CEV = \Sigma(\text{quantity condition state} \times \text{weighing factor}) \times \text{failure cost} \tag{5.3}$$

The weighting factors depend on the number of condition states under considerations. Table 5.1 presents these factors.

Table 5.1 Condition State Weighting Factors

Number of condition states	**State 1 (WF)**	**State 2 (WF)**	**State 3 (WF)**	**State 4 (WF)**	**State 5 (WF)**
3 Condition states	1.00	0.50	0.00	-------	-------
4 Condition states	1.00	0.67	0.33	0.00	------
5 Condition states	1.00	0.75	0.50	0.25	------

The HI is an average of the conditions of the bridge elements. Abu Dabous et al. (2008) argued that the HI is an overall representation of a bridge or a network condition and might not accurately reflect the conditions of specific bridge elements.

5.2.3 Sufficiency Rating (SR)

Sufficiency rating (SR) is a concept developed by the Federal Highway Administration (FHWA 1988) in the United States to rate and rank bridge inventory. The FHWA uses SR to provide an overall assessment of a bridge's condition and to determine eligibility for receiving federal funds. SR can be used in combination with other factors to prioritize bridge projects.

The SR scale ranges between 0 and 100 with 0 representing a completely deficient bridge and 100 a completely sufficient bridge. SR categorizes bridges into three groups: Bridges with SR between 80 and 100 require no action; bridges with SR between 50 and 80 are eligible for rehabilitation and those with SR between 0 and 50 are eligible for replacement.

A fairly complex formula is used and is described in the FHWA's Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. In addition, SR has some limitations (Sianipar 1997): (1) It is not sensitive to certain important factors such as average daily traffic; (2) SR is determined on the basis of a single standard; and (3) the method provides no room for optimization.

5.3 RANKING PROJECTS USING MULTIPLE CRITERIA

As discussed in Chapter 4, the Ministry of Transportation of Ontario has developed a bridge condition index. The ministry is using this index for ranking and prioritizing projects for intervention. In interviews with a manager from the ministry, he explained that adopting this ranking and prioritizing procedure has enhanced bridge inventory management and yielded up to 10% in reduced expenditures. The ranking process provides them with a systematic approach to compare bridges based on their conditions and to prioritize bridges that urgently need intervention. However, this approach uses a single criterion which is the overall bridge condition. Expanding the approach to include additional criteria can improve the obtained results since other decision elements can take part in defining the urgency of each project for intervention. Including these elements will maximize bridge condition preservation and minimize the deficiencies.

Ranking projects using multiple criteria can achieve better representation of the bridge inventory needs and can yield improved results in term of safety, performance and budget allocation. The Multi-Attribute Utility Theory is a method to perform this task. The main advantages of this theory lie in its flexibility in expressing the decision makers' degree of satisfaction with each attribute as that attribute value changes, and its ability to capture the decision makers' attitude toward risk. In addition, MAUT eliminates the need to assign dollar values to the indirect cost elements since evaluating the indirect cost impact is a difficult task. The following sections discuss the theory and present a procedure developed in this research to construct the necessary utility functions.

5.3.1 Multi Attribute Utility Theory (MAUT)

The basic principle of the MAUT is based on estimating performance using attributes that are concrete, measurable and representative to the degree of satisfaction with the various aspects of each alternative. The attributes of each alternative specify the characteristics of that particular alternative and can serve as scales against which the levels of achievement of the alternative are measured. The foundation of the MAUT is the use of utility functions, which are utilized to quantify the preference of the decision maker by depicting the degree of satisfaction, as the attribute under consideration takes values between the most and least desirable limits.

The purpose of the utility functions is to transform the measures of the different attributes into a common dimensionless scale ranging from zero to one. The utility functions can transform objective data such as the alternative measurable number of units or subjective knowledge such as expert judgment into a utility score. Having a representative set of utility functions, alternatives can be scored and ranked in a systematic way given that the value of the various attributes (objective and subjective) are readily available. To evaluate an alternative, the utility values of its attributes can be aggregated to estimate an overall utility or degree of satisfaction. The preferred alternative is normally the alternative with the highest overall utility score.

The most challenging step in implementing the MAUT is the development of the utility functions. Several procedures have been proposed to this end. Keeney and Raiffa (1993) discussed the most elaborate methods to develop these functions. The utility value is often defined on a normalized scale as the attribute changes between its lower and upper bounds and the function is usually evaluated by the certainty equivalence method developed by Keeney and Raifa (1993). However, it has been recognized that the convergence procedure in assessing a certainty equivalent is time-consuming and complicated (Pan and Rahman 1998).

Benefiting from the guidelines established by Keeney and Raiffa (1993) and from the intuitive Eigenvector approach embedded in the AHP, a novel procedure to develop the utility functions is developed and discussed in the next section.

5.3.2 Procedure to Develop Utility Functions

Keeney and Raiffa (1993) discussed how utility is relative and not absolute. In order to establish an origin or unit of measure, we can arbitrarily assign utilities to certain consequences and then assess utilities for the other consequences, relative to the assigned ones. This procedure is even easier to illustrate if we define a least-preferred consequence x_L and a most-preferred consequence x_M. Then, a utility function scale is set by assigning the least-preferred consequence the lowest possible utility and by assigning the most-preferred consequence the maximum possible utility. For any x greater than x_L and smaller than x_M, the utility value is greater than the lowest utility and less than the maximum one.

In addition, Keeney and Raiffa (1993) recommended that utility functions be monotonic. This characteristic forces the decision maker to subscribe to a certain attitude and restricts the utility function for the purpose of simplifying its assessment. The utility functions can be either monotonically increasing or decreasing. In the case of a monotonically increasing function, a higher value for the attribute means higher utility and can be represented as follows:

$$[\, x_1 > x_2 \,] \Leftrightarrow [\, u(x_1) > u(x_2) \,]$$

In the case of a monotonically decreasing function, a higher value of the attribute means less utility, as in the following representation:

$$[\, x_1 > x_2 \,] \Leftrightarrow [\, u(x_1) < u(x_2) \,]$$

Evaluating the relative importance between the different levels of each attribute can define the utility associated with each of these levels. The utility associated with specific values of an attribute can be estimated by performing pairwise comparisons between these values.

To develop a utility function, the AHP can be used to extract the judgments regarding the relative importance between the different levels of the attribute, and the Eigenvector approach can be used to estimate the utility associated with each of these levels. The following is a detailed description of the procedure.

1) Define boundaries of the utility function:
   - Choose a value for the attribute under consideration that corresponds to the lowest utility and represents the least desirable scenario. This value represents the least preferred consequence x_L and has the lowest utility.
   - Assign a value of the attribute under consideration that corresponds to the highest utility and represents the most desirable scenario. This is the most preferred consequence x_M and has the highest utility. The x_M value can be found by finding the value of the attribute that has absolute importance over the least preferred consequence, x_L.
   - If $x_L < x_M$, then the utility function is monotonically increasing and if $x_L > x_M$, then the utility function is monotonically decreasing. A

monotonically increasing function means that the attribute values selected in the following steps must be higher than x_L and are increasing in value each step, while the monotonically decreasing function means that the attribute values selected in the following steps must be lower than x_L and are decreasing in value with each step.

2) Within the defined boundaries (x_L and x_M), define a value of the attribute that has a slight importance over the least desirable scenario. This value is the attribute value that experience and judgment slightly favour over the value for the least desirable scenario. The intensity of the relative importance between this value and the least desirable scenario is 3 according to the scale of relative importance developed and validated by Saaty (1980).
3) Repeat step 2 to define a value of the attribute that has demonstrated importance when compared with the least desirable scenario. This value is the attribute value that experience and judgment strongly favour over the value for least desirable scenario and its dominance is demonstrated in practice. The intensity of the relative importance between this value and the least desirable scenario is 7 according to the scale of relative importance (Saaty, 1980).
4) Develop a reciprocal and consistent matrix using the judgments from steps 2, 3 and 4. The consistent matrix can be developed by applying the following two constraints: $a_{ji} = 1/a_{ij}$ and $a_{ij} = a_{ik} \times a_{kj}$. Enforcing consistency is permissible in this case since the decision maker will review the

developed utility function and revise the judgments in the previous steps if the function does not represent the attribute under consideration. The eigenvector can be estimated for the developed matrix and used to develop the utility points that correspond to the various levels of the attribute as shown in Figure 5.1. For convenience, the range is set from 0 to 100 instead of the 0 to1 conventional range.

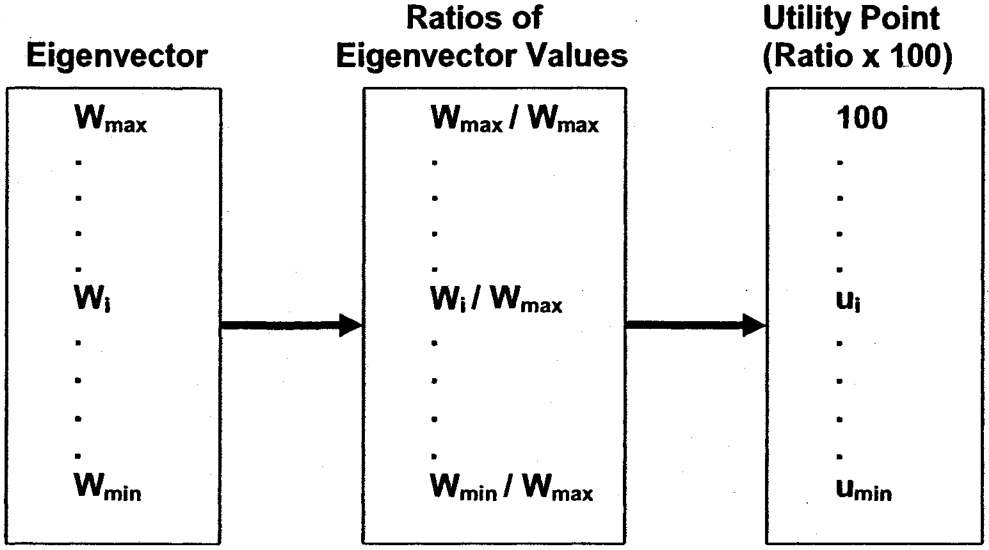


Figure 5.1 Transforming the Eigenvector to Utility Points

5.3.3 Sample Application of the Utility Function Development

The following is an example to demonstrate utility function development using the above procedure. A utility function for the bridge deck condition index is developed. The index ranges between 0 and 100 where 100 signifies the best possible condition. The utility function is required to represent the urgency for intervention based on the bridge deck condition.

First, the boundaries of the utility function are established. A bridge with a condition index higher than 90 is considered to be in excellent condition and does not require intervention. The 90 condition index is the least desirable value of the attribute and corresponds to the lowest utility value. On the other hand, the bridge index is not allowed to drop bellow 40 since a bridge with a condition index less than 40 becomes unsafe for the public. As a result, the most desirable value of the attribute is 40 which represents absolute importance over the lease desirable one and this value is given the maximum utility of 100. The utility function is monotonically decreasing.

Within the defined boundaries, the decision maker should specify the value of the bridge index that has weak importance, and the one that has demonstrated importance with respect to the least desirable scenario which is the condition index of 90. The decision maker realizes that a bridge with a condition index of 80 does not need intervention and as a result, it has a weak importance compared to 90. Meanwhile, a bridge with condition index 65 is due for intervention and has essential importance compared to 90. Based on these judgments, a consistent reciprocal matrix is developed and the utility points are estimated as shown in Table 5.2.

The utility points are plotted against the different values of the bridge index, as shown in Figure 5.2. In this case, the condition index 40 is given the highest utility and it is more than double the utility given for condition index 80.

Table 5.2 Pairwise Comparison Matrix, Eigenvector and Utility Points

		Condition Index				**Eigen-vector**	**Utility Point**
		90	80	65	40		
Condition Index	90	1	1/3	1/7	1/9	0.05	11.11
	80	3	1	3/7	3/9	0.15	33.33
	65	7	7/3	1	7/9	0.35	77.77
	40	9	3	9/7	1	0.45	100

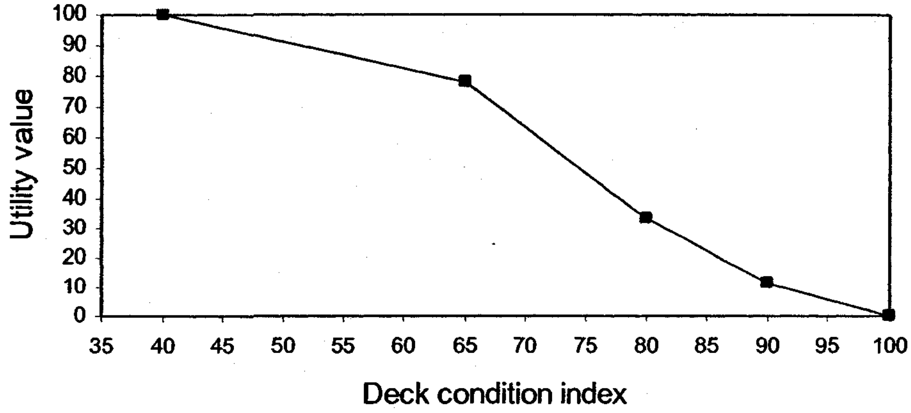


Figure 5.2 Utility Curve for the Bridge Deck Condition Index

The decision maker(s) can inspect the developed utility function to ensure that it reflects the degree of satisfaction with the different levels of the attribute and can resubmit the judgments to adjust the function if necessary.

5.4 DEVELOPMENT OF THE RANKING METHOD

The ranking method is based on the MAUT. The first step toward the development of the ranking method is breaking down the problem under consideration into a hierarchy structure. Eleven interviews with bridge engineers and decision makers from two ministries of transportation and two private companies were performed as a part of the research information collection. One objective of the interviews is to question the main elements of the decision making process. These decision elements collected from the interviews are organized into a four-level hierarchy structure, which was found to be sufficient to capture the main elements of the problem under consideration. The natural top-down approach is used to develop the structure. This approach starts with identifying the overall goal and proceeding downward until all the measures of value are included.

The first level of the hierarchy is the overall goal of the ranking exercise. The second level contains the objectives necessary to achieve the overall goal. The third level of the hierarchy holds the criteria to be used for evaluating the objectives. The alternatives are added at the bottom level. Figure 5.3 presents the hierarchy structure developed in this research. Each objective or criterion has a specific weight reflecting its importance. The utility functions measure the level of attainment of the various attributes of each bridge with respect to the evaluating criteria. The problem hierarchy structure development is discussed in Sections 5.5 through 5.7.

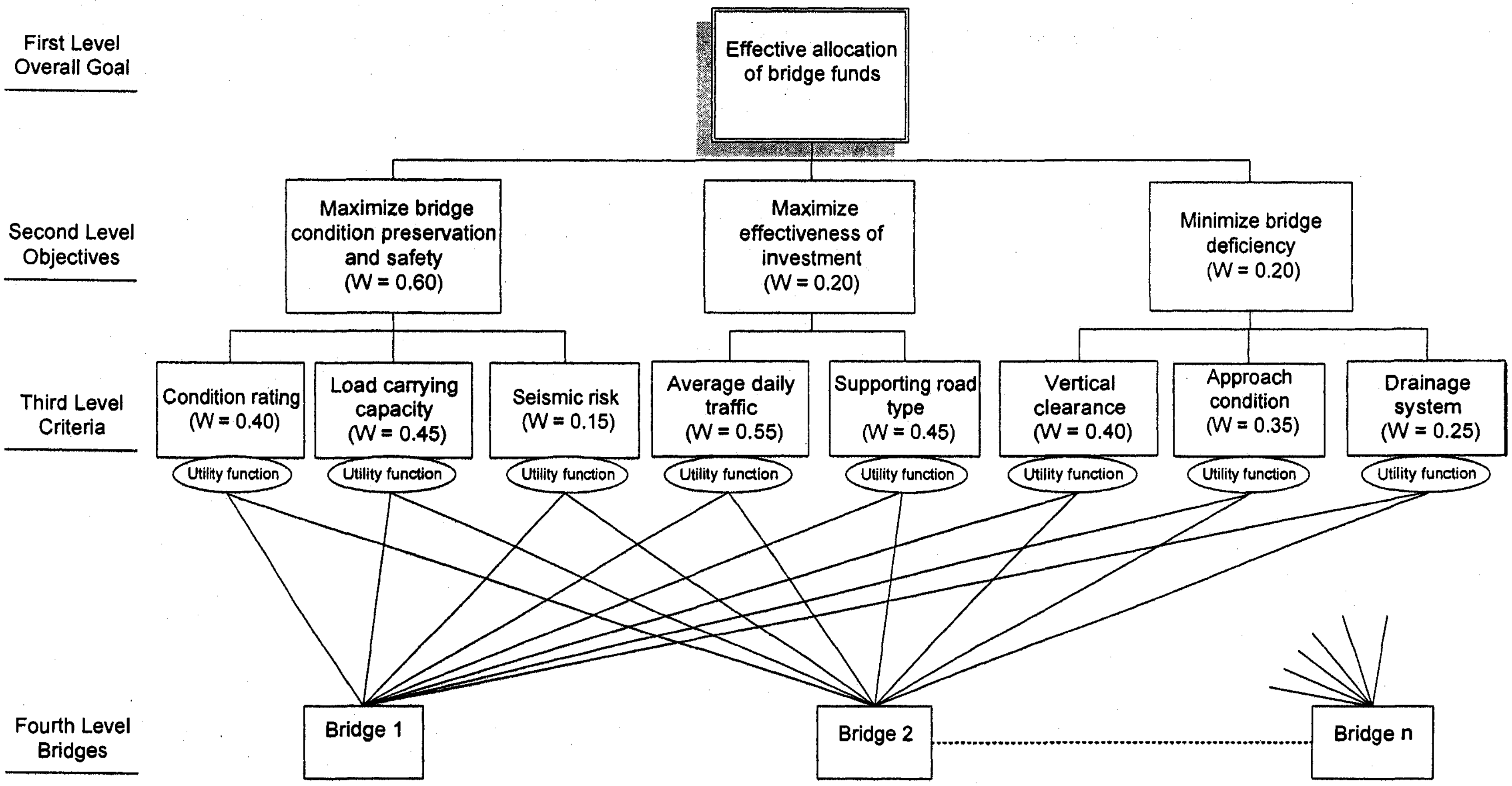


Figure 5.3 Hierarchy Structure for the Ranking Method

5.5 DECISION OBJECTIVES AND CRITERIA

During the interviews performed to solicit knowledge from bridge engineers and decision makers, the main objectives and criteria associated with the decision making process are identified. Since the most challenging task bridge managers face is using limited available funds effectively, the overall goal of the ranking exercise is the effective allocation of these available funds. This efficient use of the limited funds must aim toward improving the bridge network condition and to maximize benefits to the users and the community.

The overall goal can be achieved by accomplishing three major objectives. These objectives are maximizing the investment effectiveness, maximizing bridge safety, and minimizing bridge deficiencies. Each objective can be evaluated using specific criteria. The following three sections discuss in detail the objectives in the second level of the hierarchy and the corresponding evaluation criteria in the third level.

5.5.1 Bridge Condition Preservation and Safety

Bridge condition preservation and safety are major concerns for bridge managers. As a result, maintaining bridges within acceptable limits of safety and serviceability is among the main objectives of any bridge management system. It is essential to include this objective in the ranking method.

In this context, both the material deterioration of the elements and the functional degradation of the bridge structural system must be considered. These elements are particularly important since the bridges are affected by an aggressive environment and must carry increased truck loads. In addition, the risk of unforeseen factors such the risk of having an earthquake must be considered. In conclusion, maximizing bridge preservation and safety can be achieved by prioritizing bridges that have a higher level of deterioration, reduced live load carrying capacity and bridges in geographic locations with seismic risk.

The condition rating is a criterion to discriminate between the decks based on their conditions. The element condition index developed in Chapter 4 is used here to represent the degree of deterioration of each bridge deck. This index is adopted as an attribute to measure the condition of the deck for the various bridges under consideration. The purpose of this criterion is prioritizing bridge decks that have a low condition index.

The Canadian Highway Bridge Design Code CAN/CSA-S6-00 (2000) includes Section 14 which provides methods for evaluating existing bridges. The purpose of this evaluation is to determine if the bridge under consideration can carry a particular set of loads. The method is practical, simple to use and takes into account the type of traffic supported by the bridge. The live load capacity factor presented in Clause 14.14 of the CAN/CSA-S6-00 is adopted within the developed ranking method as a criterion to evaluate the load carrying capacity of each bridge. Bridges with reduced live load carrying capacity must be prioritized for action since such bridges are becoming a safety concern.

The code recommends using a live load capacity factor, F, for bridge evaluation purposes. If the live load capacity factor equals one then the element can carry exactly the required load and if it is less than one then the element is substandard. Bridges with a live load capacity factor less than one should be assigned the highest utility and should be prioritized for intervention. As the live load capacity factor increases to be greater than one, the utility value must decrease to reflect a safer bridge in terms of the live load carrying capacity. The live load capacity factor is evaluated for its ultimate limit state, given by the following equation:

$$F=\frac{U\varphi R-\ddagger''\alpha_D D-\ddagger''\alpha_A A}{\alpha_L L(1+I)} \tag{5.4}$$

where U is the resistance adjustment factor; φ is the resistance factor; R is the nominal unfactored resistance; α_D and α_L are the load factors for force effects due to dead load and live loads, respectively; D and L are the nominal unfactored loads due to dead load and live load effects, respectively; α_A is the load factor for force effects due to additional dead loads including wind and creep; A is the force effect due to additional load; and I is the nominal unfactored dynamic component of the live load. The values for these factors are included in Clause 14 of the CAN/CSA-S6-00. The live load capacity factor can be estimated for any structural member. In the method developed here, the live load capacity factor for the bridge girders is used as the criterion to rank and prioritize bridges.

If the bridge cannot carry standard-weight vehicles, the CAN/CSA-S6-00 provides Clause 14.17 to define bridge posting requirements. The bridge posting means limiting the weight of the vehicles using the bridge. The posting is done by using posting signs which specify the gross vehicle weight that can use the bridge, to the nearest tonne. By law, any vehicle that exceeds this weight is not permitted to pass over the bridge. Bridge posting is an important aspect of bridge safety that will be linked to the decision making process, and shall be revisited in Chapter 7.

Seismic vulnerability risk is an important criterion to be included in the ranking procedure. The Ministry of Transportation of Quebec (MTQ 1995) has adopted a seismic prioritizing procedure based on a seismic vulnerability index (SVI). This index is estimated by combining a global structural influence coefficient, a foundation factor and a seismic risk factor (Filiatrault et al. 1994). Since the structural factor is considered as a separate criterion in the hierarchy structure, it should not be included again with the seismic risk criterion to avoid using the same criterion twice and to maintain independence between the various criteria in the same level of the hierarchy. As a result, the SVI is evaluated by multiplying the seismic risk factor (SRF) by the foundation factor (FF) as follows:

$$\mathrm{SVI} = \mathrm{SRF} \times \mathrm{FF} \tag{5.5}$$

The SRF depends on the geographical location of the bridge and is based on the seismic zones defined by the Canadian Highway Bridge Design Code, CAN/CSA-S6-00. For each city in each Canadian province, the code defines velocity and acceleration values according to the seismic zone that the city is located in. The velocity and acceleration related to each seismic zone are referred to as Z_V and Z_A, respectively, and both can range between zero and six. These values for all of the cities in the Canadian Province of Quebec are presented in Appendix A.

Filiatrault et al. (1994) recommended the use of an effective seismic zone, Z_E, which equals Z_V if Z_A is less than or equal to Z_V, or equals one plus Z_V if Z_A is greater than Z_V. Also, they recommended SRF values based on the values of Z_E as shown in Table 5.3.

Table 5.3 Effective Seismic Zones and Seismic Risk Factors

Effective seismic zone, Z_E	**SRF**
0	0.0
1	1.0
2	2.0
3	3.0
4	4.0
5	4.5
6	5.0

The FF is related to the type of soil supporting the foundation since the type of soil has a direct effect on the seismic behaviour of bridge structures. The nature and the behaviour of the soil can change during earthquakes due to liquefaction. As a result, it can be cumbersome to estimate the liquefaction potential and the shear strength of soil for all bridges sites. To resolve this problem, Filiatrault et al. (1994) classified soil into four categories and specified a value for the FF corresponding to each category as shown in Table 5.4.

The SVI can be estimated for any bridge in the network using the values provided in Tables 5.3 and 5.4. The estimated value of the SVI can range between 0 and 10, where 0 reflects no potential for seismic vulnerability and 10 reflects a significant risk.

Table 5.4 Soil Categories and Foundation Factors (FF)

Category	Description	FF
I	Rock, dense and compact soil	1.0
II	Dense and compact soil, stiff clay deeper than 50 m	1.3
III	Loose soil deeper than 10 m	1.5
IV	Very loose soil potentially liquefiable	2.0

5.5.2 Effectiveness of Investment

The second objective is to maximize the effectiveness of investment by prioritizing the more important bridges. Bridge importance is a subjective factor which can be defined using a variety of factors or measures depending on the decision maker's perspective. An important bridge can be one that serves a large number of users every day, one that carries an important utility line or one that is connecting two parts of a city at a critical node. In addition, bridge importance can increase or decrease under specific circumstances, such as earthquakes. It is the decision maker's task to establish the criteria which specify the bridge importance level.

Within the developed framework, this objective can be attained by allocating more funds to bridges that serve a high number of users and to bridges that support a significant type of roadway. The average number of daily users of any bridge is usually represented by the average daily traffic (ADT). This is a commonly used factor which is normally available in transportation agency databases. The ADT is an essential factor which reflects the importance of a bridge and as such is adopted as a basic criterion to determine a bridge's importance. This criterion serves the objective of maximizing the effectiveness of the investment by maximizing the number of users that can benefit from the bridge improvement projects achieved with the funds available.

The second criterion identifies the various road types served by the bridges. This criterion achieves the objective of maximizing the effectiveness of an investment by prioritizing bridges that are connected to important roads. The Ministry of Transportation of Quebec (MTQ 1995) classifies the roads and provides a weighted index for each type as in Table 5.5.

Table 5.5 Supporting Road Type Index

Supporting road type	**Importance Index**
Local or collector	2.5
Regional	5.0
National	7.5
Highway	10.0

This criterion is important to include since it balances the ADT criterion in order to insure that bridges with relatively low daily users but which serve an important road such as the highway to be prioritized for action and allocated the necessary funds.

5.5.3 Bridge Deficiencies

A number of deficiencies can reduce a bridge's level of service and accelerate the deterioration process. Therefore, it is beneficial to consider the elimination of these deficiencies within the decision making process. Discussions with bridge engineers illuminated the existence of a number of deficiencies that should be minimized or eliminated. From these, three main deficiencies are selected to be included within the framework of the developed ranking method, since these deficiencies can seriously affect bridge safety and serviceability. The selected deficiencies are the vertical clearance, the approach condition, and the drainage system.

The vertical clearance is the clear height below and above the bridge deck. This can be a major safety factor since vehicles or trains passing under or on the bridge must have enough vertical clearance to pass safely. Otherwise, the top of the vehicle or the train can crush into the structure. In the case of insufficient clearance, postings which mandate the height of vehicles passing under or on the bridge are mandatory. Also, inadequate clearance can be a safety concern in the case of floods for bridges crossing a waterway.

The CAN/CSA-S6-00 Code requires that the clearance values for roadways must comply with the standards of the Regulatory Authority. For waterways, the clearance between the soffit of the structure and the high-water level shall be sufficient to prevent damage to the structure by the action of flowing water, ice floes, or debris and shall not be less than 1 meter. The MTQ (1995) provides a mandatory clearance value depending on the type of route. These values are 4.15 m for roads and 7.16 m for railroads.

The bridge attribute which can be used to evaluate this criterion is the percentage of the difference between the vertical clearance and the mandatory clearance. The vertical clearance deficiency can be estimated using the following equation:

$$I_V = \frac{Y - Y_M}{Y_M} \tag{5.6}$$

where Y is the bridge vertical clearance and Y_M is the mandatory clearance.

The second major deficiency is the settlement of the bridge approaches. Each bridge has two approaches, which are the links between the road and the bridge structure. Approach slabs may or may not exist. However, when approach slabs are not provided, the backfill soil behind the bridge abutment can settle rapidly. This defect can cause a differential settlement between the road and the bridge slab. Settlement can cause an abrupt change in the road surface elevation, which can be a hazard for drivers (and their vehicles) and can become a safety issue. To overcome the problem, bridge approach slabs are normally added and constructed upon the approach embankment at each end of the bridge structure and anchored to the abutment wall. Their purpose is to provide a smooth transition between the approach pavement and the deck for vehicles traveling onto and off the structure. However, settlement of the embankment soil below the approach slabs will cause the same problem.

The performance of the approaches and the approach slabs is measured by their ability to provide a smooth and safe transition onto and off the bridge. Settlement of the embankment soil on both ends of the bridge can reduce the performance of the bridge approaches or approach slabs. This inadequacy requires prioritizing the bridge for intervention.

The OSIM requires inspecting the bridge approaches as a secondary component of the bridge deck and to assign for it one of four condition states: Excellent, Good, Fair or Poor. The condition rating reflects the serviceability level of the approaches. Excellent condition can be given when the approach is at the same level of the bridge and transition is smooth for vehicles approaching the bridge. A Good condition state is assigned when slight settlement in the embankment has happened but the difference in the levels is not a safety concern for vehicles traveling on the bridge. The Fair condition state reflects the beginning of deterioration in the approach slab material due to settlement. A Poor condition state is given when the difference in elevation is noticeable and it can be a safety concern for vehicles.

The third deficiency is associated with the reduced performance of the drainage system. A bridge deck drainage system is an important item since it directly affects the safety of traveling vehicles and the durability of the structure. Water accumulated on the bridge can be a hazard for drivers. If the drainage system is poor, ice may form, producing slippery surfaces. The application of deicing salt during winter, associated with poor drainage, can accelerate corrosion of the deck-reinforcing steel, which is a primary deterioration factor for concrete elements.

The drainage system can be made defective due erosion and/or it could be jammed due to dirt and debris. Also, the drainage system might not be adequate to drain the water accumulated on the bridge deck. It is necessary to evaluate the performance of the drainage system during an inspection. The OSIM requires the inspection of the drainage system but does not specify a performance measure. Based on discussions with bridge engineers, the following index is developed to evaluate the performance of the drainage system of each bridge:

$$I_D = I_{D1} + I_{D2} + I_{D3} \tag{5.7}$$

where I_{D1} equals 0.30 when the drains are eroded and equals 0 when erosion does not exist; I_{D2} equals 0.3 when the drains are blocked and equals zero when the drains are not blocked; I_{D3} equals 0.4 when the drainage performance is not sufficient and it does not prevent water accumulation and equals 0 when the drains are sufficient.

5.6 DETERMINATION OF WEIGHTS FOR OBJECTIVES AND CRITERIA

The hierarchy structure developed in the previous section consists of four levels. The highest level is the overall goal of the decision making process, which is allocating the available funds in the most efficient way. The lowest level of the hierarchy contains the various bridges to be evaluated using the criteria in the third level. The objectives and criteria in the second and third level of the hierarchy are divided into elements. The elements in each of these levels are independent and capture all of the decision aspects of the elements in the level above. The independent elements in each level can have the same weight or different weights.

The weights of the elements in each level are defined based on their relative importance with respect to the elements in the next higher level of the hierarchy. For example, the weight of each objective in the second level is assigned based on how important the objective is when compared to the ones with respect to the overall objective of allocating funds for projects in an effective way. In a similar manner, the weights of the criteria in the third level are defined with respect to the objective that each criterion is related to. These weights reflect the willingness of the decision makers to give up in one item in order to gain in another.

The typical approach to develop weights for the related elements is to use the decision makers' or the experts' judgment regarding the relative importance of the various elements under consideration. The decision maker can directly assign weights for the various elements.

Some techniques can be useful to extract the decision makers' or experts' judgments regarding the relative importance of the various elements. One technique involves using the eigenvector approach, which can be implemented by requesting the decision maker to compare the elements in pairs to define the intensity of the relative importance between each pair of elements. The pairwise comparisons are assembled in a reciprocal matrix and the eigenvector can be estimated. The eigenvector represents the weight of each of the elements under consideration. Another technique is the Delphi method proposed by Dalkey and Helmer (1963), which requires the decision makers to establish an order of preference among the different elements. A cardinal ranking is then used to assign a weight to each element.

The method developed in this research uses weights extracted directly by requesting the opinion of a bridge expert. This method provides flexibility for the decision maker to revise these weights if necessary. This flexibility is essential since different decision makers can give different weights for the objectives and criteria depending on their preferences. Figure 5.3 includes the weights for the objectives and the criteria developed from expert opinion. The weight of each element is provided under its name.

5.7 DEVELOPMENT OF UTILITY FUNCTIONS

Utility functions are needed to transfer the degree of satisfaction with each bridge attribute into a common dimensionless measure. The degree of satisfaction with all of the attributes can then be aggregated into an overall utility by using a utility model.

Utility functions can be developed by implementing the procedure presented in Section 5.3.2. That procedure uses the eigenvector approach, since pairwise comparisons are intuitive, easy to follow, and extract judgments in a systematic way. The procedure develops a reciprocal matrix while enforcing consistency in the provided judgments. Enforcing consistency is permissible since the decision maker can review the developed utility function and revise his/her judgments. The procedure is repeated until the developed utility function represents the criterion under consideration and reflects the decision maker's attitude toward risk.

The decision maker's attitude toward risk can be analyzed by comparing the certainty equivalent value with the average value of the attributes' limits. The certainty equivalent value corresponds to 0.5 utility. The attitude toward risk can be averse, prone, or neutral based on the certainty equivalent value. For an averse risk attitude, the certainty equivalent value is less than the average value of the attributes' limits, while with the prone risk attitude, the certainty equivalent value is greater than the average value of the attributes' limits. If the certainty equivalent and the average attributes' limits value are equal then the decision maker has a neutral attitude toward risk. Figure 5.4 presents these types of utility functions.

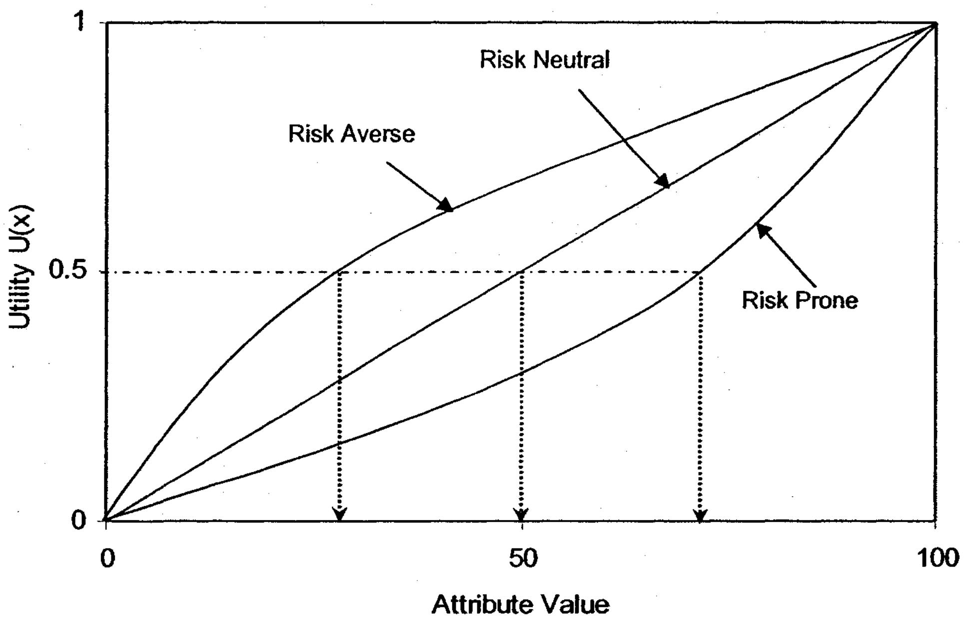


Figure 5.4 Utility Functions Reflecting Experts' Attitude toward Risk

The developed framework within this research provides utility functions to transform bridge attributes into common dimensionless measures. These measures evaluate the level of attainment for each bridge with respect to a specific criterion.

Figure 5.5 presents the utility functions developed to be incorporated within the proposed decision support system. These functions are developed based on data and judgments extracted during interviews with bridge engineers from the Ministry of Transportation of Ontario and from a private consulting company in Montreal, Canada.

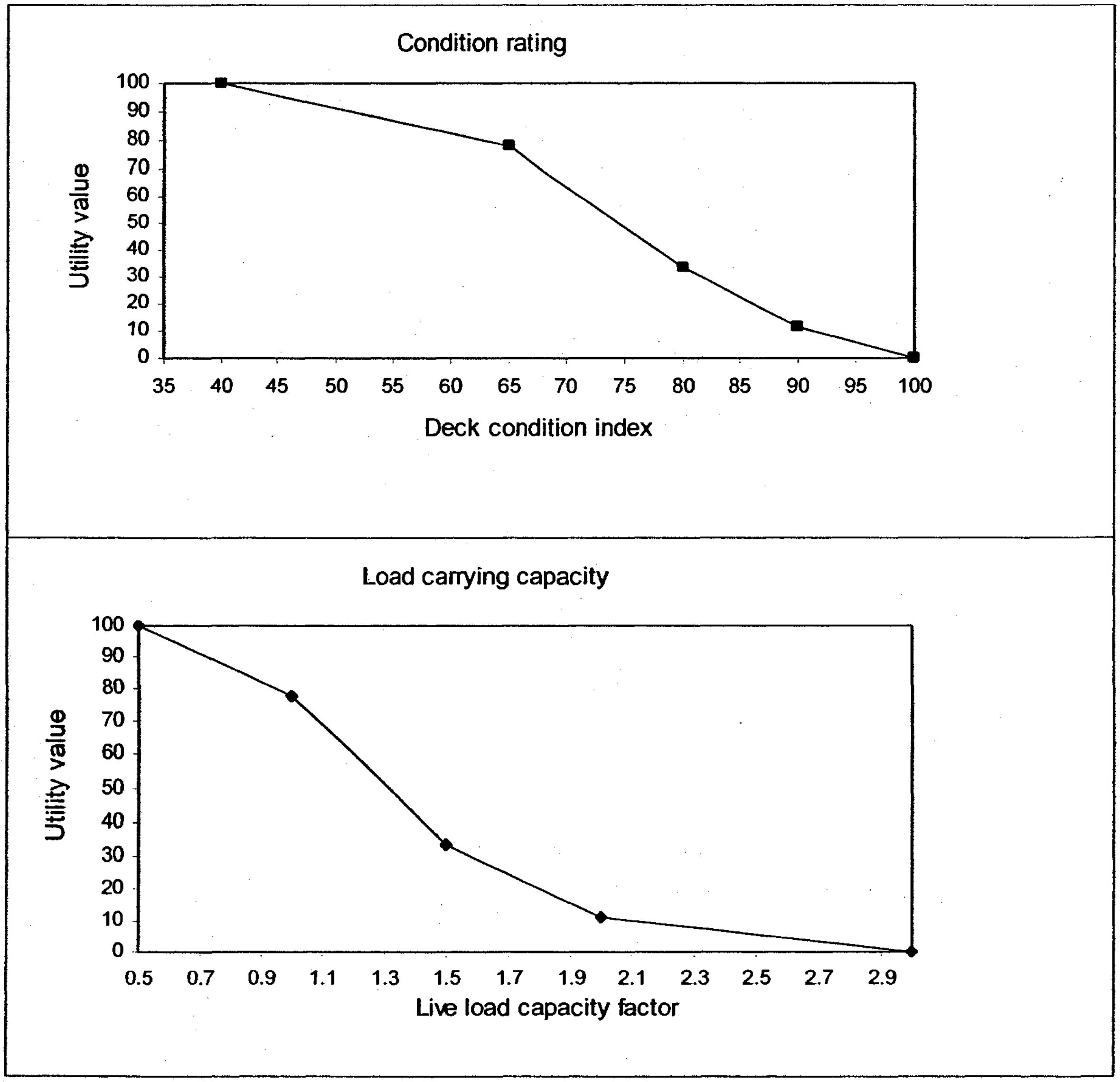


Figure 5.5 Utility Functions for the Bridge Attributes

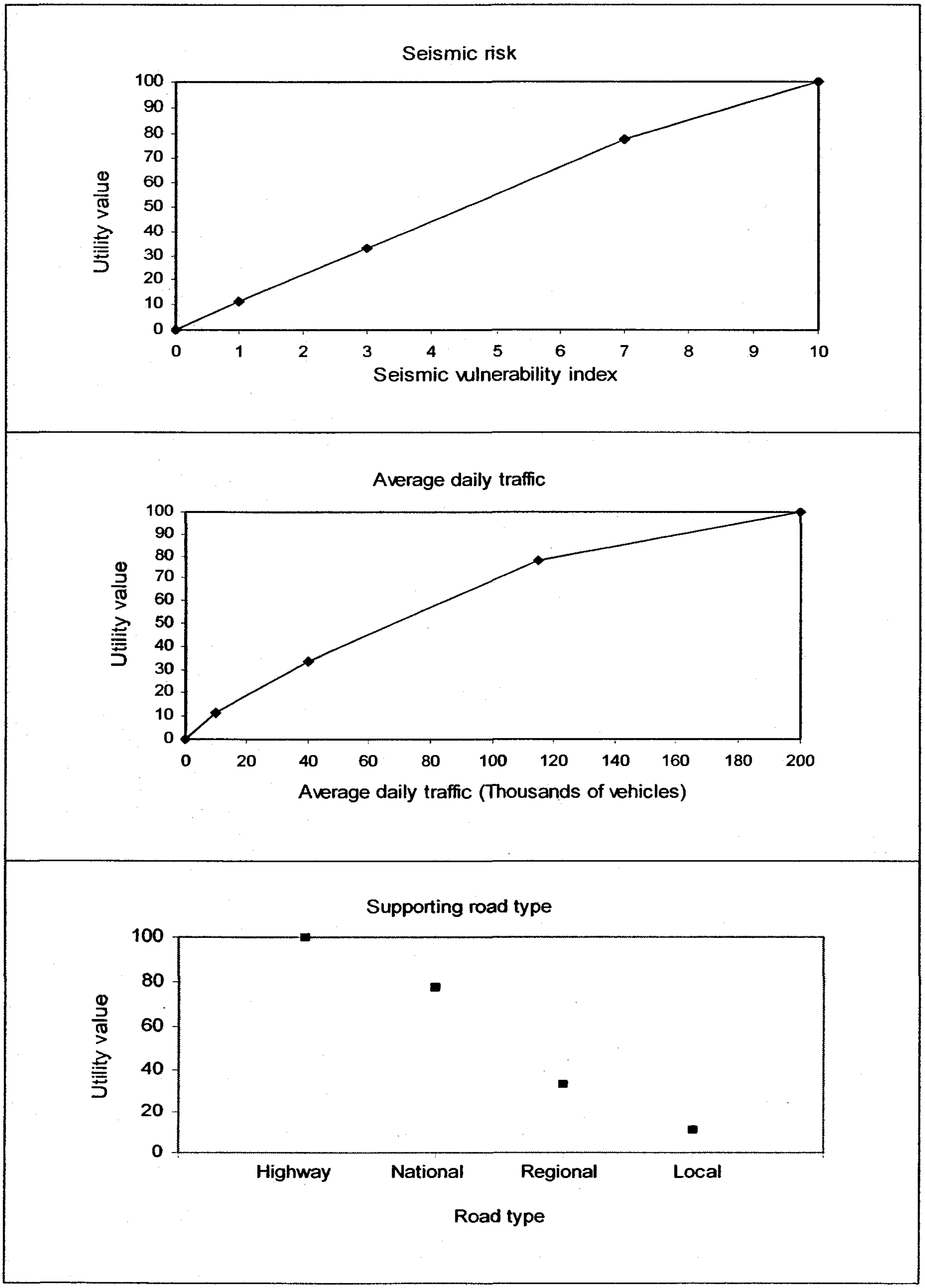


Figure 5.5 (continued) Utility Functions for the Bridge Attributes

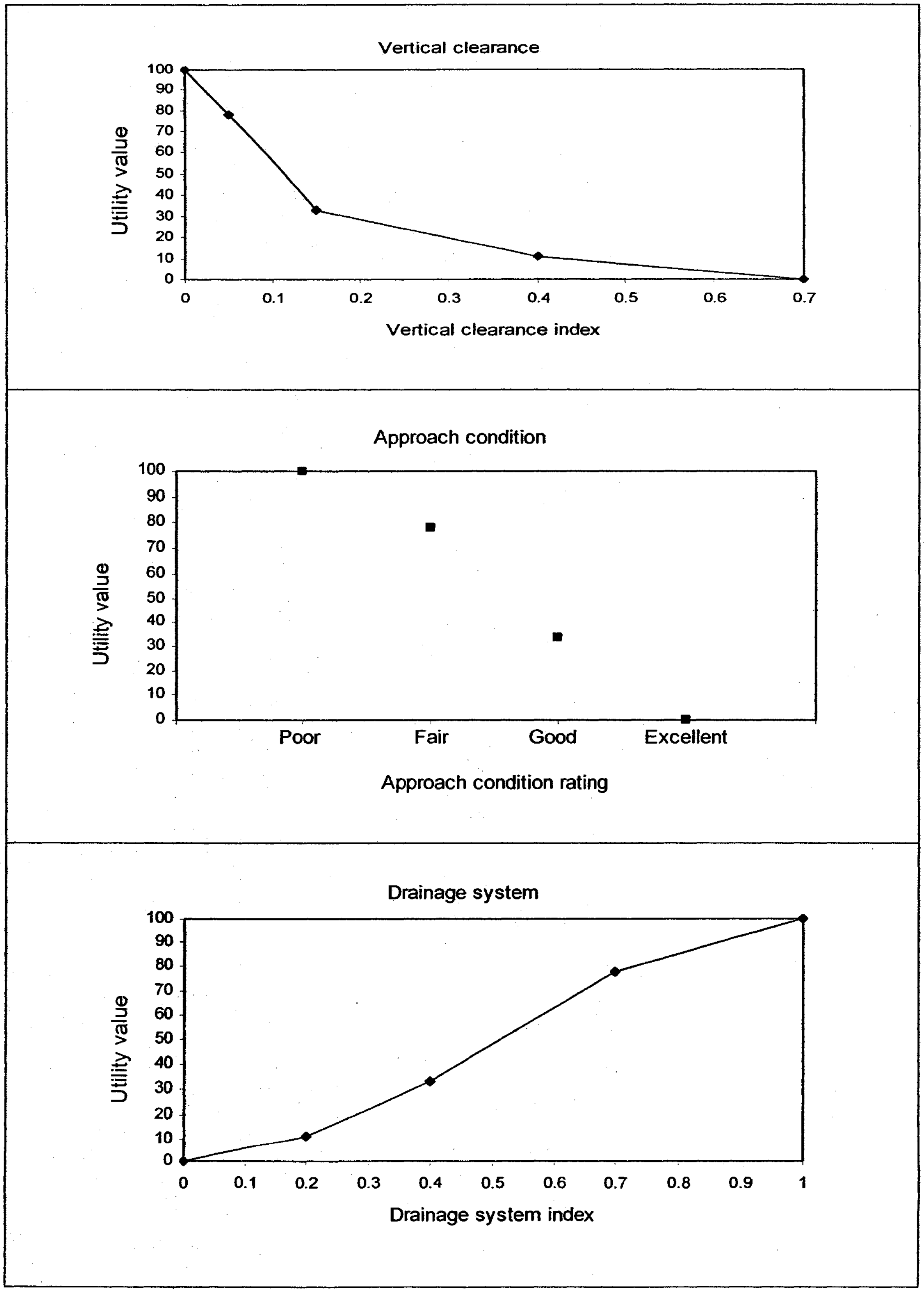


Figure 5.5 (continued) Utility Functions for the Bridge Attributes

5.8 EXPECTED UTILITY VALUE

Upon constructing the decision hierarchy and selecting the appropriate utility functions, a utility model can be used to aggregate the utility values for the various attributes. Since the elements in each level of the hierarchy structure are considered to be independent, the additive utility model can be used as a simple and practical approach to aggregate utilities (Keeney and Raiffa 1993). In such a model, the overall relative utility is expressed as follows:

$$U(x_1, x_2, \ldots, x_3) = \sum_{i=1}^{n} k_i u_i(x_i) \qquad (5.8)$$

where k_i is the weight for attribute i, and u_i is utility value for attribute i.

The utility scores obtained from the utility functions are aggregated using Equation 5.8 to estimate the utility associated with each objective. Then, the utilities of the various objectives are aggregated using the same equation to evaluate the overall utility of the bridge. All bridges in the network or sub-network can be ranked based on the overall utility values

5.9 RANKING PROCEDURE

This chapter discusses the development of a ranking method for bridges based on the MAUT. The research targeted collecting data and information to develop the framework of the ranking method. This framework includes questioning the decision-making elements for ranking and prioritizing projects, the development of a hierarchy structure based on the decision elements and the development of the necessary utility functions.

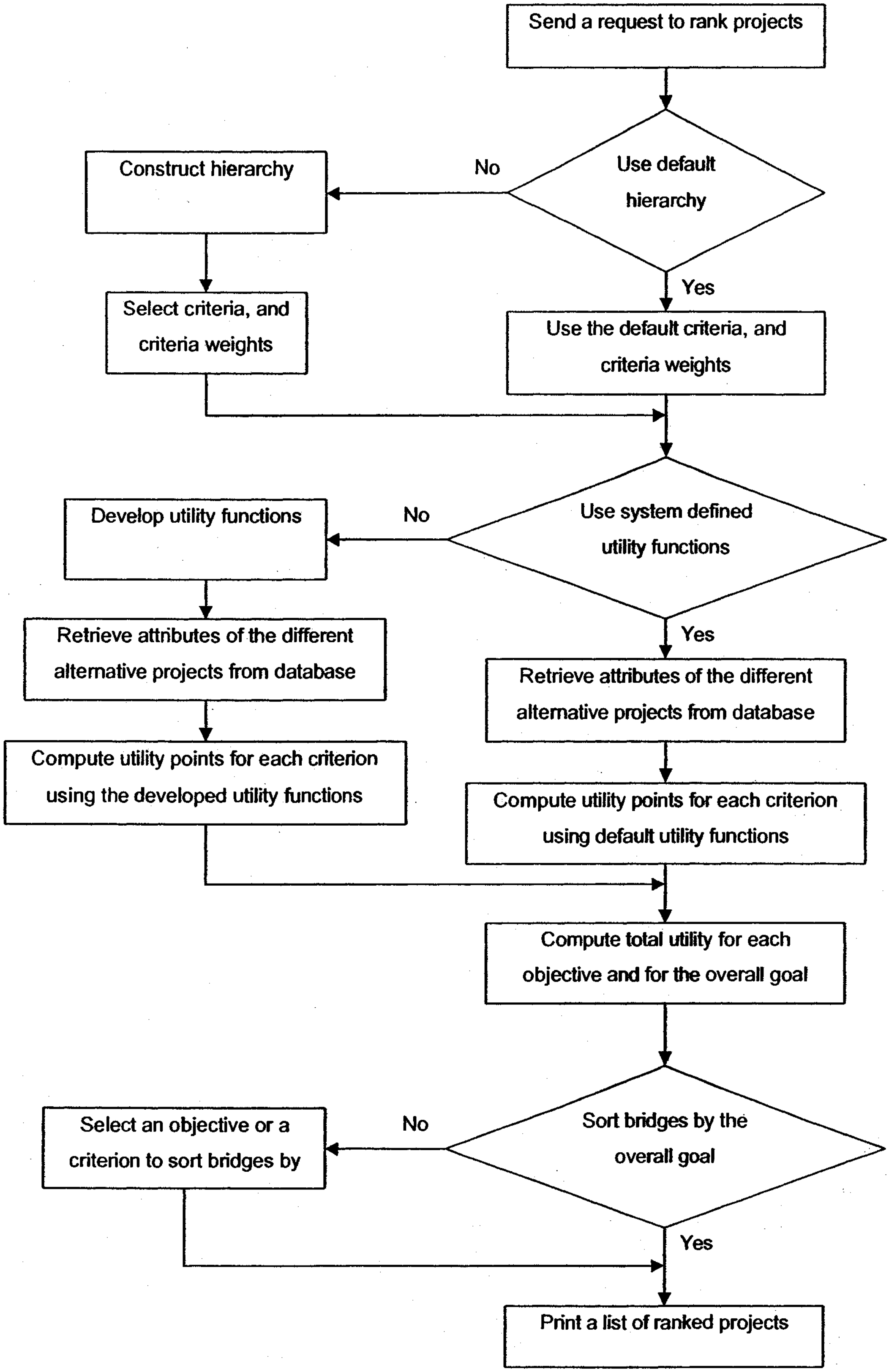


Figure 5.6 Flow Chart for the Proposed Ranking Procedure

Figure 5.6 presents a flow chart for the ranking procedure based on the MAUT. The procedure uses the default hierarchy, the criteria and the objectives, and the utility functions developed in this chapter, and, at the same time, provides flexibility for the decision makers to modify these elements based on judgment and preferences.

Nevertheless, the ranking method provides flexibility to decision makers to provide their inputs to the decision making process. This flexibility enables the decision makers to develop alternative hierarchy structures and to develop alternative utility functions if different criteria or attributes are selected to be incorporated in the decision making process.

5.10 CASE STUDY

In order to demonstrate the application of the developed ranking method, a sample sub-network consisting of eleven bridge projects is considered. Data for these bridges is extracted from reports provided by the Ministry of Transportation of Ontario. Some data is not available in the provided reports, such as the load carrying capacity. This was compensated by requesting an expert from the industry to provide his assessments for the missing data. The data is shown in Tables 5.6 through 5.9.

Table 5.6 List of Attributes and the Utility Values of Projects 10, 20, and 30

	Bridge 10		**Bridge 20**		**Bridge 30**	
Criterion	**Attribute value**	**Utility Value**	**Attribute value**	**Utility value**	**Attribute value**	**Utility value**
Condition rating	64	78.66	66.36	73.6	37.37	100
Load carrying capacity	1.6	28.89	2.2	8.88	1.3	51.11
Seismic risk	2.6	28.89	4.5	50	8.0	85.18
Average daily traffic (Thousands)	40	33.33	50	39.25	35	29.63
Supporting road type	Local	11.11	Regional	33.33	Local	11.11
Vertical clearance	0.25	24.44	0.20	28.89	0.12	46.66
Approach condition	Fair	77.77	Fair	77.77	Poor	100
Drainage system	0.60	62.95	0.60	62.95	0.70	77.77
Expected utility value	**44.49**		**42.78**		**64.35**	

Table 5.7 List of Attributes and the Utility Values of Projects 40, 50, and 60

	Bridge 40		**Bridge 50**		**Bridge 60**	
Criterion	**Attribute value**	**Utility value**	**Attribute value**	**Utility value**	**Attribute value**	**Utility value**
Condition rating	62.27	80.20	74	51.11	58.44	83.60
Load carrying capacity	0.85	84.44	3.2	0	1.6	28.89
Seismic risk	6.0	66.66	5.85	65	4.5	50
Average daily traffic	60	45.18	75	54.07	30	25.92
Supporting road type	Regional	33.33	Regional	33.33	Local	11.11
Vertical clearance	0.20	28.89	0.30	20	0.15	33.33
Approach condition	Fair	77.77	Good	33.33	Good	33.33
Drainage system	0.60	62.95	0.30	22.22	0.70	77.77
Expected utility value	**66.92**		**32.11**		**45.10**	

Table 5.8 List of Attributes and the Utility Values of Projects 70, 80, and 90

	Bridge 70		**Bridge 80**		**Bridge 90**	
Criterion	**Attribute value**	**Utility value**	**Attribute value**	**Utility value**	**Attribute value**	**Utility value**
Condition rating	45	95.55	57.33	84.59	52.83	88.59
Load carrying capacity	0.9	82.22	1.8	20	1.1	68.88
Seismic risk	9	92.59	6.5	72.21	7.5	81.47
Average daily traffic	60	45.18	25	22.22	35	29.63
Supporting road type	Regional	33.33	Local	11.11	Local	11.11
Vertical clearance	0.10	55.55	0.20	28.89	0.25	24.44
Approach condition	Poor	100	Fair	77.77	Good	33.33
Drainage system	1.0	100	0.60	62.95	0.60	62.95
Expected utility value	**77.88**		**46.55**		**58.89**	

Table 5.9 List of Attributes and the Utility Values of Projects 100, and 110

	Bridge 100		**Bridge 110**	
Criterion	**Attribute value**	**Utility value**	**Attribute value**	**Utility value**
Condition rating	74.33	50.12	75.36	47.07
Load carrying capacity	3.70	0	2.8	2.22
Seismic risk	5.85	65	5.2	57.77
Average daily traffic	65	48.14	70	51.10
Supporting road type	Highway	100	Highway	100
Vertical clearance	0.30	20	0.35	15.55
Approach condition	Excellent	0	Good	0
Drainage system	0	0	0	0
Expected utility value	**33.77**		**32.96**	

The expected utility value for each project in the network is estimated using Equation 5.8. The utility values for the various attributes of each project are aggregated using the weights of criteria and objectives. The weights for attributes and criteria are provided in Figure 5.3. For example, the expected utility value for bridge 10 is as follows:

$$
\begin{aligned}
U = & ((78.66 \times 0.4 + 28.89 \times 0.45 + 28.89 \times 0.15) \times 0.60) \\
& + ((33.33 \times 0.55 + 11.11 \times 0.45) \times 0.20) \\
& + ((24.44 \times 0.4 + 77.77 \times 0.35 + 62.95 \times 0.25) \times 0.20 \\
= & \ 44.49
\end{aligned}
$$

Projects in the sub-network can be ranked according to the overall expected utility, where bridges with higher overall expected utility must be prioritized for action. Table 5.10 shows the projects ranked according to the expected utility values.

Table 5.10 Ranking of Bridges in the Sub-Network

Rank	Project	Expected utility value
1	Bridge 70	77.88
2	Bridge 40	66.92
3	Bridge 30	64.35
4	Bridge 90	58.89
5	Bridge 80	46.55
6	Bridge 60	45.10
7	Bridge 10	44.49
8	Bridge 20	42.78
9	Bridge 100	33.77
10	Bridge 110	32.96
11	Bridge 50	32.11

5.11 SUMMARY

This chapter presents the main ranking procedures currently used by transportation agencies and proposes a ranking method for bridge networks, based on the MAUT. The theory provides flexibility for the decision makers in expressing their degree of satisfaction with each bridge attribute and captures the decision makers' attitude toward risk. A technique to develop the necessary utility functions is discussed.

The chapter discusses a framework to perform this ranking exercise. The framework includes the development of a hierarchy structure, defining the objectives and the decision criteria and preparing the utility functions. A generic procedure which allows the decision makers to provide their inputs is also presented.

CHAPTER 6: A MULTI-CRITERIA METHOD FOR BRIDGE REHABILITATION STRATEGEY SELECTION

6.1 INTRODUCTION

The previous chapter discussed a method developed to rank and prioritize bridge projects. The decision maker can identify bridges with the highest priority for intervention using multiple criteria. For each of the prioritized projects, the decision maker is required to select a rehabilitation strategy to improve the bridge condition. A decision support method for selecting the most efficient rehabilitation strategy for each project is needed.

During interviews, two managers from the Canadian Ministry of Transportation confirmed that decision support methods are needed to assist practitioners in improving the condition of the bridge networks by selecting the suitable rehabilitation strategy for each project. They specified the following qualities as warranting inclusion in any proposed decision support method:

1. Enables engineers to utilize their experience and judgment in the decision making process.
2. Allows for refinement of results and modification of constraints.
3. Develops decisions based on a set of criteria defined by the decision maker. Black box decision support tools may not be useful.

This chapter discusses a multi-criteria method for selecting an intervention strategy for bridge deck management. This method is based on a modified Analytic Hierarchy Process (AHP), which is used to evaluate and rank the MR&R

alternatives in a systematic and robust manner while incorporating experts' judgment in the decision process.

6.2 MULTIPLE-CRITERIA DECISION MAKING

Decision techniques are rational procedures to utilize information, data, and experience in order to facilitate and perform the decision making process in a systematic way. Several decision making techniques have been developed and used in a variety of applications. Some of these techniques are simple qualitative procedures to evaluate the advantages and disadvantages of each available alternative and to evaluate the alternatives accordingly. Other techniques are quantitative procedures which incorporate data and experience as an input to evaluate and rank a group of alternatives based on multiple criteria. It is essential to use quantitative procedures for bridge management decision making. Miyamoto et al. (2000) reported that sound bridge management decision making must be based on considering multiple and conflicting criteria simultaneously.

Abu Dabous et al. (2007) discussed and evaluated four multi-criteria decision making techniques proposed in the literature. These techniques are the Analytic Hierarchy Process (AHP), the Multi-Attribute Utility Theory (MAUT), the Cost Benefit Analysis (C/B), and the Kepner-Tregoe Decision Analysis (K-T), defined in Table 6.1.

Table 6.1 Decision Making Techniques

Technique	Description
MAUT	Combine dissimilar measures of costs, risks, and benefits, along with individual and stakeholder preferences, into high-level, aggregated preferences
C/B Ratio	Discounting benefits and costs to transform gains and losses occurring in different time periods into a common unit of measurement
K-T	Team of experts numerically scores criteria and alternatives based on individual judgments and assessments
AHP	Pairwise comparisons of alternatives based on their relative performance for each criterion

The analysis concluded that the AHP is a valuable tool for evaluating alternatives using multiple criteria while incorporating expert judgment. It facilitates complex decisions and makes them intuitive and rational. In addition, the AHP has the major advantage of allowing the decision maker to perform a consistency check for the provided judgment regarding its relative importance among the decision making elements. As a result, the decision maker(s) can revise their judgments to enhance the consistency and to provide more-informed judgments for the problem under consideration. The following sections discuss the AHP.

6.3 ANALYTIC HIERARCHY PROCESS (AHP)

The AHP is a general theory of measurements developed by Thomas Saaty (1980). It was initially used in solving problems for the Department of Defense in the United States and was then utilized in several fields including medicine, business, natural resource allocation and engineering. Recently, the ASTM International published ASTM E2495-07 as a standard practice which establishes an asset priority index based on the AHP. The index can be used for prioritizing asset resources in acquisition, utilization, and disposition using predefined criteria.

Two fundamental steps are required to use the AHP methodology. First, a complex system is broken into a hierarchic structure to represent the problem. Second, pairwise comparisons are performed to measure the relative impact of different elements in the hierarchy and to establish relations within the structure. The pairwise comparisons are performed using a fundamental scale of absolute values that represents the strength of judgments. The scale was developed and validated by Saaty (1980). The final step in the process is to synthesize judgments and determine the overall priorities of the variables and the criteria.

6.3.1 Modeling Fuzziness in the AHP

Saaty (1978) identified two types of fuzziness associated with objects or ideas. The first is fuzziness in perception caused by complexity of objects or ideas. The second is fuzziness in meaning since the meaning of objects is linked to what functions those objects can perform to fulfill different purposes. He then developed the AHP methodology to account for both types of fuzziness by measuring the fuzziness relativity. The relativity of fuzziness is evaluated by structuring the functions of a system hierarchically and generating the relative importance of the system attributes using pairwise comparisons and the eigenvector approach.

Laarhoven and Pedrycz (1983) and Buckley (1985) criticized the indirect fuzziness modeling in Saaty's AHP (1980). They proposed extended AHP algorithms that use fuzzy logic to represent the fuzziness directly. In the extended approach, fuzzy numbers are used to specify the relative importance of the elements in the reciprocal matrix.

Laarhoven and Pedrycz (1983) used triangular fuzzy numbers to represent the reciprocal matrix. The computation steps are similar to the AHP methodology proposed by Saaty (1980). However, the least square method is adopted and arithmetic operations for fuzzy triangular numbers are applied to estimate fuzzy weights and fuzzy performance scores.

Buckleys (1985) criticized Laarhoven and Pedrycz (1983), showing that the arithmetic operations on fuzzy numbers develop a system of linear equations which does not always have a unique solution. In addition, the arithmetic operations on triangular fuzzy numbers do not necessarily produce a triangular fuzzy number. Additional approximate methods must be applied to enforce the triangular fuzzy number shape required for these operations. Alternatively, Buckleys (1985) proposed the use of the geometric mean method to derive fuzzy weights and performance scores. This method guarantees a unique solution for the reciprocal comparison matrix. In addition, he used trapezoidal fuzzy numbers instead of triangular fuzzy numbers.

Using either triangular or trapezoidal fuzzy numbers to represent the relative importance among the different elements requires much more computational effort than the approach initially developed by Saaty (1980). Examples analyzed using both techniques have proven that the crisp utility can be as good as the fuzzy utility in terms of discriminating among alternatives (Chen and Hwang 1992). Further, Saaty (2006) referred to other authors who performed experiments on given data and concluded that the fuzzy sets may give poor results compared to other methods.

6.3.2 Proposed Modified AHP

The AHP accounts for the fuzziness in the decision making process by measuring the fuzziness relativity. The AHP uses deterministic numbers to define the relative importance of the different elements of the decision making problem.

Using deterministic numbers to define the relative importance between two elements with respect to a specific criterion can be a difficult task due to uncertainty in the behavior of the different elements under consideration. This conclusion was drawn while performing judgments to choose bridge deck rehabilitation strategy (Abu Dabous et al. 2007). For instance, unless comparing an element to itself, it is difficult to specify that two different elements have exactly equal importance when compared pairwise with respect to a specific criterion.

To account for the uncertainty associated with performing pairwise comparisons, a modified AHP methodology is developed in this research. This methodology incorporates statistical analysis within the AHP in order to model the uncertainty associated with the incomplete knowledge inherent in the decision making process. To perform this task, the intensities of the pairwise comparisons are defined using ranges of values and the Monte Carlo simulation technique is used to evaluate priorities and to check consistency. The proposed modified AHP is explained in the following two sections.

6.3.3 Scale of Relative Importance

The scale of relative importance proposed by Saaty (1980) defines the intensity of importance between two elements using deterministic numbers. If one element has a weak importance over another with respect to a specific criterion, the relative importance is 3 according to that scale. Alternatively, the proposed approach in this research uses a range. For weak importance, a range between 2.5 and 3.5 can represent the relative intensity between these two elements. A probability distribution for values within this range can be defined to represent the probability of each value within the range to be the intensity for the pariwise comparison. For example, 3 can be defined as the most likely value, 2.5 as the pessimistic value and 3.5 as the optimistic value for the intensity of the relative importance and a triangular distribution can be used to represent the distribution of the random variables within this range.

Table 6.2 presents a proposed range of values for the intensity of relative importance as an extension of the scale of relative importance developed by Saaty (1980). A default triangular probability distribution is used for values within each range. However, the decision maker can select an alternative distribution such as the normal or the log normal distribution.

The purpose of this approach is to account for the uncertainty in the value of relative importance between the compared elements while making judgments. The range of values reflects the decision maker's confidence regarding the value of the relative importance between the compared elements.

Table 6.2 Ranges for the Proposed Scale of Relative Importance

Definition	Description	Pessimistic	Most Likely	Optimistic
Equal importance	Two activities contribute equally to the objective	0.5	1	1.5
Weak importance of one over another	Experience and judgment slightly favour one activity over another	2.5	3	3.5
Essential or strong importance	Experience and judgment strongly favours one activity over another	4.5	5	5.5
Demonstrated importance	An activity is strongly favoured and its dominance demonstrated in practice	6.5	7	7.5
Absolute importance	The evidence favouring one activity over another is of the highest possible order of affirmation	8.5	9	9.5

6.3.4 Procedure for the Modified AHP

The procedure for the modified AHP to evaluate alternatives under conflicting criteria is summarized in the following steps:

1) Identify alternatives and decision criteria and decompose the problem into a hierarchy. Decision makers can choose a group of alternatives to evaluate. The best alternative is the one that meets most of the multiple criteria established by the decision maker.

Figure 6.1 shows a typical three-level hierarchy which is used as the default structure for the modified AHP. The first level represents the overall goal of the decision making process. The second level represents criteria that contribute to the overall goal. The third level represents the candidate alternatives to be evaluated using criteria from the second level.

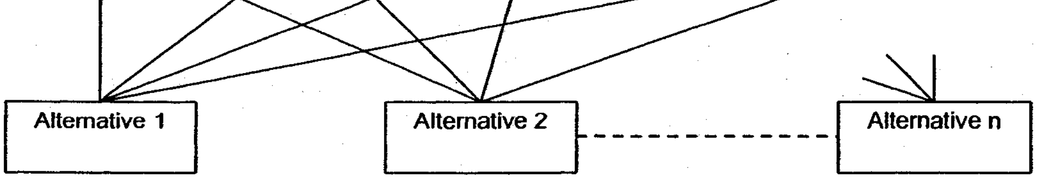


Figure 6.1 Hierarchy Structure for Problem Decomposition

2) Perform comparative judgments between the elements in the same level of the hierarchy structure using the scale of relative importance presented in Table 6.2. At the middle level, a matrix of comparison on the order of (m × m) is derived to define the relative preferences among the different criteria; m is the number of criteria used to evaluate the alternatives. This preference is elicited from the expert judgments regarding the relative importance of the criteria with respect to the overall goal. Criteria are compared in pairs by asking which one is considered more important and how much more important with respect to the overall goal. The scale of relative importance presented in Table 6.2 is used to give the range of values for each linguistic judgment expression. The range is presented as [p,m,o] where p is the pessimistic value, m is the most likely value and o is the optimistic value. Elements in the developed comparison matrix are reciprocal since these elements satisfy the following two conditions: 1) $[p_{ji},m_{ji},o_{ji}] = [1/o_{ij}, 1/m_{ij}, 1/p_{ij}]$ for all i and j; and 2) $a_{ii} = 1$ for all i.

At the bottom level, pairwise comparisons between the different alternatives with respect to each criterion are performed. For each criterion, a matrix on the order of (n × n) is developed to represent the relative preference of the different alternatives with respect to that particular criterion.

3) Use Monte Carlo simulation to evaluate vectors of priorities and to perform consistency check for each matrix developed in step 2.

The Monte Carlo simulation is used to analyze each matrix of comparison developed in step 2 by performing the calculation for several iterations. In each iteration, the simulation selects random values from the ranges defined for the relative importance among the various elements and uses the selected values to develop a reciprocal matrix. Once the reciprocal matrix is developed, a vector of priorities can then be estimated.

The vector of priorities is a normalized eigenvector. An exact normalized eigenvector requires a major computational effort. An alternative crude estimate can be used to yield an acceptable approximation for the priority vector and can be performed in two steps. First, the developed matrices are normalized. This is done by computing the sum of each column and dividing each element in a column by the sum of that column. Second, the average of each row is computed. The average value of each row represents the priority weight of the corresponding element or criterion. The vector of priorities holds the priority weight for each element.

Performing the simulation for n number of times, n eigenvectors are developed. The final vector of priorities is estimated as the average vector for the several eigenvectors developed from the simulation.

An important feature of the AHP is the ability to check for consistency in judgments. The process allows a certain extent of inconsistency in the pairwise comparisons. If all the comparisons are perfectly consistent, then $w_{ij} = w_{ik} \times w_{kj}$ should always be true for any combination of comparisons taken from the judgment matrices.

In each iteration of the simulation, a consistency check is performed by estimating the consistency index and the consistency ratio (CR). The detailed calculations of the consistency index and ratio are discussed in Chapter 4. A consistency ratio less than 10% is acceptable since it reflects an informed judgment about the problem under study that can be attributed to expert knowledge.

The simulation evaluates the frequency of having consistent matrices. The decision maker can specify the required frequency of having a CR less than 10% and can define a maximum value for the CR. For example, the decision maker can specify that 70% of the iterations must be consistent judgments with a CR less than 10% and can specify that the maximum CR must not exceed 20% for any iteration. If these limits are not achieved, the expert is required to revise the pairwise comparisons to improve the consistency.

4) Compute the overall weight of the different alternatives.

Lay out the weights for local priorities of each alternative with respect to each criterion. Multiply each weight by the corresponding criterion weight and add across each row to find the overall weight for each alternative.

The different alternatives are ranked according to their overall weights and the alternative with the highest overall weight is selected.

6.4 PROCEDURE FOR RANKING MR&R STRATEGIES

This section presents a procedure to rank MR&R strategies for bridge deck improvement projects. The procedure is based on the modified AHP discussed earlier. A default hierarchy structure is developed and incorporated within the procedure.

6.4.1 Structure of the Default Hierarchy

The default hierarchy structure consists of three levels. The first level is the overall goal of choosing a rehabilitation strategy. The second level represents the criteria that contribute to the overall goal, and the third level represents the candidate MR&R strategies to be evaluated. However, flexibility within the procedure is provided for the decision maker to use an alternative hierarchy structure.

6.4.2 Selection of Ranking Criteria

Analysis of the decision making process performed on the Jacques Cartier Bridge led to five primary decision criteria to be considered in choosing the most appropriate MR&R strategy. These criteria are agency cost, user cost, bridge safety, useful life and environmental impact.

Agency cost is the direct cost for the bridge improvement project, which includes material, labour and equipment costs. User cost is a major indirect cost component which can occur during bridge closure to perform the bridge improvement project. The user cost includes delay costs, increased vehicle operating costs and the cost of accidents that may happen during the projects.

Safety is a subjective criterion that reflects the safety of the bridge users and workers during the improvement project and traffic safety after its completion. The useful life reflects the estimated remaining service life of the bridge after performing the improvement project. The environmental impact is harm to the environment as a result of the improvement project. This harm can include any pollutant emitted into the air or drained into the soil or water surface during the bridge improvement project.

6.4.3 Selection of Rehabilitation Strategies

For each bridge that requires intervention, a number of maintenance and rehabilitation strategies are available. These strategies can range from routine maintenance to complete replacement. In interviews, engineers from Canadian transportation departments reported that a deteriorated bridge deck can be left in service until a major rehabilitation or replacement decision is made. In other words, do nothing is one viable option from the management point of view; however, bridge serviceability and safety should be considered. These interviews revealed that four classes of MR&R strategies are available for the decision makers:

1) Replacement of the component: This option improves the component to an excellent condition rating. It is normally performed when the component is in poor condition. Replacement provides the longest remaining life of a component but this option has the highest cost.

2) Major Rehabilitation: This option significantly improves the component's condition. Major rehabilitation is chosen if the component is in poor or fair condition and funds are not sufficient to replace the component. It is assumed that if a component is in poor condition, then a major rehabilitation would improve it to a good condition.

3) Minor Rehabilitation: This option marginally improves the component condition. It can improve the component condition from poor to fair or from fair to good. This option is most feasible when the component condition is fair and needs an upgrade to good.

4) Do Nothing: This option does not need any investment and is normally performed by routine cleaning of the deck and the drainage system. This option is associated with monitoring the component condition while keeping it in service until the time for a major repair or replacement.

Figure 6.2 presents a general three levels hierarchy to rank the discussed four MR&R strategies according to the selected set of criteria.

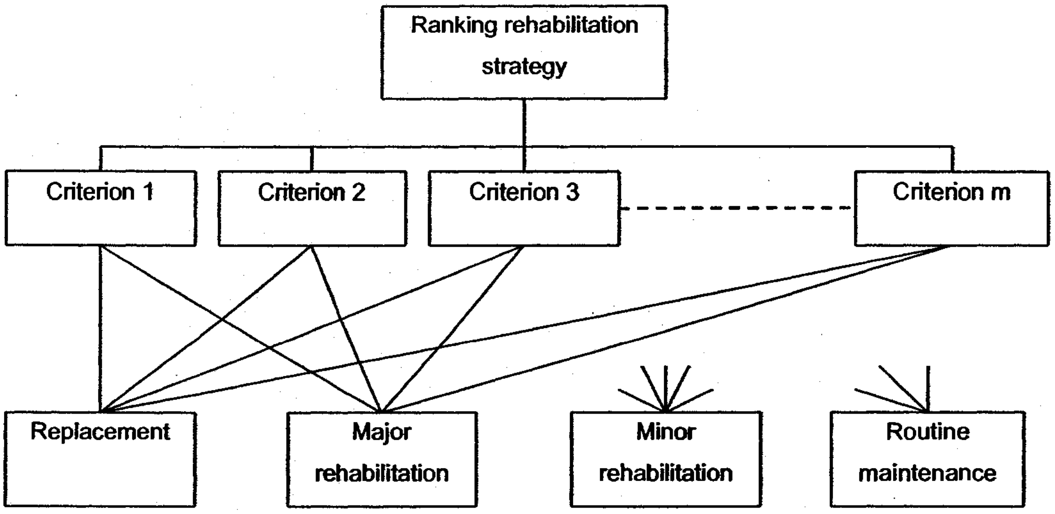


Figure 6.2 Hierarchy structure for choosing bridge deck rehabilitation strategy

6.4.4 Ranking procedure

This research develops a ranking procedure to choose an appropriate MR&R strategy for each bridge project. This procedure evaluates the four MR&R

strategies presented above or a subset of these four. In addition, the procedure provides flexibility in selecting the criteria to be used to evaluate the rehabilitation strategies. Figure 6.3 presents a flow chart of the proposed ranking procedure for MR&R strategies, which can be applied for each bridge that requires intervention.

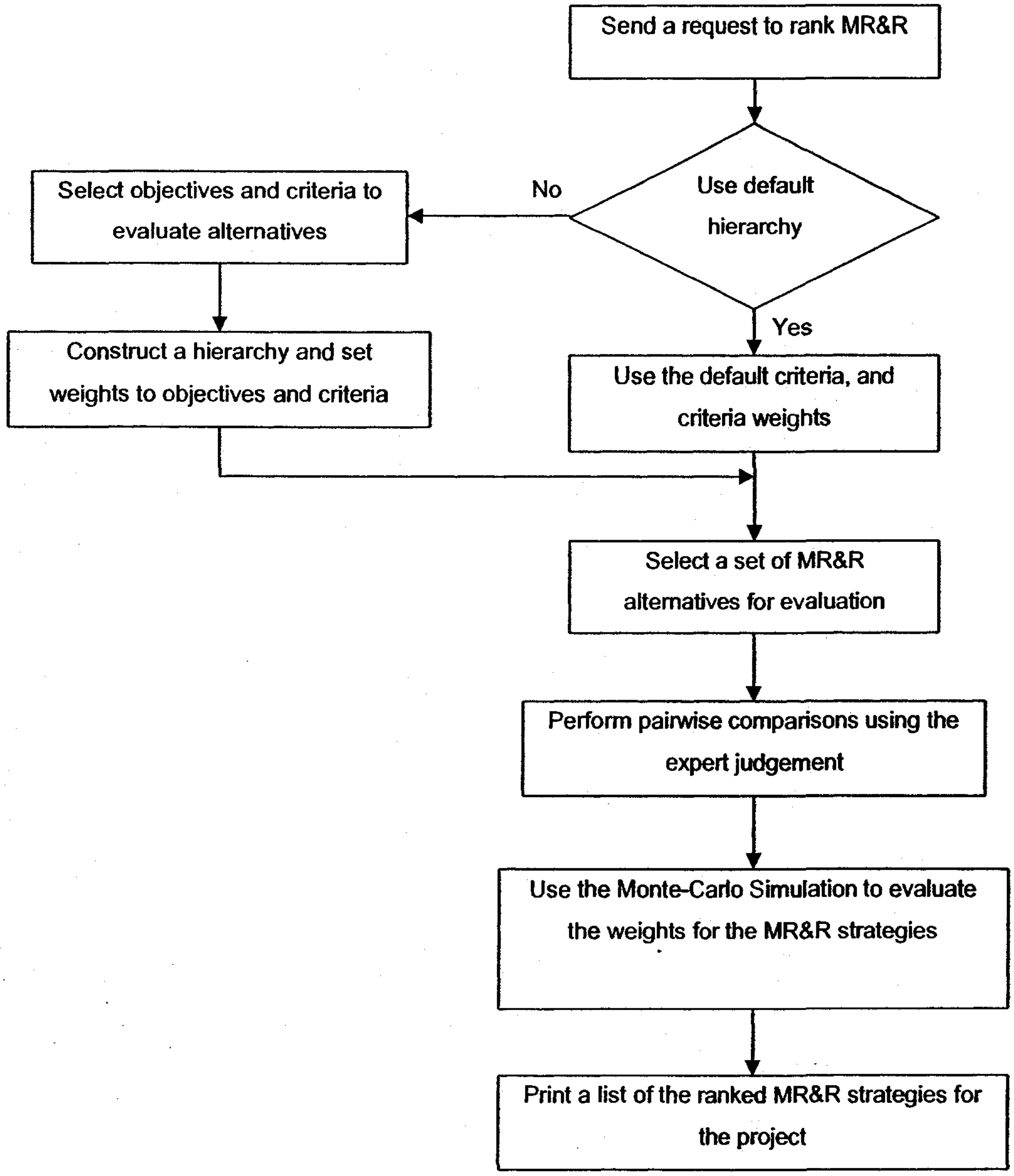


Figure 6.3 Flow Chart of the Proposed Ranking Procedure for MR&R Strategies

6.5 CASE STUDY

The Jacques Cartier Bridge's major rehabilitation project was selected as an actual case study to illustrate the practicality and to validate the output of the proposed method. This bridge measures 2.7 Km and spans the St. Lawrence River between Longueuil and Montreal, Canada. In 2001 and 2002, the bridge underwent a major rehabilitation project to reconstruct its 70-year-old deck.

The bridge condition was assessed and alternative rehabilitation strategies were analyzed and evaluated. Zaki and Mailhot (2003) reported that multiple criteria were considered in the decision making process for this major rehabilitation project, including: 1) inconvenience to users, 2) safety to users and workers, 3) the negative impacts to the environment, 4) the useful life of the bridge, and 5) completing the project in the least possible time. Based on the analysis, bridge deck replacement was found the most effective strategy.

To support the present research, the Jacques Cartier & Champlain Bridges Inc. provided a detailed report that was developed and used in the decision making process for reconstruction of the bridge deck. The project data is used to validate the proposed method by comparing the results obtained from it against the actual decisions made for the bridge.

The procedure for the modified AHP is applied to evaluate the alternative rehabilitation strategies that were available for the Jacques Cartier Bridge. The first step is decomposing the problem into a hierarchy structure. A three-level hierarchy structure similar to the one presented in Figure 6.2 is used, where the first level is the overall goal of the ranking exercise, the second level holds the evaluation criteria and the third level contains the available rehabilitation strategies. The evaluation criteria are the agency cost, the user cost, bridge safety, the bridge deck's useful life and the environmental impact of each rehabilitation strategy, while the available alternatives are replacement of the deck, major rehabilitation and minor rehabilitation.

The second step is to perform comparative judgments between the elements in each level of the hierarchy. Elements in each level are compared in pairs and intensities for the pairwise comparisons are assigned using the scale of relative importance provided in Table 6.2. To perform this step, an expert from the industry who was involved in the Jacques Cartier Bridge project was requested to provide the judgments. The expert was first required to compare five criteria in pairs with respect to the overall goal. Table 6.3 presents the intensities of the pairwise comparisons between the criteria.

Table 6.3 Comparison of Criteria with Respect to the Overall Goal

Criteria	Agency cost	User cost	Bridge safety	Useful life	Environmental impact	Vector of priorities
Agency Cost	1	[1.5,2,2.5]	[0.15,0.17,0.18]	[0.5,1,1.5]	[0.5,1,2]	0.13
User cost	[0.4,0.5,0.67]	1	[0.29,0.33,0.4]	[0.4,0.5,0.67]	[0.4,0.5,0.67]	0.09
Bridge Safety	[5.5,6,6.5]	[2.5,3,3.5]	1	[5.5,6,6.5]	[5.5,6,6.5]	0.53
Useful life	[0.5,1,1.5]	[1.5,2,2.5]	[0.15,0.17,0.18]	1	[0.5,1,1.5]	0.13
Enviro. Impact	[0.5,1,1.5]	[1.5,2,2.5]	[0.15,0.17,0.18]	[0.5,1,1.5]	1	0.12

For example, the expert anticipated that bridge safety has a demonstrated importance once it is compared with agency cost. As a result, it is most likely that bridge safety is 6 times more important than the agency's cost as shown in Table 6.3.

Then the expert was required to compare the alternative rehabilitation strategies in pairs with respect to each criterion. Table 6.4 presents the intensities of these pairwise comparisons.

Table 6.4 Comparison of Alternatives with Respect to each Criterion

	Agency Cost		
	Replace	Major	Minor
Replace	1	[0.29,0.33,0.4]	[0.15,0.17,0.18]
Major	[2.5,3,3.5]	1	[0.22,0.25,0.29]
Minor	[5.5,6,6.5]	[3.5,4,4.5]	1
	Average CR = 0.09		

	User Cost		
	Replace	Major	Minor
Replace	1	[0.22,0.25,0.29]	[0.15,0.17,0.18]
Major	[3.5,4,4.5]	1	[0.4,0.5,0.67]
Minor	[5.5,6,7]	[1.5,2,2.5]	1
	Average CR = 0.03		

	Environmental		
	Replace	Major	Minor
Replace	1	[1.5,2,2.5]	[3.5,4,4.5]
Major	[0.4,0.5,0.67]	1	[1.5,2,2.5]
Minor	[0.22,0.25,0.29]	[0.4,0.5,0.67]	1
	Average CR = 0.03		

	Bridge Safety		
	Replace	Major	Minor
Replace	1	[1.5,2,2.5]	[3.5,4,4.5]
Major	[0.4,0.5,0.67]	1	[1.5,2,2.5]
Minor	[0.22,0.25,0.29]	[0.4,0.5,0.67]	1
	Average CR = 0.03		

	Useful Life		
	Replace	Major	Minor
Replace	1	[2.5,3,3.5]	[7.5,8,8.5]
Major	[0.29,0.33,0.4]	1	[3.5,4,4.5]
Minor	[0.12,0.125,0.13]	[0.2,0.25,0.32]	1
	Average CR = 0.04		

The last step in the procedure is to use the Monte Carlo simulation to evaluate the vectors of priorities and to perform the consistency check. Performing the simulation for 1000 iterations, the average values for the vector of priorities and the consistency ratio for each matrix are estimated.

The vectors of priorities in Table 6.3 is developed using the simulation. From the many iterations, a probability distribution for the priority values is developed and the average priority value is estimated. This average value is the priority of the particular criterion. Taking the bridge safety criterion as an example, it has the highest average priority of 0.53. Figure 6.4 shows the probability distribution for the bridge safety criterion and the statistics associated with this criterion as estimated from the simulation.

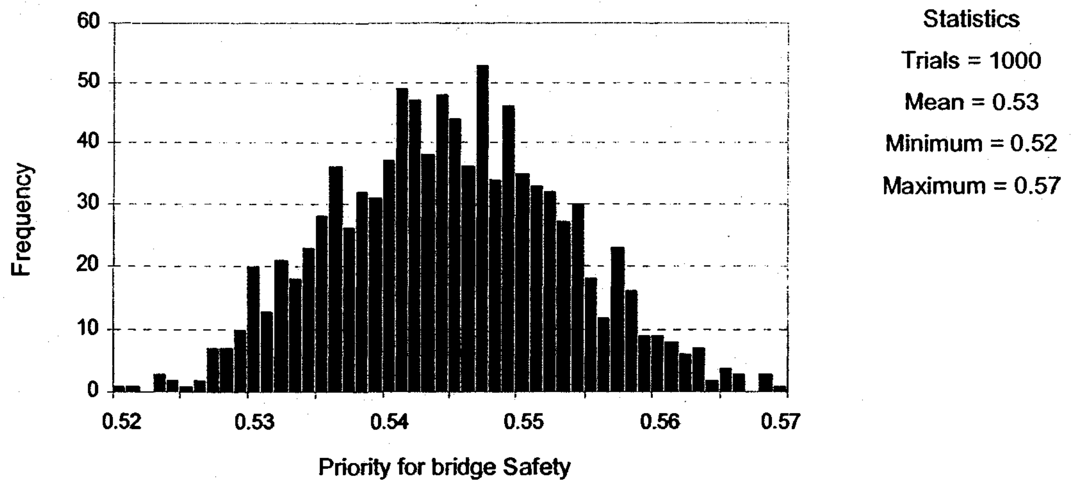


Figure 6.4 Priority for Bridge Safety Obtained from the Simulation

The same process is applied to evaluate the vector of priorities for each matrix in Table 6.4. For example, Figure 6.5 presents the priority for major rehabilitation when evaluated using the agency cost criterion. Similarly, the simulation is used to estimate the priorities for the replacement and the minor rehabilitation with respect to the agency cost criterion.

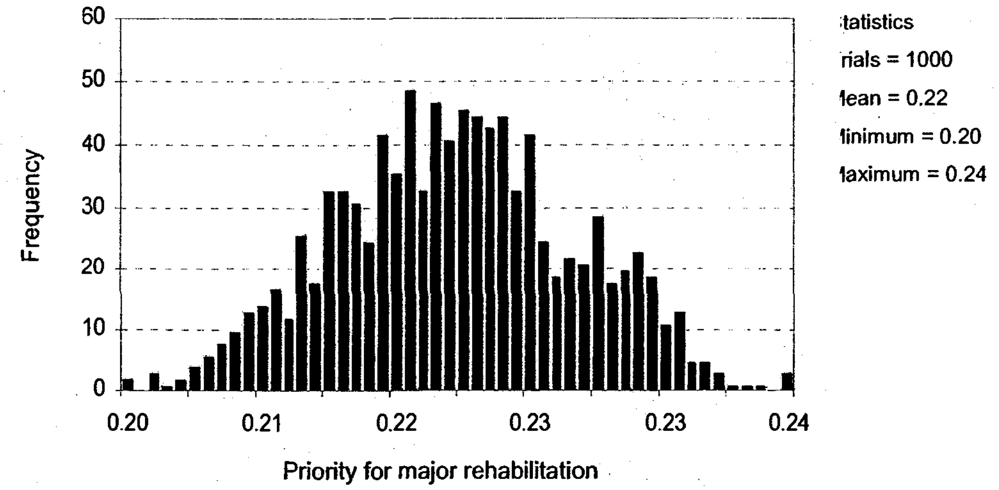


Figure 6.5 Priority for Major Rehabilitation with respect to the Agency Cost

The priorities for the rehabilitation strategies with respect to the different criteria can be estimated. Table 6.5 shows the priorities of the three rehabilitation strategies with respect to the five criteria. Each column in this table represents the vector of priorities for the three rehabilitation strategies with respect to each criterion under consideration.

Table 6.5 Priorities for the MR&R Strategies with respect to each Criterion

	Agency Cost	User Cost	Environmental	Bridge Safety	Useful Life
Replace	0.09	0.09	0.57	0.57	0.67
Major	0.22	0.33	0.29	0.29	0.26
Minor	0.68	0.58	0.15	0.14	0.07

To check for consistency, the simulation evaluates a mean value of the CR for each matrix in Tables 6.4 and 6.5. The mean values for the CR are less than 10%, which reflects an informed and consistent judgment in performing the pairwise comparisons. In addition, the simulation can evaluate the frequency of consistent judgments. For example, the frequency of having a CR less than 10% is 73.33% and the maximum CR from all the iterations is 17% for the judgments provided in Table 6.3. The sensitivity analysis from the simulation provides the decision maker with an improved evaluation of judgment consistency.

Finally, global priorities of the different rehabilitation strategies are estimated by multiplying the weights of the strategy with respect to each criterion by the criterion weight and finding the overall sum as follows:

Deck replacement = $0.09\times0.13 + 0.09\times0.09 + 0.57\times0.53 + 0.57\times0.13 + 0.67\times0.12 = 0.48$

Major rehabilitation = $0.22\times0.13 + 0.33\times0.09 + 0.29\times0.53 + 0.29\times0.13 + 0.26\times0.12 = 0.28$

Minor rehabilitation = $0.68\times0.13 + 0.58\times0.09 + 0.15\times0.53 + 0.14\times0.13 + 0.07\times0.12 = 0.24$

The analysis prefers bridge deck replacement and gives approximately the same weight for major and minor rehabilitation. The results obtained from the decision method agree with the decision to replace the bridge deck which was undertaken in 2001. The proposed method quantifies the priority of each alternative which provides the decision maker with the required insight on the available alternatives.

6.6 SUMMARY

A review of bridge management decision making regarding maintenance and rehabilitation is presented and the multiple-criteria nature of such a problem is discussed. Sound decision making requires including multiple and conflicting criteria in the process. The AHP is analyzed and a modified AHP is developed. The modified AHP accounts for the uncertainty associated with the values representing the intensity of the relative importance. In addition, the modified AHP produces a sensitive evaluation of the consistency in judgments. A bridge deck decision support method based on the modified AHP is proposed. A real case study is used to validate the developed decision support method. The analysis of the case study shows that the developed decision support method evaluates the available MR&R alternatives and produces valid decisions regarding choosing an alternative for bridge deck improvement projects. The weights for the rehabilitation strategies estimated using the decision support method are important inputs to develop a work program for bridge network. Chapter 7 discusses the development of a recommended work program.

CHAPTER 7: WORK PROGRAM DEVELOPMENT

7.1 INTRODUCTION

The presented research has developed quantitative and analytical methods that can be used in bridge deck rehabilitation management. These methods are for bridge condition assessment and deterioration modeling, project ranking and prioritizing, and evaluation and selection of alternative MR&R strategies.

The condition assessment and the deterioration methods define the current and forecast the future conditions of bridges in a network. The decision maker can define a specific condition rating as the intervention level. Once a bridge deck reaches the intervention level, it needs improvement. All projects which have reached or will reach the intervention level at a specific point of time in the future can be retrieved from the database. These projects can be ranked and prioritized using the method developed in Chapter 5. For each project, the available rehabilitation strategies are evaluated and each strategy is assigned a weight. The assessment includes the direct cost and the indirect impact of each rehabilitation strategy.

The purpose of this chapter is to discuss a technique to develop a recommended work program under the constraint of a limited budget. The technique uses the outputs of the different methods presented in Chapters 4, 5, and 6 to allocate the limited budget to the most deserving projects.

7.2 RECOMMENDED WORK PROGRAM

If transportation agencies had unlimited budgets, bridge networks could be maintained at an excellent condition. However, transportation agencies have limited budgets available for bridge improvement projects. In addition, it has become obvious that these agencies have to deal with an increasing number of deficient bridges which will require intervention in the near future. This will make the challenge of managing bridges even more difficult.

The limited budget availability and the high cost of MR&R actions require rational justification of budget allocation decisions. Rational justification can be attained through specific techniques to develop a recommended work program which maximizes benefits to the users and the agency.

One of the most challenging tasks for bridge managers and decision makers is to select a work program to be performed when the available budget is limited. The purpose of this work program is to recommend a list of projects for improvement and to specify which MR&R action to be performed for each project. The selection of the projects and the actions must aim to maximize the benefits to users and the network.

Defining a set of rehabilitation strategies to be considered and estimating their costs are essential steps in the development of a recommended work program. The following two sections describe the available rehabilitation strategies for the decision maker and develop estimates for their costs. These strategies and their costs will be included within the framework of the developed decision support system. However, flexibility to incorporate additional strategies and to specify the costs must be provided for the decision makers.

7.3 REHABILITATION STRATEGIES

As discussed in Chapter 6, a number of maintenance and rehabilitation strategies are available for the bridge deck once it reaches the intervention level. These strategies can range from do-nothing to complete replacement. Two engineers involve in the decision making process explained that it is common to leave a deteriorated bridge deck in service until a major repair or replacement decision is made. This means that the do-nothing option is available even for deteriorated bridge decks. However, this decision must be associated with increased monitoring and increased routine maintenance, such as cleaning and patching of the bridge deck.

From the available rehabilitation strategies three main actions are included within the framework of the decision support system. These actions are:

1) Replacement: This strategy is normally performed when the component is in poor condition. Replacement provides the longest remaining life for the deck but the cost of this option is the highest.

2) Major Repair: This strategy is chosen if the component is in poor or fair condition and funds are not sufficient to replace it. The major repair option would improve the element to good or excellent condition.

3) Increased Routine Maintenance: This option does not improve the component condition. It is intended to increase the monitoring of the element condition to

ensure safety. In addition, it prevents the deck from exceeding the intervention level in order to keep it in service until the time of major repair or replacement.

The cost of each action must be estimated, since that will be needed to estimate an overall cost for the developed work program. This is important to ensure that the overall cost of the recommended work program does not exceed the available budget. The following section discusses the development of cost models for the MR&R actions.

7.4 COST ESTIMATES FOR REHABILITATION ACTIONS

This research targets the development of a cost model to be integrated within the developed framework of the decision support system. The cost model is developed based on data and information collected from a Ministry of Transportation in Canada. Personnel interviews with two cost engineers from the ministry were conducted to develop a work breakdown structure and to extract the relevant cost data.

The data and information collected are for two rehabilitation actions which are bridge deck replacement and bridge deck major repair. The work breakdown structures developed during the interviews use elements standardized by the ministry for bidding purposes on rehabilitation projects. The cost of each element is extracted from the ministry database. The following sections discuss the development of cost models for bridge improvement projects.

7.4.1 Bridge Deck Replacement

Bridge deck replacement provides a brand new deck with the longest useful life. This option is normally performed by replacing the superstructure of the bridge. In concrete bridges, a bridge deck is integral with the girders which makes it difficult to remove the deck slab while keeping the girders in place. Hence, deck replacement typically includes replacing the girders which provides a new superstructure for the bridge. This is a major improvement with a relatively high cost.

The cost of replacing the bridge deck depends on the type of the new superstructure to be constructed and the area of the deck. Saito et al. (1988) reported that the unit superstructure cost can be estimated in terms of dollar per square unit of deck area. The cost model for deck replacement developed in this research is based on estimating the total cost for the new superstructure, including the deck, and then dividing this cost by the deck area. This procedure will estimate a replacement cost per unit area of the deck.

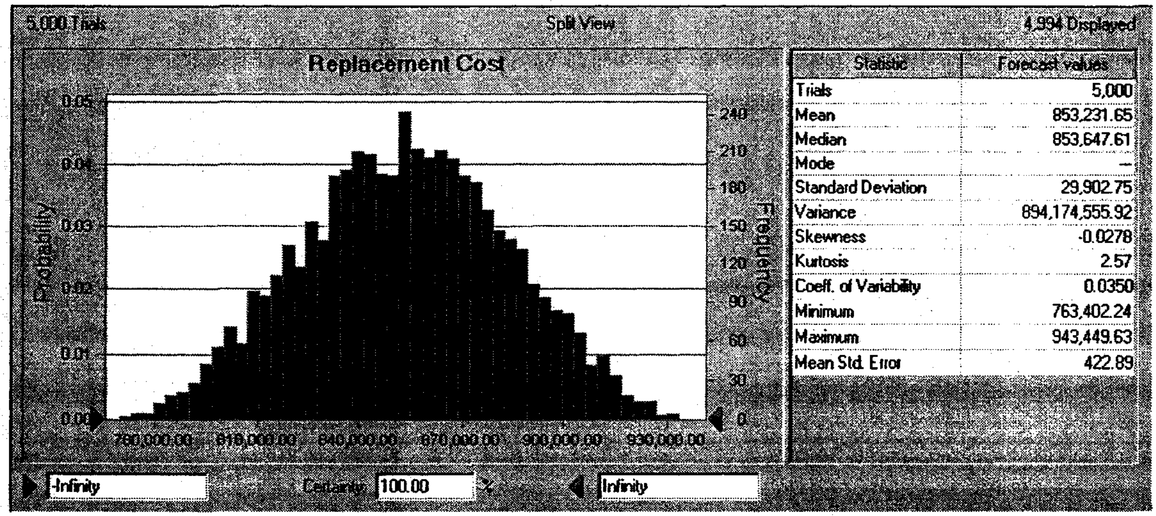
The superstructure type is defined according to the slab and girders configuration. The most common arrangement is pre-stressed girders with a composite concrete slab on top. Interviews with bridge engineers targeted the development of a work breakdown structure for this type of arrangement and collected cost data for all the elements included in the structure.

Table 7.1 presents the work breakdown structure and the cost elements for bridge deck replacement. The total deck area is 930 m^2 and the superstructure arrangement is 150 mm thickness concrete slab on pre-stressed concrete girders. The cost data presented in the table includes both direct and indirect cost elements in addition to the overhead. This is because the ministry database is developed using bidding cost data provided in bid proposals submitted by the contractors performing projects for the ministry. The cost data is in Canadian dollars, adjusted for inflation and based on the 2008 dollar value.

Table 7.1 Cost Elements for Bridge Deck Replacement

Item	Item Description	Unit	Quantity	Unit Cost
A.1	Removal of asphalt wearing surface	m^2	830	$6
A.2	Removal railing	LS	1	$3,000
A.3	Removal of concrete end posts	LS	1	$7,500
A.4	Removal of existing deck including curbs	m^3	270	$525
A.5	Removal of top of pier	m^3	6	$1,500
A.6	Removal of existing approach slab	m^3	51	$150
B.1	Granular backfill	m^3	75	$60
B.2	Concrete in new top of existing piers	m^3	10	$750
B.3	Prestressed members (Fabr.&Erect.)	m	505	$900
B.4	Concrete in barrier wall	m^3	12	$1,275
B.5	Concrete in deck (150 mm topping)	m^3	100	$675
B.6	Concrete in new deck extensions	m^3	12	$900
B.7	Concrete in approach slabs	m^3	50	$375
B.8	Stainless steel rebar in barrier wall	tonne	1.6	$15,000
B.9	Coated rebars in deck topping	tonne	9	$2,250
B.10	Rebars in deck extensions	tonne	0.6	$1,500
B.11	Rebars in approach slabs	tonne	1	$1,500
B.12	Bearings	each	84	$165
B.13	Abutment Repairs	m^3	2	$6,000
B.14	Bridge deck waterproofing	m^2	650	$18
B.15	Asphalt	tonne	180	$90

The contingency associated with the cost elements is 15%, as specified and used by the Ministry. In this research, the Monte Carlo simulation technique is used to estimate the cost for a bridge deck replacement, while including the contingency in each element cost. The statistics obtained from the simulation are shown in Figure 7.1. The cost estimate mean value is \$853,231 and estimate can be between \$763,402 and \$943,449. The unit replacement cost is estimated by dividing the cost mean value by the 930 m^2 deck area which yields \$917.50 per square meter.



Statistic	Forecast values
Trials	5,000
Mean	853,231.65
Median	853,647.61
Mode	---
Standard Deviation	29,902.75
Variance	894,174,555.92
Skewness	-0.0278
Kurtosis	2.57
Coeff. of Variability	0.0350
Minimum	763,402.24
Maximum	943,449.63
Mean Std. Error	422.89

Figure 7.1 Simulation Results for the Deck Replacement Cost Estimate

7.4.2 Bridge Deck Major Repair

Major repair can improve the deck to an excellent condition state. This option is performed by repairing the deck surface and installing a cathodic protection system. It involves the removal of the delaminated concrete from the deck surface and soffit and patch repair of the removal areas. A titanium mesh anode embedded in a normal concrete overlay will be installed to ensure cathodic protection of the reinforcing steel in the deck. This system is recommended since the overlay will allow the placing of waterproofing to prevent the ingress of water and deicing salts into the concrete.

The work breakdown structure for this option is developed by interviewing the cost engineers and analyzing previous projects. The cost data are extracted from the Ministry of Transportation database. The total cost is estimated and linked to the bridge deck area in order to evaluate the cost per square meter for this option. Table 7.2 presents the work breakdown structure for the major repair and the cost associated with each item in the structure. The cost includes both direct and indirect cost elements. As before, the cost data are in Canadian dollars based on the 2008 value.

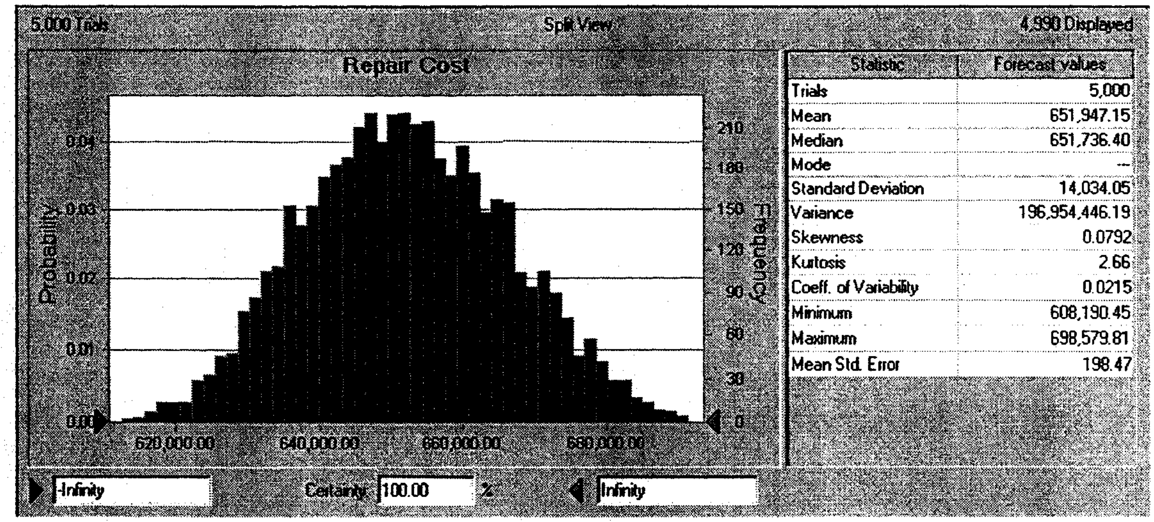
Table 7.2 Cost Elements for Bridge Deck Major Repair

Item	Item Description	Unit	Quantity	Unit Cost
C.1	Removal of asphalt wearing surface	m^2	830	6
C.2	Removal of railings	LS	1	3,000
C.3	Removal of concrete end posts	LS	1	7,500
C.4	Removal of concrete curbs	m^3	20	525
C.5	Type A removals from top of deck	m^2	300	285
C.6	Access to work area	LS	1	7,500
C.7	Type B removals from deck soffit	m^3	2	6,000
C.8	Type C removals from fascia	m^3	5	4,500
C.9	Type C removals from deck ends	m^3	1	15,000
C.10	Removal of existing approach slab	m^3	51	150

Table 7.2 (continue) Cost Elements for Bridge Deck Major Repair

Item	Item Description	Unit	Quantity	Unit Cost
D.1	Granular backfill	m^3	75	60
D.2	Scarify deck surface	m^2	625	17
D.3	Cathodic protection	m^2	625	300
D.4	Abrasive blast cleaning of rebar	m^2	300	82
D.5	Abrasive blast cleaning for overlays	m^2	325	26
D.6	Concrete overlay (Includes padding for	m^3	100	638
D.7	Finish and cure overlay	m^2	625	38
D.8	Concrete barrier wall	m^3	12	1,275
D.9	Concrete in new deck extensions	m^3	12	900
D.10	Concrete in approach slabs	m^3	50	375
D.11	Stainless steel rebar (barrier wall & deck)	tonne	2.2	15,000
D.12	Coated rebar for overlay padding area	tonne	4	2,250
D.13	Rebars in deck extensions	tonne	0.6	1,500
D.14	Rebars in approach slabs	tonne	1	1,500
D.15	Abutment Repairs	m^3	2	6,000
D.16	Deck soffit repairs	m^3	4	6,000
D.17	Bridge deck waterproofing	m^2	650	18
D.18	Asphalt	tonne	180	90

The Monte Carlo simulation is used to estimate the major repair cost while taking the 15% contingency into account. The statistics obtained from the simulation are shown in Figure 7.2. The mean value for the total cost is $651,947 and the cost can range between $608,190 and $698,580. The unit cost for the major repair is $701 per square meter.



Statistic	Forecast values
Trials	5,000
Mean	651,947.15
Median	651,736.40
Mode	---
Standard Deviation	14,034.05
Variance	196,954,446.19
Skewness	0.0792
Kurtosis	2.66
Coeff. of Variability	0.0215
Minimum	608,190.45
Maximum	698,579.81
Mean Std. Error	198.47

-Infinity

Certainty: 100.00 %

Infinity

Figure 7.2 Simulation Results for the Deck Major Repair Cost Estimate

7.4.3 Bridge Deck Maintenance Cost

The maintenance option does not involve any improvements to the condition or the structural aspects of the bridge deck. The maintenance activities include patching, sealing cracks or eliminating visible distresses which can accelerate the corrosion of the deck reinforcement. The maintenance cost depends on the condition of the bridge. The available studies report that annual maintenance costs can range from 1% to 2% of the reconstruction cost (Wicke 1988, Lindbladh 1990, Van der Toorn and Reji 1990, Branco and de Brito 2004).

De Brito and Branco (1998) developed a graphical representation for maintenance cost in relation to the bridge deck area. They described a linear relationship between the deck area and the maintenance cost. In addition, they specified that the maintenance cost for a 4000 m^2 deck is double the maintenance cost for a 400 m^2 deck and that the maintenance cost for a 400 m^2 deck is double the maintenance cost for a 100 m^2 deck. The maintenance cost in this linear relationship may be obtained either by statistical analysis or it may be developed based on experience. Branco and de Brito (2004) further discussed that in the long term, the relationship between annual maintenance for each bridge and the initial costs is approximately the same for all network structures.

Following these principles, the maintenance cost for a bridge deck is determined to be 5% of the reconstruction cost. This is higher than the routine maintenance cost since the bridges under consideration are those that have reached the intervention level and thus require increased attention. The decision maker can adjust this value and specify an alternative percentage for the maintenance cost which can be higher or lower than 5%.

The unit replacement cost is $917.50 per square meter as estimated in Section 7.3.1 for the 930 m^2 area deck. The unit maintenance cost for the same deck is 5% of $917.50 or $45.90 per square meter. Using this value as the unit cost for the 930 m^2 area and applying the linear relation suggested by Branco and de Brito (2004), the linear representation for the maintenance cost is developed as shown in Figure 7.3. From this representation, the unit cost for a 400 m^2 deck is $40 per square meter and for a 4000 m^2 deck it is $80 per square meter.

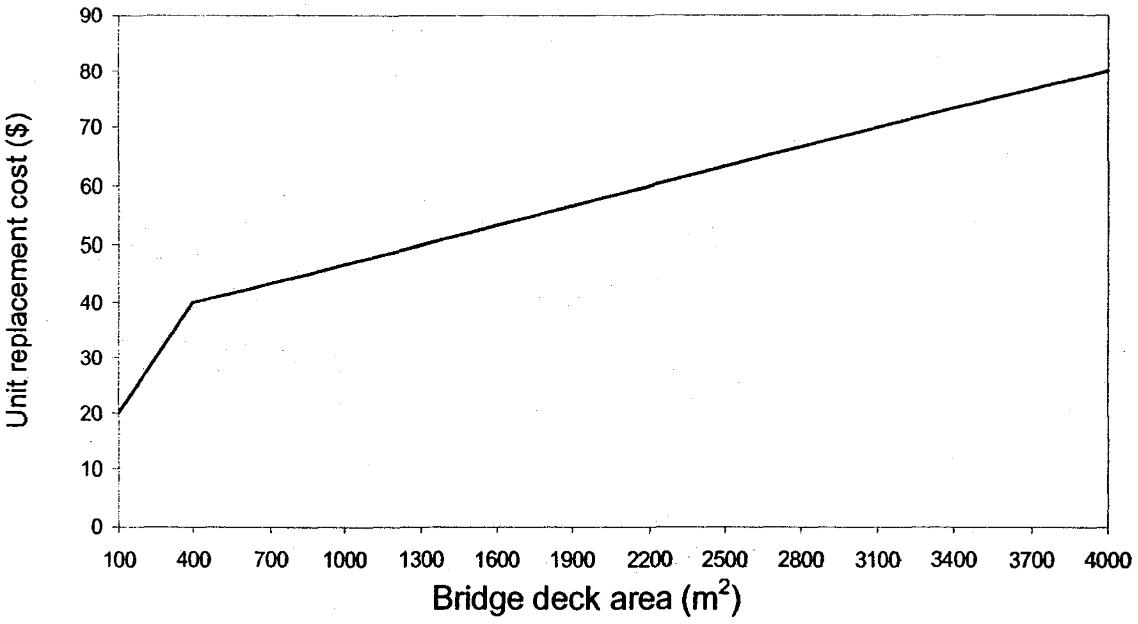


Figure 7.3 Model for Predicting the Bridge Deck Maintenance Cost (De Brito and Branco 1998)

Using this graphical representation, the unit maintenance cost for any bridge deck can be estimated.

7.5 WORK PROGRAM DEVELOPMENT USING SIMULATION

As discussed earlier, a recommended work program specifies which bridge projects to be included in the program and what action to be selected for each project. The recommended work program is developed to maximize benefits to the agency and the users within the available budget.

The recommended work program is developed by evaluating the various combinations of the different projects and the available rehabilitation strategies. The problem under consideration is difficult to analyze manually since a large number of combinations can be developed and considered for evaluation. Bridge networks normally consist of several thousand bridges and at least two or three rehabilitation strategies are available for each bridge that requires intervention. In certain cases, there can be up to five alternative strategies ranging from the do nothing option to complete replacement of the element.

Simulation is an extremely useful tool with which to perform a large number of “what if scenarios”, and it can be used to develop the various possible combinations between bridge projects and the available MR&R strategies. Each combination is a candidate recommended work program. The total cost of any candidate work program must be within the available budget.

A set of criteria can be defined in order to compare two candidate work programs. The simulation develops the first candidate work program and assigns it to be the current best. Then it develops the second work program and compares it with the first using the defined criterion. If the first candidate work program is better than the second one, the first remains the current best, while if the second one is better, it then becomes the current best. The procedure develops a third candidate work program and compares it with the current best. This process continues until all the possible candidate work programs have been compared. The final current best is the recommended work program.

The ranking method presented in Chapter 5 ranks and prioritizes projects based on the overall goal of efficient, effective and equitable allocation of the available funds. Projects in a network are included in the recommended work program based on the priority assigned for each one from the ranking method. In other words, the bridge with the highest priority is included first in the work program, followed by the bridge with the second highest priority, and so on.

In Chapter 6, a method for selecting a rehabilitation strategy for each bridge project is developed. The method assigns a weight for each of the available rehabilitation options. The weight for each option is developed based on the degree that each option satisfies certain multiple criteria defined by the decision maker. The simulation uses these weights as the selection criterion to compare the different candidate work programs. For example, if the weight for replacement is 0.40, the weight for repair is 0.35 and the weight for maintenance is 0.25 and the available budget is sufficient to apply only two of these options on two different projects, the optional selection will be to perform a replacement on one project and repair for the other, since this will produce the maximum sum of weights of 0.75. For instance, a candidate work program which recommends replacement on one project and maintenance for the other will produce a sum of weights of 0.65 which is less than 0.75. The maximum sum of weights is expected to produce the maximum benefits. As a result, the recommended work program is replacing one and repairing one.

The following is a description of the first three iterations of the simulation process. These iterations are intended to explain how a work program can be developed.

- In the first iteration of the simulation, one project is considered. The selected project is the one with the highest priority. The priorities are estimated using the project ranking method (Chapter 5). For each project, the candidate work programs are the available rehabilitation actions: replacement, repair or maintenance of the deck. The cost of each work program is estimated. If the available budget is sufficient to perform any of these three alternatives, the one that has the highest weight is selected as the current recommended work program. The weight of each option is estimated using the rehabilitation strategy selection method (Chapter 6).

- The second iteration of the simulation considers two projects, which have the highest and the second highest priority. The available three MR&R options can be performed for each project. However, only one option must be selected for each project. In this case, nine candidate work programs can be developed for evaluation. These work programs are: (replace1 and replace2), (replace1 and repair2), (replace1 and maintain2), (repair1 and replace2), (repair1 and repair2), (repair1 and maintain2), (maintain1 and replace2), (maintain1 and repair2), or (maintain1 and maintain2). If the available budget is enough to perform any of these nine programs, the combination with the highest sum of weights for their rehabilitation options is selected to become the current recommended work program and to replace the current work program from the previous iteration. If the estimated cost for each of the nine candidate work programs developed in this iteration exceeds the available budget, the process stops and the current work program from the previous iteration is the recommended work program. Also, it is possible that a subset of the nine candidate work program can be performed within the available budget. For example, assume three candidate work programs each have a cost equal to or less than the available budget. In this case, the one of the three with the highest sum of weights for its rehabilitation options becomes the current best.

- The third iteration will include the three highest priority projects and can have twenty seven candidate work programs. If the available budget is sufficient to perform any of these programs, the program with the highest sum of weights for its rehabilitation options is selected to become the current recommended work program.

The process continues until a recommended work program that includes projects with the highest priority and maximum weight of the available rehabilitation options is developed. This program is identified as the recommended work program.

Further, the decision maker can retrieve more than the work program for further evaluation. For example, the decision maker can retrieve the three best work programs developed during the simulation. These three programs can be considered for a second round of evaluation to select a recommended work program based on particular criterion specified by the decision maker. One approach is by selecting the work program that will produce the maximum improvement for the network. A technique to quantify the improvement gained from each improvement program is described in the following section.

7.6 NETWORK HEALTH INDEX

Marshall et al. (1999) reported that it is critical for a bridge management system to allow for moving projects from one scenario to another in order to build a program that represents the agency's current plan. One approach that provides decision makers with this flexibility is quantifying the improvement on a bridge network gained from implementing a recommended work program. This can help the decision maker to estimate the overall improvement to the network condition achieved by implementing a specific work program and to decide if the available budget can achieve the agency's current plan.

A health index (HI) concept was developed by the California Department of Transportation (Caltrans) and is discussed in Roberts and Shepard (2000). Inspired by the HI concept, a network health index is developed in this research to quantify the improvement attained from implementing a recommended work program.

The network health index provides an overall representation for the condition of a specific element in a network or sub-network. This index is an average of the health indices of all the same-type elements. For example, the health index for a network or a sub-network can be estimated by assigning a health index for each deck based on its condition rating, and then estimating the average value of the indices for all the deck elements in the sub-network. The condition of each bridge deck can be evaluated using the element-level condition rating method discussed in Chapter 4. The health index value for each element is defined using the element's condition rating. The index is 90, 70, 45, and 15 for Excellent, Good, Fair and Poor condition states, respectively. The values of these indices are selected to be consistent with the element remaining values developed in Chapter 4.

The amount of improvement to the sub-network health index value can be used to compare the candidate recommended work programs. The technique is based on estimating a percentage improvement of the health index attained from each work program. This percentage can be calculated by estimating the current health index and the health index after implementing the recommended work program. The percentage improvement to the health index provides an evaluation of the effectiveness of the recommended work program under consideration. The work program that provides the maximum improvement to the network health index is the one selected.

Once the condition rating process is performed, the appropriate health index is assigned for each bridge deck and the average value is estimated to represent the network health index. Knowing the current network health index and the network health index after implementing the recommended work program, the percentage change in the health index gained from the recommended work program can be evaluated to quantify the improvement thus attained.

The process is repeated for each of the work programs. The work program with the highest percentage of improvement is selected for implementation.

7.7 ILLUSTRATIVE EXAMPLE

To illustrate the development of a recommended work program, the following example is presented, using the case study discussed in Chapter 5. The three bridges with the highest rank from the case study are considered since they have the highest utility and must be prioritized for intervention. The cost of the three rehabilitation strategies for each project is estimated from the cost models developed in Section 7.3. These costs are shown in Table 7.3.

Table7.3 Rehabilitation Strategy Costs for the Three Top-Ranked Bridges

Bridge	Deck area (m^2)	Replacement cost ($)	Repair cost ($)	Maintenance cost ($)
Bridge 70	1,250	1,146,875	876,250	61,806
Bridge 40	1,100	1,009,250	771,100	52,556
Bridge 30	950	871,625	665,920	39,583

The decision maker provides specific judgments for each bridge to evaluate the different rehabilitation actions and to develop a weight for each option as discussed in Chapter 6. The weights for the rehabilitation actions are provided in Table 7.4.

Table7.4 Weighted Priorities for the Rehabilitation Strategies

Bridge	Replacement	Repair	Maintenance
Bridge 70	0.45	0.30	0.25
Bridge 40	0.35	0.35	0.30
Bridge 30	0.60	0.32	0.08

The 27 possible work programs are developed from all the possible combinations of projects and rehabilitation strategies as shown in Table 7.5. These are the candidate work programs. One of these programs must be selected as a recommended work program. The recommended work program's cost must not exceed the available budget and it should maximize benefits to the network and to the users.

The total cost in Table 7.5 is estimated by finding the sum for the cost of all the rehabilitation actions associated with each program. The cost of each action is provided in Table 7.3. Similarly, the total weight is estimated by finding the sum for the weights of all the rehabilitation strategies involved in the program. The priority for each action is given in Table 7.4.

Assuming that the available budget is $2.10 million, work programs that cost more than the available budget are not possible, which means that work programs 2, 3, 5, 6, 11, 12, 14, and 15 must be eliminated.

Work program 9 has the highest total weight of 1.35 and a total cost of $2,071,056, and work program 18 has the second highest weight of 1.20 and a total cost of 1,800,431. The decision makers must compare these two work programs. One has a higher cost but will produce more network improvement. It is recommended to select the work program .that will produce the greatest improvement to the sub-network, provided that the cost is within the available budget.

Table 7.5 Candidate Work Programs

Program	Action 1	Action 2	Action 3	Total cost	Total weight
Program 1	Replace 70	Repair 40	Maintain 30	1,957,558	0.88
Program 2	Replace 70	Repair 40	Repair 30	2,583,895	1.12
Program 3	Replace 70	Repair 40	Replace 30	2,789,600	1.4
Program 4	Replace 70	Replace 40	Maintain 30	2,195,708	0.88
Program 5	Replace 70	Replace 40	Repair 30	2,822,045	1.12
Program 6	Replace 70	Replace 40	Replace 30	3,027,750	1.4
Program 7	Replace 70	Maintain 40	Maintain 30	1,239,014	0.83
Program 8	Replace 70	Maintain 40	Repair 30	1,865,351	1.07
Program 9	**Replace 70**	**Maintain 40**	**Replace 30**	**2,071,056**	**1.35**
Program 10	Repair 70	Repair 40	Maintain 30	1,686,933	0.73
Program 11	Repair 70	Repair 40	Repair 30	2,313,270	0.97
Program 12	Repair 70	Repair 40	Replace 30	2,518,975	1.25
Program 13	Repair 70	Replace 40	Maintain 30	1,925,083	0.73
Program 14	Repair 70	Replace 40	Repair 30	2,551,420	0.97
Program 15	Repair 70	Replace 40	Replace 30	2,757,125	1.25
Program 16	Repair 70	Maintain 40	Maintain 30	968,389	0.68
Program 17	Repair 70	Maintain 40	Repair 30	1,594,726	0.92
Program 18	**Repair 70**	**Maintain 40**	**Replace 30**	**1,800,431**	**1.2**
Program 19	Maintain 70	Repair 40	Maintain 30	872,489	0.68
Program 20	Maintain 70	Repair 40	Repair 30	1,498,826	0.92
Program 21	Maintain 70	Repair 40	Replace 30	1,704,531	1.2
Program 22	Maintain 70	Replace 40	Maintain 30	1,110,639	0.68
Program 23	Maintain 70	Replace 40	Repair 30	1,736,976	0.92
Program 24	Maintain 70	Replace 40	Replace 30	1,942,681	1.2
Program 25	Maintain 70	Maintain 40	Maintain 30	153,945	0.63
Program 26	Maintain 70	Maintain 40	Repair 30	780,282	0.87
Program 27	Maintain 70	Maintain 40	Replace 30	985,987	1.15

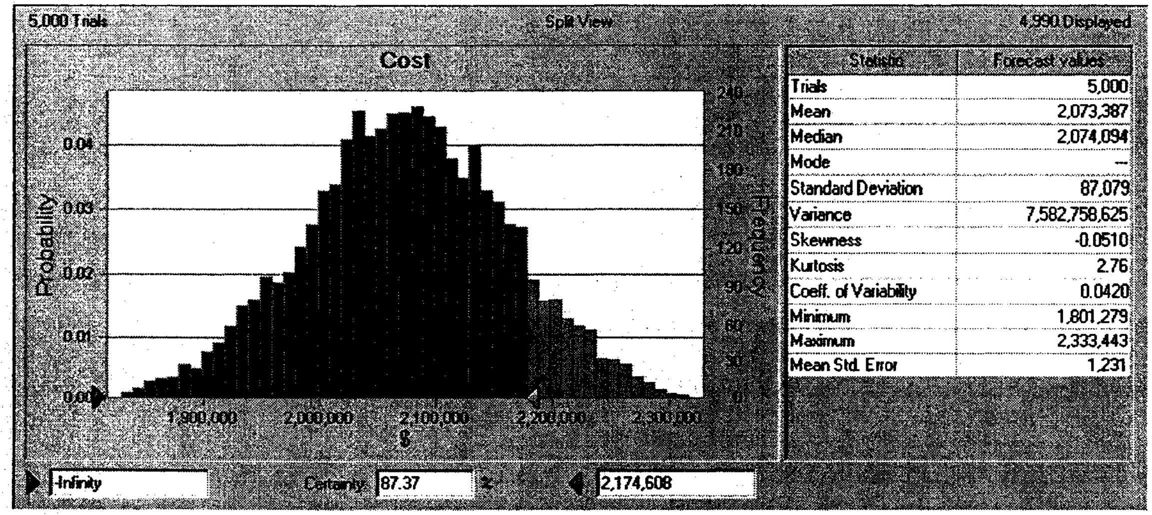
The current health index and the health index after implementing the work program on the sub-network of the three bridges can be estimated, as shown in Table 7.6.

Table 7.6 Improvement to the Health Index Attained From the Work Programs

Current health index			**Health index after work program 9**			**Health index after work program 18**		
Bridge	Rating	Index	Bridge	Rating	Index	Bridge	Rating	Index
10	Good	70	10	Good	70	10	Good	70
20	Good	70	20	Good	70	20	Good	70
30	Fair	45	30	Excellent	90	30	Excellent	90
40	Good	70	40	Good	70	40	Good	70
50	Good	70	50	Good	70	50	Good	70
60	Good	70	60	Good	70	60	Good	70
70	Fair	45	70	Excellent	90	70	Good	70
80	Fair	45	80	Fair	45	80	Fair	45
90	Fair	45	90	Fair	45	90	Fair	45
100	Good	70	100	Good	70	100	Good	70
110	Good	70	110	Good	70	110	Good	70
Health index = 60.91			Health index = 69.91			Health index = 67.27		

The current network health index is 60.91. The health index after implementing work program 9 is 69.91, which means a 14.77% improvement to the network health index. The health index after implementing work program 18 is 67.27, or a 10.44% improvement. Work program 9 is selected for implementation since it will provide the maximum benefit to the network and to the users.

Sensitivity analysis can be performed to estimate the probability that the cost of the recommended work program will be within specific limits. For example, the cost estimate for the recommended work program is $2,071,056. The Monte Carlo simulation can evaluate the probability that the work program cost will not exceed this value by 5% while taking the contingency in the cost estimate for these rehabilitation strategies into account. In this case, the simulation estimates the probability that the actual cost will be less than $2,174,608. The result of the simulation is shown in Figure 7.4. It is estimated that 87.37% of the time, a recommended work program will not exceed its estimated cost by more than 5%.



Statistic	Forecast values
Trials	5,000
Mean	2,073,387
Median	2,074,094
Mode	---
Standard Deviation	87,079
Variance	7,582,758,625
Skewness	-0.0510
Kurtosis	2.76
Coeff. of Variability	0.0420
Minimum	1,801,279
Maximum	2,333,443
Mean Std. Error	1,231

-Infinity

Certainty: 87.37

2,174,608

Figure 7.4 Probability of the Cost Estimate to be within a Specific Limit

7.8 BRIDGE POSTING

The recommended work program is developed to allocate limited available funds to the most deserving project and to maximize benefits to the users and the network. As a result, there are a certain number of bridges that reached the intervention level but cannot be considered for improvement due to budget considerations. To ensure safety, these bridges must be evaluated in terms of limiting the weight of the vehicles crossing them. This aspect was discussed earlier in relation to bridge load-carrying capacity, which was included as a criterion in the ranking and prioritizing procedure presented in Chapter 5.

The relationship between the live load capacity and a bridge's posting is established by the Canadian Highway Bridge Design Code CAN/CSA-S6-00. Clause 14.17 provides guidelines for calculating posting loads for three levels of loads as defined by the code. For each level, the code describes the weight and dimensions of a live load model, which can consist of a standard truck or lane load.

The code guidelines specify that if the live load capacity factor is greater than or equal to 1 then posting is not required, and if the live load capacity factor is less than 0.3 then consideration shall be given to closing the bridge. Posting is necessary for a live load capacity factor greater than 0.3 and less than 1. In this case, the code provides a chart to aid in specifying the posting limit for a bridge.

7.9 PROTOTYPE SOFTWARE

A prototype software has been developed to validate the practicality of the proposed methodology in performing the management tasks, as a proof-of-concept. The software is developed using Microsoft Access 2003, and the functions are coded using Visual Basic for Applications (VBA).

As discussed in Chapter 3, the developed system uses a relational database as the data storage media. The prototype software database consists of 10 tables as shown in Figure 7.5. The figure shows the name and the key attribute(s) of each table. These tables contain the data necessary to perform bridge condition rating, ranking and decision making.

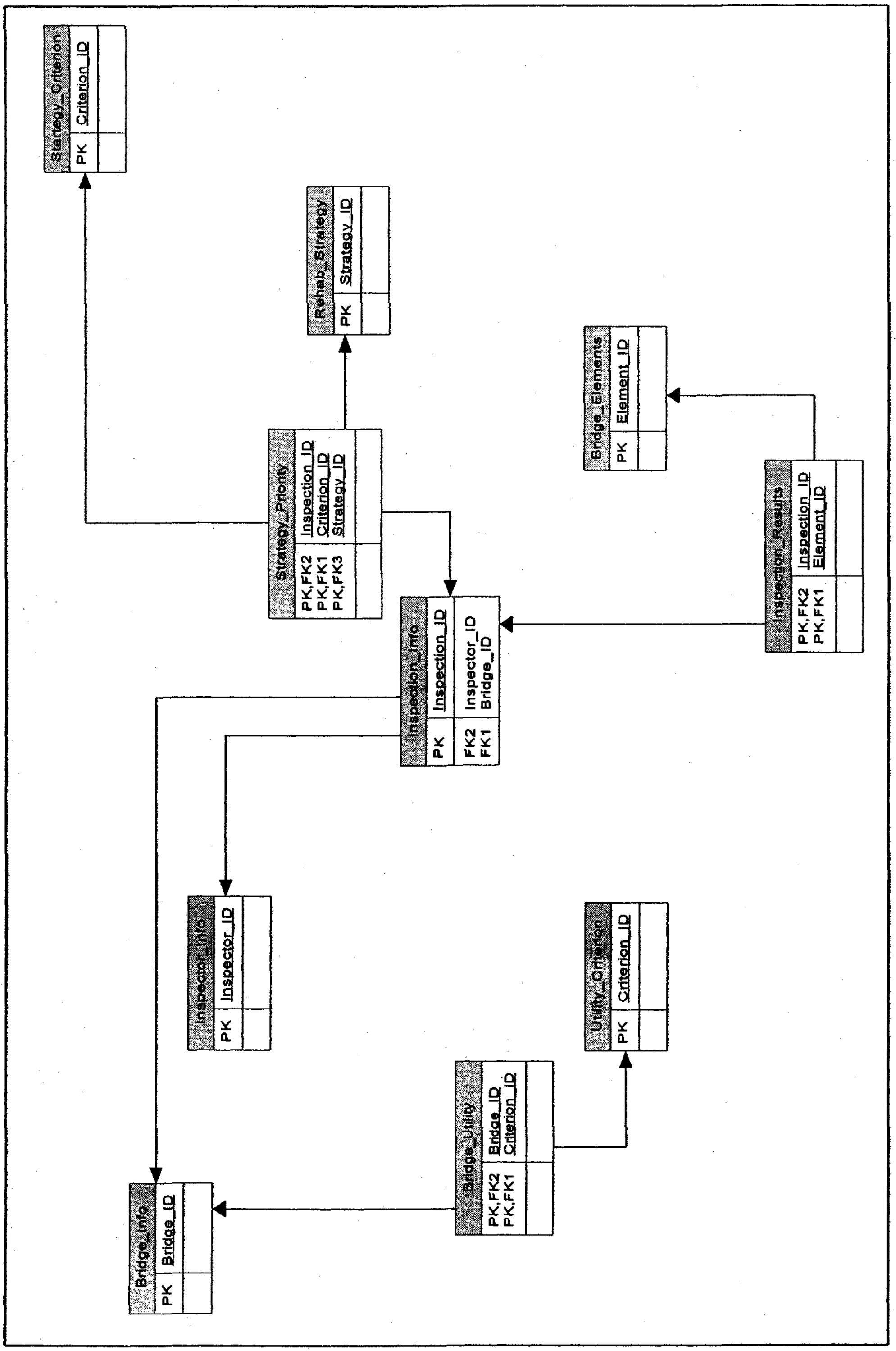
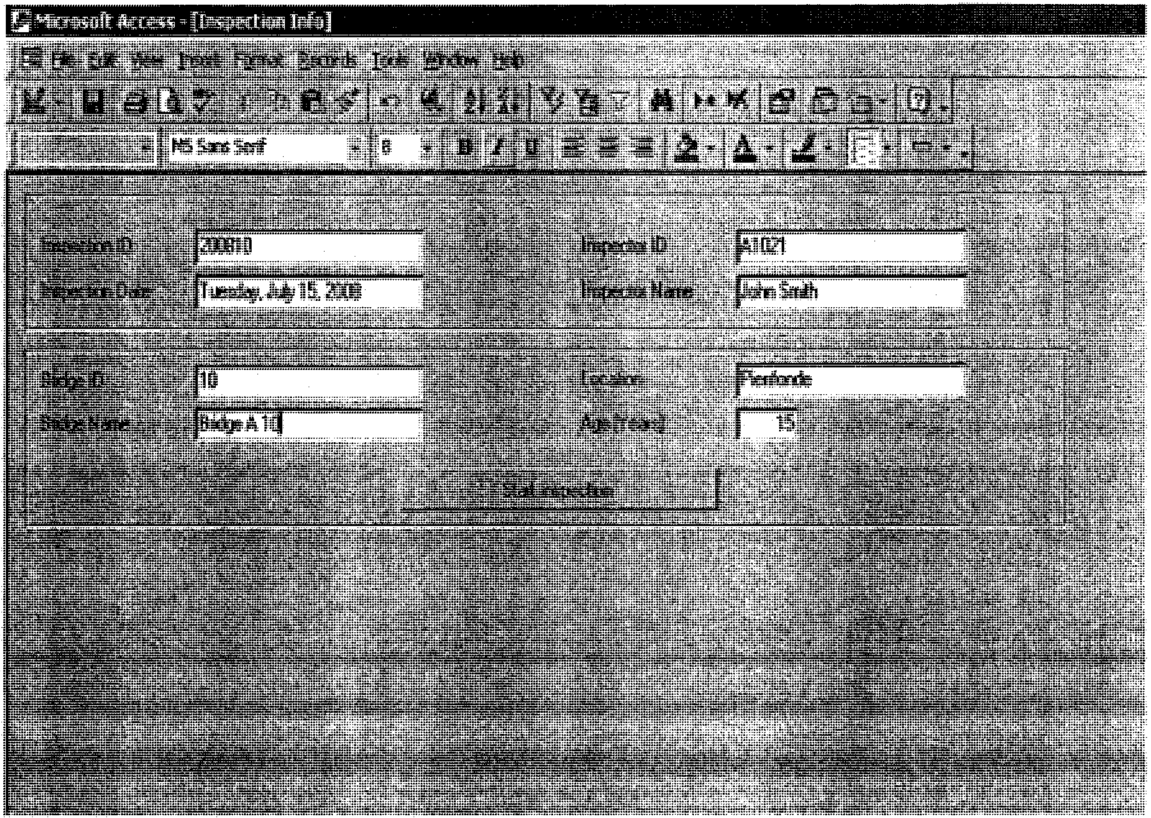


Figure 7.5 Database Structure for the Prototype Software

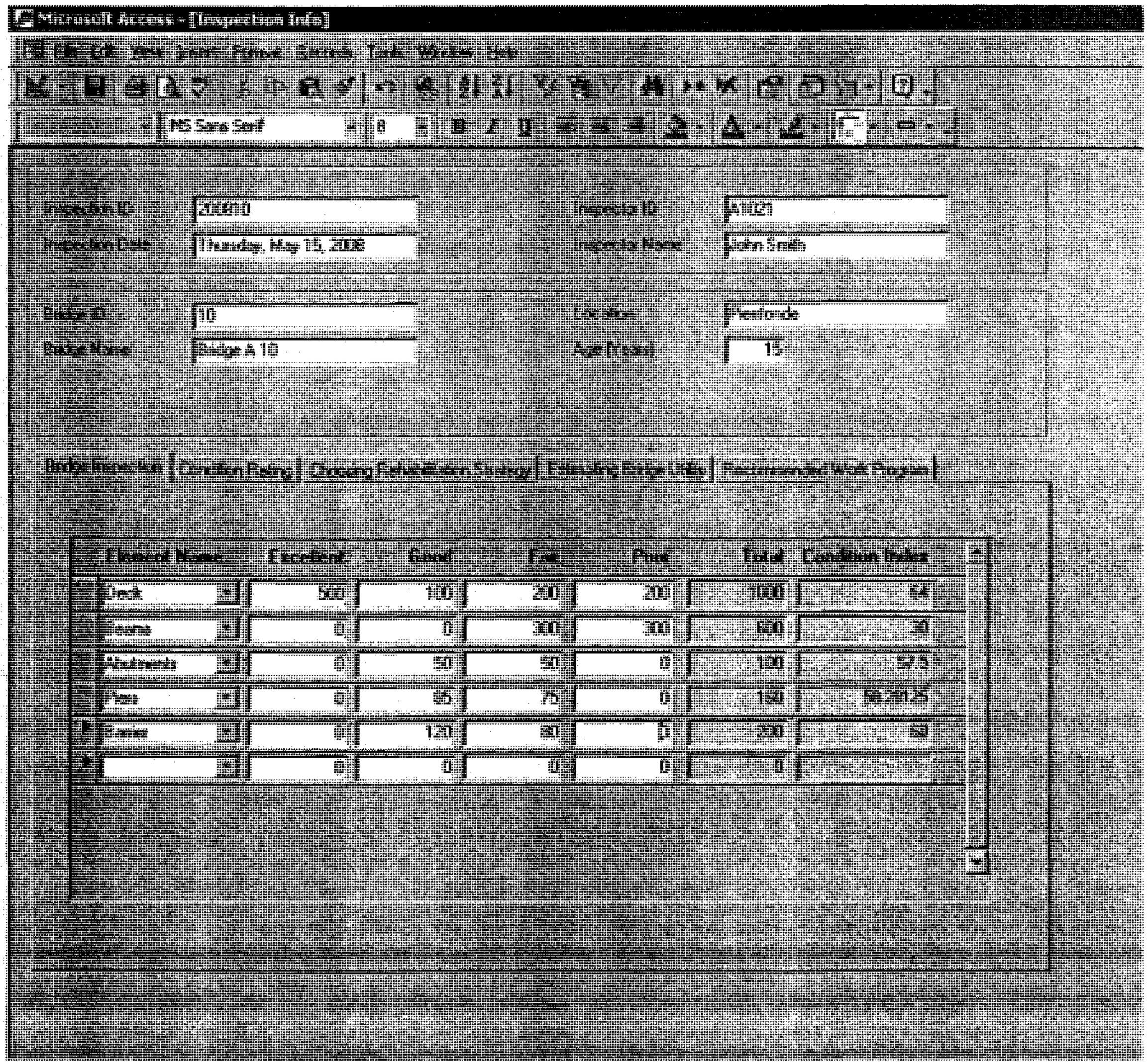
The inspection information screen enables an inspector to specify certain information about the bridge and about the inspection task. Figure 7.6 is a snapshot of a bridge inspection information screen.



Inspection ID: 200810
Inspection Date: Tuesday, July 15, 2008
Inspector ID: A1021
Inspector Name: John Smith
Bridge ID: 10
Bridge Name: Bridge A 10
Location: Pierrefonds
Age (Years): 15

Figure 7.6 Inspected Bridge Information

Once the inspection process starts, the inspector is required to enter the quantities in each of the four condition states for each element. The element condition index is estimated and displayed for the bridge elements, as shown in Figure 7.7.

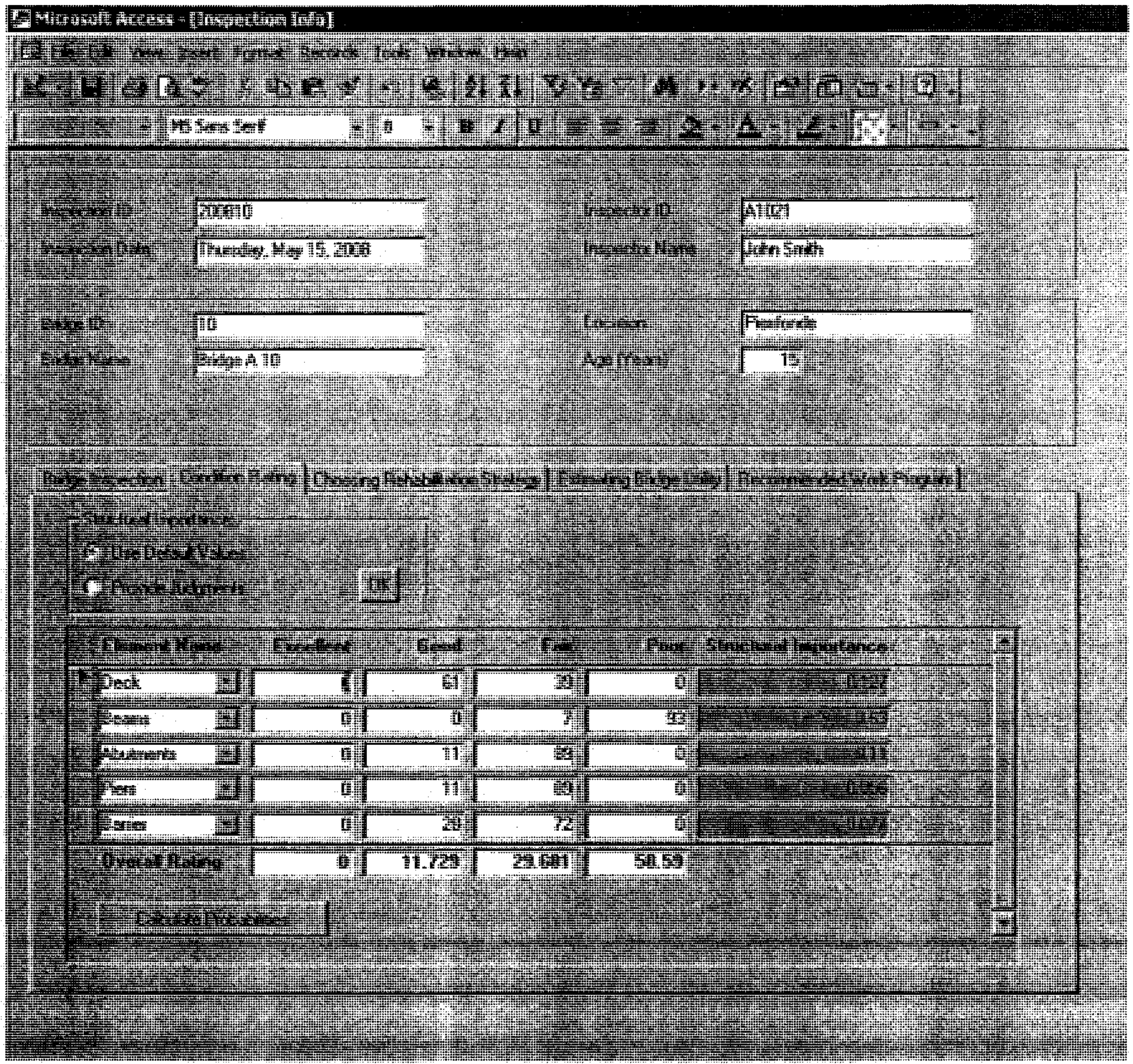


Inspection ID	200810	Inspector ID	A1021
Inspection Date	Thursday, May 15, 2008	Inspector Name	John Smith
Bridge ID	10	Location	Pierrefonds
Bridge Name	Bridge A 10	Age (Years)	15

Element Name	Excellent	Good	Fair	Poor	Total	Condition Index
Deck	500	100	200	200	1000	64
Beams	0	0	300	300	600	30
Abutments	0	50	50	0	100	57.5
Piers	0	85	75	0	160	58.28125
Barriers	0	120	80	0	200	60
	0	0	0	0	0	

Figure 7.7 Bridge Inspection Results

The condition rating for each element is estimated by performing the Monte Carlo Simulation. For the purpose of the prototype software, the simulation is performed for 100 iterations and the elements' ratings are displayed so that the probability of each element being in each condition state can be seen. Figure 7.8 presents the elements' ratings.



Microsoft Access - [Inspection Info]

Inspection ID: 200610

Inspection Date: Thursday, May 15, 2008

Inspector ID: A1021

Inspector Name: John Smith

Bridge ID: 10

Bridge Name: Bridge A 10

Location: Riverside

Age (Years): 15

Structural Importance:

● Use Default Values

○ Provide Judgments

Element Name	Excellent	Good	Fair	Poor	Structural Importance
Deck	0	61	39	0	0.127
Beams	0	0	7	93	0.63
Abutments	0	11	89	0	0.11
Piers	0	11	89	0	0.056
Bearings	0	28	72	0	0.077
Overall Rating	0	11.729	29.681	58.59	

Figure 7.8 Bridge Condition Rating

The system can use the default structural importance values for the bridge elements to develop the bridge overall rating as shown in Figure 7.8. At the same time, the system provides flexibility for the decision maker to submit judgments based on the inspection results and then evaluates alternative structural importance values. If the bridge expert decides to provide judgments, another form will open to prompt the user to provide the required judgments in terms of pairwise comparisons, as shown in Figure 7.9. The system performs a consistency check by estimating the consistency ratio. If the judgments provided are not consistent, a message will request the expert to resubmit the judgments. If the judgments are consistent, the system evaluates the structural importance factors for the elements, using the AHP.

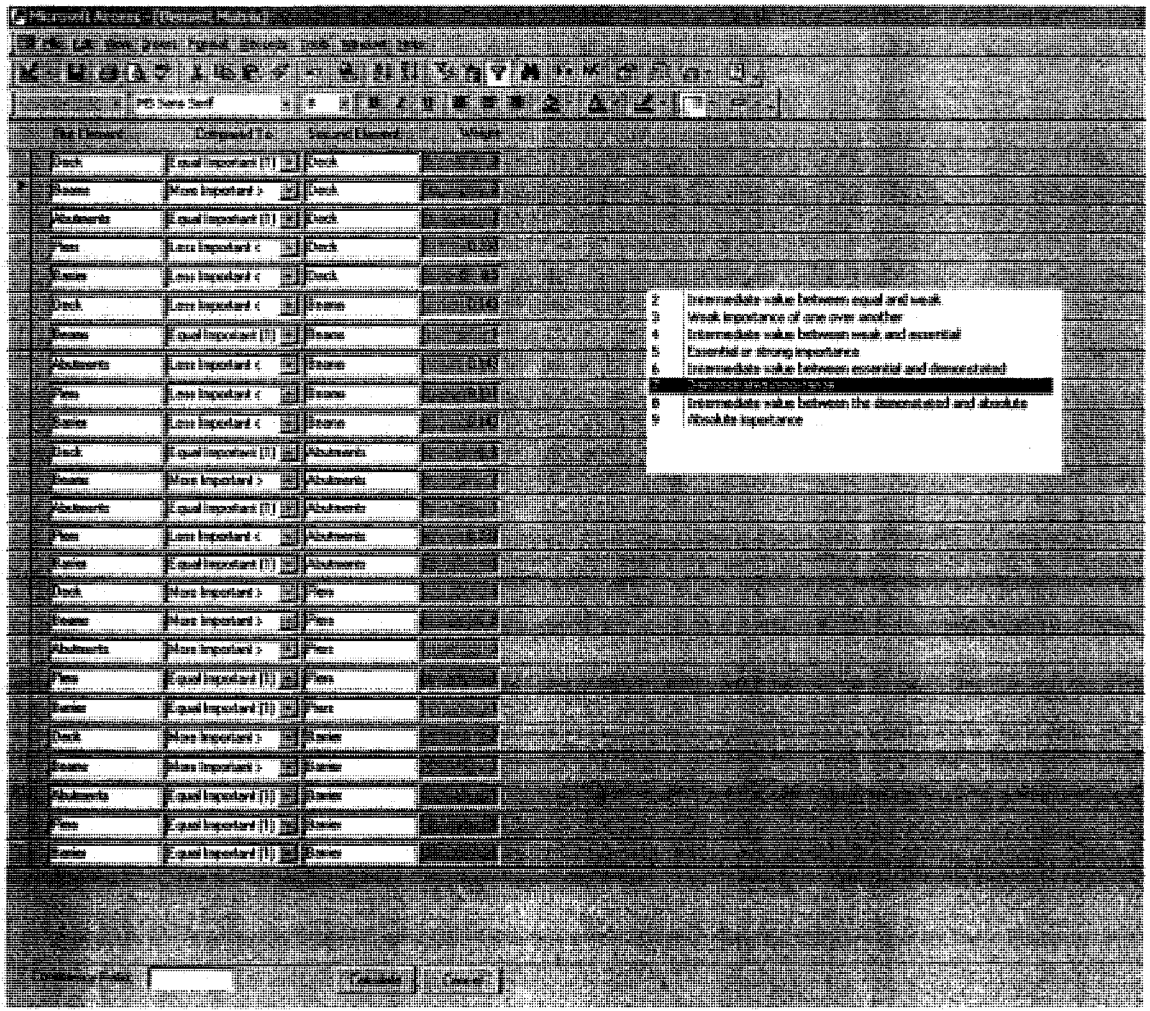
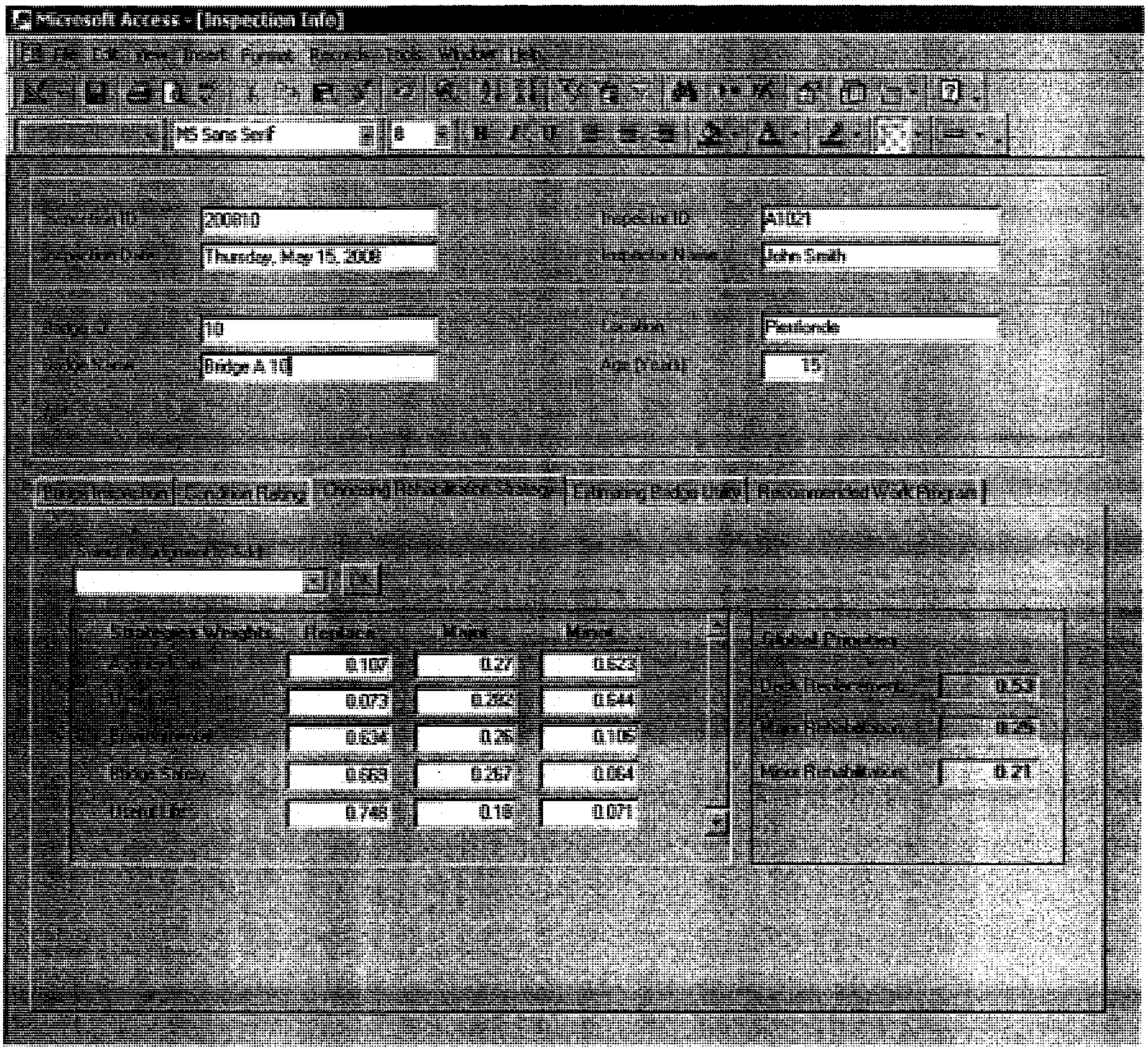


Figure 7.9 Elements Relative Importance

Once the structural importance values are estimated, the overall condition rating for the bridge can be evaluated and displayed. Bridges or elements at a specific condition rating can be retrieved from the database to be considered for intervention.

The software evaluates the available rehabilitation strategies by extracting the decision maker's preference to evaluate and then rank the available rehabilitation strategies. The decision maker can evaluate the strategies using a set of criteria, as shown in Figure 7.10.



Inspection ID	200810	Inspector ID	A1021
Inspection Date	Thursday, May 15, 2008	Inspector Name	John Smith
Bridge ID	10	Location	Pierrefonds
Bridge Name	Bridge A 10	Age (Years)	15

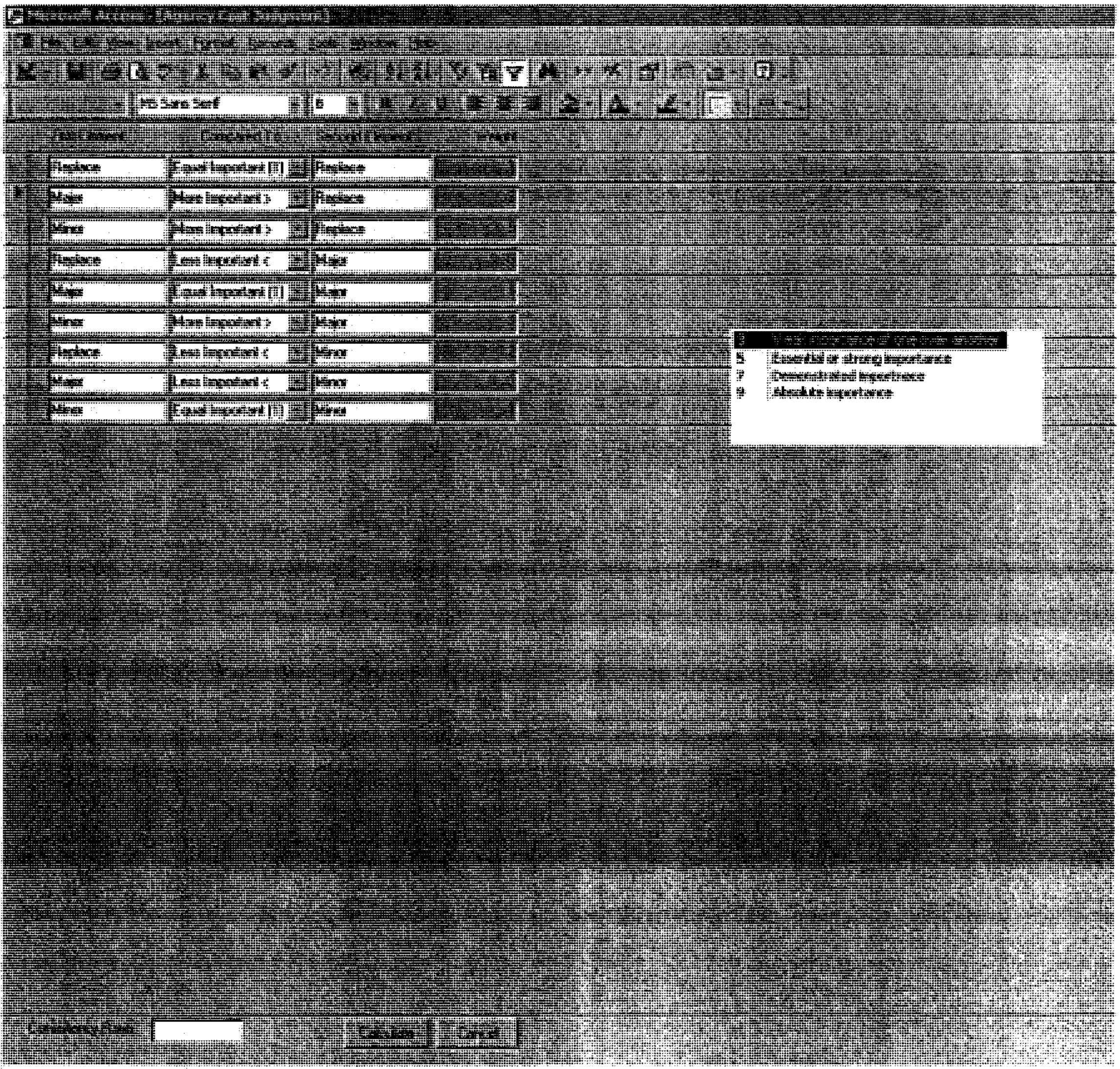
Strategies Weights	Replace	Major	Minor
[illegible]	0.107	0.27	0.623
[illegible]	0.073	0.283	0.644
[illegible]	0.634	0.26	0.105
Bridge Safety	0.669	0.267	0.064
Useful Life	0.749	0.18	0.071

Global Priorities

Deck Replacement	0.53
Major Rehabilitation	0.25
Minor Rehabilitation	0.21

Figure 7.10 Weights for the Criteria and the Strategies

For each criterion, the decision maker compares the available strategies in pairs, as shown in Figure 7.11. Then the system estimates the weight of each strategy with respect to each criterion and evaluates the global priorities for each rehabilitation strategy. Then it displays the results as presented in Figure 7.10.



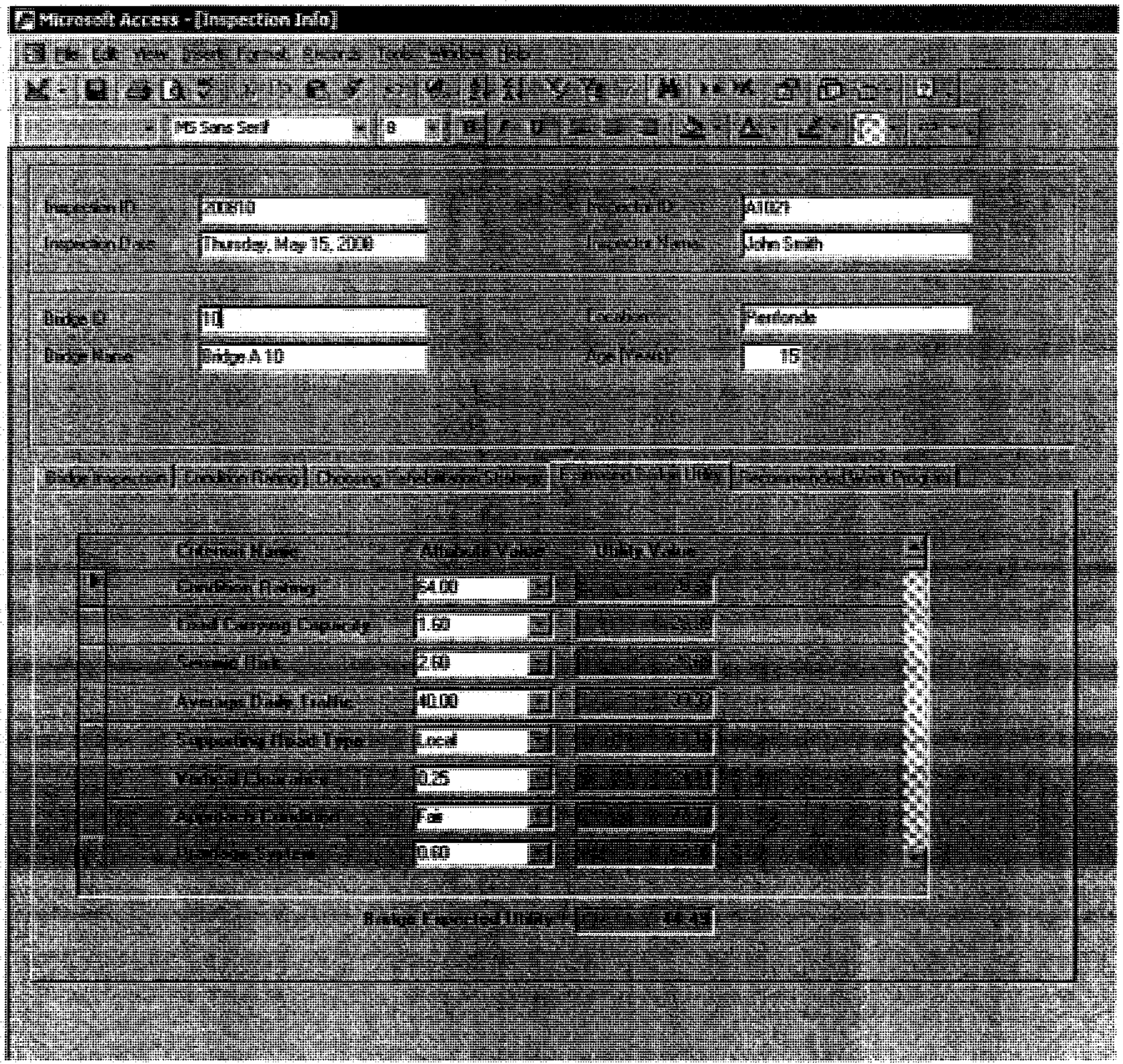
First Element	Compared To	Second Element	Weight
Replace	Equal Important (=)	Replace	[illegible]
Major	More Important >	Replace	[illegible]
Minor	More Important >	Replace	[illegible]
Replace	Less Important <	Major	[illegible]
Major	Equal Important (=)	Major	[illegible]
Minor	More Important >	Major	[illegible]
Replace	Less Important <	Minor	[illegible]
Major	Less Important <	Minor	[illegible]
Minor	Equal Important (=)	Minor	[illegible]

3 [illegible]
5 Essential or strong importance
7 Demonstrated importance
9 Absolute importance

Consistency Ratio:

Figure 7.11 Judgments Regarding the Rehabilitation Strategies

The software includes a form to add the specific attribute values of each bridge project. The system can evaluate the utility associated with each attribute value using the utility functions developed in this research, and it then estimates the expected overall utility for the bridge project as shown in Figure 7.12.



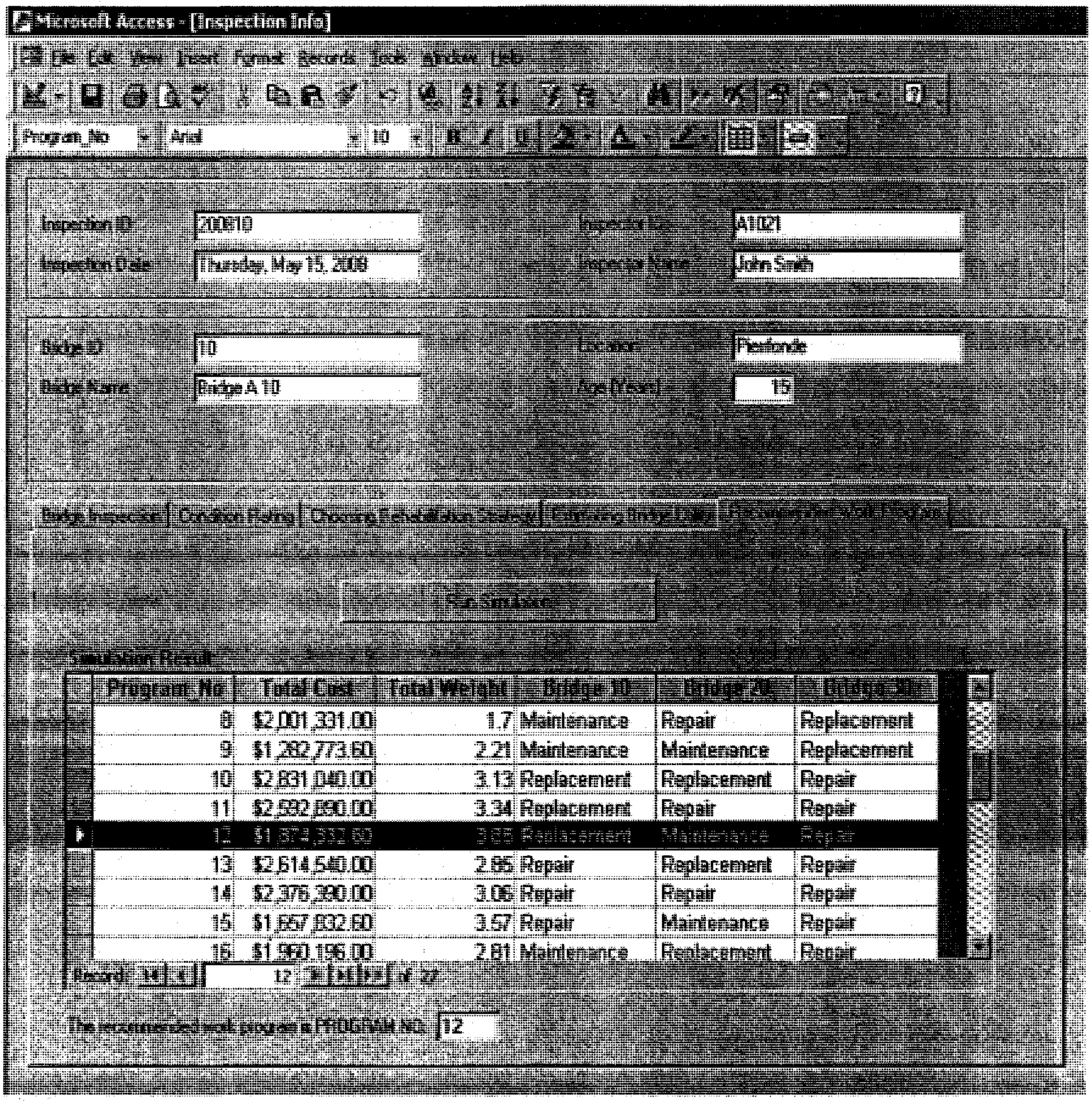
Inspection ID	200610
Inspection Date	Thursday, May 15, 2008
Inspector ID	A1021
Inspector Name	John Smith
Bridge ID	10
Bridge Name	Bridge A 10
Location	Pierrefonds
Age (Years)	15

Criterion Name	Attribute Value	Utility Value
Condition Rating	54.00	[illegible]
Load Carrying Capacity	1.60	[illegible]
Seismic Risk	2.60	[illegible]
Average Daily Traffic	40.00	[illegible]
Supporting Road Type	Local	[illegible]
Vertical Clearance	0.25	[illegible]
Approach Condition	Fair	[illegible]
Drainage System	0.60	[illegible]

Bridge Expected Utility: 64.49

Figure 7.12 Overall Expected Utility for a Project

The prototype software is programmed to retrieve the three bridge projects with the highest overall utility and to develop a recommended work program for these three projects. Figure 7.13 presents the recommended work program for the three bridges with the highest overall expected utilities.



Inspection ID	200810	Inspector ID	A1021
Inspection Date	Thursday, May 15, 2008	Inspector Name	John Smith
Bridge ID	10	Location	Pierrefonds
Bridge Name	Bridge A 10	Age (Years)	15

Program_No	Total Cost	Total Weight	Bridge 10	Bridge 20	Bridge 30
8	$2,001,331.00	1.7	Maintenance	Repair	Replacement
9	$1,282,773.60	2.21	Maintenance	Maintenance	Replacement
10	$2,831,040.00	3.13	Replacement	Replacement	Repair
11	$2,592,890.00	3.34	Replacement	Repair	Repair
12	$1,874,332.60	3.65	Replacement	Maintenance	Repair
13	$2,614,540.00	2.85	Repair	Replacement	Repair
14	$2,376,390.00	3.06	Repair	Repair	Repair
15	$1,657,832.80	3.57	Repair	Maintenance	Repair
16	$1,960,196.00	2.81	Maintenance	Replacement	Repair

Record: 12 of 27

The recommended work program is PROGRAM NO: 12

Figure 7.13 Recommended Work Program

7.10 SUMMARY

This chapter presents a technique to develop a recommended work program by combining the outputs of the various methods developed in the previous chapters. The technique uses the simulation to develop all the possible work programs and to select the best one, based on specific criteria. The recommended work program's cost must be within the available budget. The chapter presents cost models to estimate the cost of three rehabilitation strategies. The chapter also presents an illustrative example to demonstrate the work program development approach.

A prototype software that demonstrates the main functionalities of the different methods discussed in this dissertation is presented. Snap shots of the different forms and reports produced by the prototype software are included.

CHAPTER 8: CONCLUSION, CONTRIBUTION AND RECOMMENDATIONS

8.1 CONCLUSION

Bridges connect highways and roadways as linking nodes and support an increasing amount of daily traffic and increasing weights for trucks and other heavy vehicles. Deterioration of the existing bridge infrastructure is a major social and economic concern for society. Among the bridge components, the bridge deck is a major component of the structure and normally has the highest deterioration rate due to direct interaction with vehicles and dynamic loads. In addition, application of deicing salt during winter accelerates the deterioration process.

The objective of this research was to develop a decision support methodology for bridge deck rehabilitation management. An intensive literature survey was performed to review the current practice in bridge management. The status of bridge infrastructure in Canada was reviewed and the current practice in bridge condition assessment was investigated. The need to develop a unified bridge management practice in Canada was established.

A conceptual design of the proposed decision support system was presented and the underlying methods were explained. The decision support system consists of four modules: 1) Condition Assessment; 2) Deterioration Modeling; 3) Ranking of Projects; and 4) Decision Module. These modules interact together and with a central database that contains bridge information.

A probabilistic bridge deck condition assessment methodology was developed that is consistent with the current practice of bridge inspection, and which uses a Markovian approach to model deterioration.

A network level ranking method was developed. The method ranks and prioritizes projects in a network or sub-network according to multiple criteria. The features of this method include using the Multi-Attribute Utility Theory (MAUT) to evaluate projects with multiple and conflicting criteria and using the intuitive Eigenvector approach to develop the required utility functions.

A multi-criteria method for bridge rehabilitation strategy selection is developed. The method evaluates alternative maintenance and rehabilitation strategies while incorporating both the quantitative measurements and qualitative criteria in the process. This method is based on a modified Analytic Hierarchy Process which extracts experts' judgments and evaluates the alternatives accordingly. The modified Analytic Hierarchy Process integrates the Monte Carlo simulation in order to account for the uncertainty in performing pairwise comparisons and produces a sensitive evaluation of consistency in judgments.

Both the network ranking method and the rehabilitation strategy selection method were developed and validated using information extracted during interviews with engineers from Canadian Ministries of Transportation and consultants involved in bridge rehabilitation projects.

A technique to evaluate the different combinations of projects and rehabilitation strategies was developed. This technique recommends a work program that maximizes benefits to the network and its users within a limited budget. The recommended work program specifies which bridges to perform actions on and what action to be performed for each project.

Prototype software was developed to test and validate the developed decision support methodology.

8.2 CONTRIBUTIONS

The main objective of this research was to develop a decision support methodology for bridge deck rehabilitation management which would advance knowledge in the area of infrastructure management. The contribution of this research would be beneficial to engineering consultants, transportation agencies and local municipalities involved in the rehabilitation of bridge infrastructure. The contributions of this research are outlined as follows:

- A comprehensive review of the status of bridge infrastructure and a discussion of bridge management and decision support models, along with a review of the available bridge management systems and their components.
- A review of the current practice for bridge condition assessment followed by a number of Canadian Ministries of Transportation. The review highlights the need for unifying bridge condition assessment and bridge management practice in Canada and provides insights on current practices.

- Development of a probabilistic bridge deck condition assessment methodology, which is consistent with current practice and the Markov chain approach to model deterioration.
- Development of a decision support method for multi-criteria selection of bridge rehabilitation strategy and validation of the developed method using data collected from the Jacques Cartier bridge deck replacement project.
- Development of a decision support methodology for bridge deck maintenance and rehabilitation management that has the following features:
    - Consistent with current practice in bridge management condition assessment and deterioration modeling.
    - Multiple-criteria decision making process.
    - Flexibility to allow engineers to utilize their experience and judgment in the decision making process.
    - Combines the network and project levels of the bridge management process and performs budget allocation effectively.
- Development of a prototype decision support system to validate the proposed methodology.

8.3 LIMITATIONS OF THE DEVELOPED SYSTEM

The developed methods and prototype system have certain limitations, listed below:

- The developed methods are intended for rehabilitation management of reinforced concrete bridge decks. Further research is needed to expand the method's applicability to other types of bridge deck such as pre-stressed concrete and steel bridge decks.
- The developed methodology is specific for the bridge deck. However, bridge structures have additional components, which are the bridge super-structure and the bridge sub-structure. These components must be added to develop a comprehensive bridge management system.

8.4 RECOMMENDATIONS FOR FUTURE WORK

A methodology and prototype software for bridge deck rehabilitation management have been developed and discussed in this study. The main advantages of the developed methodology are: including multiple and conflicting criteria in the decision making process, and its flexibility in accommodating bridge experts' and decision makers' inputs. Future research work is recommended to focus on the following issues:

- Quantifying direct and indirect impacts associated with bridge management decisions.
- Developing cost models to forecast the cost of the different rehabilitation strategies.
- Analyzing additional bridge elements and developing similar methods for rehabilitation management.

- Integrating the developed methods to manage the various bridge elements into a comprehensive bridge management system.
- Expanding the prototype software to full-scale software which provides flexibility to the decision maker to develop alternative hierarchy structures and to add additional decision elements.

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Appendix (A)
Seismic Zoning Factors for the Canadian Province of Quebec

Province and Location	Hourly Mean Wind Pressure, (in Pascals) for Return Periods of:				Velocity Related Seismic Zone	Zonal Velocity Ratio	Acceleration Related Seismic Zone	Zonal Acceleration Ratio
	10 yr	25 yr	50 yr	100 yr	Z_v	V	Z_a	A
Wawa	300	355	390	430	0	0.00	0	0.00
Welland	330	380	425	470	0	0.00	1	0.05
West Lorne	345	415	470	530	0	0.00	0	0.00
Whitby	430	510	575	640	1	0.05	1	0.05
White River	210	245	275	300	0	0.00	0	0.00
Wiarton	330	410	475	550	0	0.05	1	0.05
Windsor	360	420	470	520	0	0.00	0	0.00
Wingham	350	435	505	570	0	0.00	0	0.00
Woodstock	305	380	435	500	0	0.05	1	0.05
Wyoming	350	415	465	520	0	0.00	0	0.00
Québec								
Acton Vale	235	285	320	360	2	0.10	3	0.15
Alma	235	285	320	360	3	0.15	3	0.15
Amos	240	285	320	350	1	0.05	2	0.10
Ancienne Lorette	385	460	520	580	3	0.15	4	0.20
Arvida	250	310	355	400	2	0.10	—	—
Asbestos	260	310	350	390	2	0.10	2	0.10
Aylmer	295	360	410	460	2	0.10	4	0.20
Bagotville	265	325	380	430	4	0.20	5	0.30
Baie Comeau	450	535	600	660	2	0.10	4	0.20
Beaconsfield	315	365	400	440	2	0.10	4	0.20
Beauport	385	460	520	580	3	0.15	4	0.20
Bedford	305	360	405	450	2	0.10	3	0.15
Belœil	280	330	370	410	2	0.10	3	0.15
Brome	280	330	370	410	2	0.10	3	0.15
Brossard	310	365	400	440	2	0.10	4	0.20
Buckingham	305	360	405	450	2	0.10	4	0.20
Cacouna	410	510	585	660	3	0.15	—	—
Campbell's Bay	235	285	320	360	2	0.10	4	0.20
Chambly	310	365	400	440	2	0.10	4	0.20
Camp Valcartier	385	460	520	580	2	0.10	—	—
Chicoutimi	250	310	360	410	3	0.15	4	0.20
Coaticook	270	330	375	430	1	0.05	2	0.10
Contrecoeur	330	390	435	480	2	0.10	3	0.15
Cowansville	305	360	405	450	2	0.10	3	0.15
Deux-Montagnes	280	330	370	410	2	0.10	4	0.20
Dolbeau	260	315	350	390	2	0.10	3	0.15
Dorval	315	365	400	440	2	0.10	4	0.20
Drummondville	240	285	320	350	2	0.10	3	0.15
Farnham	310	365	405	450	2	0.10	3	0.15
Fort Chimo	535	640	725	815	1	0.05	—	—
Fort Coulonge	240	285	315	350	2	0.10	4	0.20
Gagnon	365	415	455	500	1	0.05	1	0.05
Gaspé	590	700	785	870	1	0.05	1	0.05
Gatineau	295	360	410	460	2	0.10	4	0.20
Gentilly	230	275	305	340	2	0.10	—	—
Gracefield	240	285	315	350	2	0.10	4	0.20
Granby	265	310	350	390	2	0.10	3	0.15
Harrington-Harbour	700	820	920	1020	1	0.05	1	0.05

Province and Location	Hourly Mean Wind Pressure, (in Pascals) for Return Periods of:				Velocity Related Seismic Zone	Zonal Velocity Ratio	Acceleration Related Seismic Zone	Zonal Acceleration Ratio
	10 yr	25 yr	50 yr	100 yr	Z_v	V	Z_a	A
Havre St. Pierre	590	700	785	870	1	0.05	1	0.05
Hemmingford	305	360	405	450	2	0.10	4	0.20
Hull	295	360	410	460	2	0.10	4	0.20
Iberville	310	365	405	450	2	0.10	4	0.20
Inukjuak	630	780	905	1030	0	0.00	0	0.00
Joliette	270	325	360	400	2	0.10	3	0.15
Jonquière	255	310	355	400	3	0.15	4	0.20
Kenogami	255	310	355	400	3	0.15	4	0.20
Knob Lake	335	385	425	460	1	0.05	—	—
Knowlton	280	330	370	410	2	0.10	—	—
Kovik Bay	675	815	930	1030	0	0.05	—	—
Lachine	315	365	400	440	2	0.10	—	—
Lachute	310	365	400	440	2	0.10	4	0.20
Lafleche	310	365	400	440	2	0.10	—	—
La Malbaie	395	480	555	630	6	0.40	6	0.40
La Salle	315	365	400	440	2	0.10	—	—
La Tuque	260	315	350	390	2	0.10	3	0.15
Laval	315	365	400	440	2	0.10	4	0.20
Lennoxville	235	285	320	360	1	0.05	2	0.10
Léry	310	365	400	440	2	0.10	4	0.20
Les Saules	385	460	520	580	3	0.15	—	—
Levis	385	460	520	580	3	0.15	4	0.20
Loretteville	385	460	520	580	3	0.15	4	0.20
Louiseville	330	390	435	480	2	0.10	3	0.15
Magog	260	310	350	390	1	0.05	2	0.10
Malartic	240	285	320	350	1	0.05	2	0.10
Maniwaki	235	275	305	340	2	0.10	4	0.20
Masson	300	360	410	450	2	0.10	4	0.20
Matane	450	535	600	660	2	0.10	3	0.15
Megantic	450	555	645	730	2	0.10	—	—
Mont Joli	450	535	600	660	2	0.10	3	0.15
Mont Laurier	240	275	305	330	2	0.10	4	0.20
Montmagny	395	480	555	630	4	0.20	5	0.30
Montréal	315	365	400	440	2	0.10	4	0.20
Montréal Nord	315	365	400	440	2	0.10	4	0.20
Mount Royal	315	365	400	440	2	0.10	—	—
Nitchequon	285	330	365	400	1	0.05	0	0.00
Noranda	260	310	350	390	1	0.05	2	0.10
Outremont	315	365	400	440	2	0.10	4	0.20
Percé	640	760	850	940	1	0.05	1	0.05
Pierrefonds	315	365	400	440	2	0.10	4	0.20
Pincourt	310	365	400	440	2	0.10	4	0.20
Plessisville	260	310	350	390	2	0.10	3	0.15
Pointe-Claire	315	365	400	440	2	0.10	—	—
Pointe-Gatineau	295	360	410	450	2	0.10	—	—
Port Alfred	250	310	355	395	3	0.15	—	—
Port Cartier	520	615	690	760	1	0.05	4	0.20
Poste-de-La-Baleine	635	745	830	950	0	0.00	—	—
Preville	310	365	400	440	3	0.15	—	—

Province and Location	Hourly Mean Wind Pressure, (in Pascals) for Return Periods of:				Velocity Related Seismic Zone	Zonal Velocity Ratio	Acceleration Related Seismic Zone	Zonal Acceleration Ratio
	10 yr	25 yr	50 yr	100 yr	Z_v	*V*	Z_a	*A*
Québec	385	460	520	580	3	0.15	4	0.20
Richmond	235	280	320	360	2	0.10	2	0.10
Rimouski	450	535	600	660	2	0.10	3	0.15
Rivière-du-Loup	410	505	585	660	5	0.30	6	0.40
Roberval	260	315	350	390	2	0.10	3	0.15
Rock-Island	300	360	410	460	1	0.05	2	0.10
Rosemere	315	365	400	440	2	0.10	4	0.20
Rouyn	260	310	350	390	1	0.05	2	0.10
Salaberry de Valleyfield	315	365	400	440	2	0.10	4	0.20
Schefferville	335	380	425	460	0	0.00	0	0.00
Senneterre	240	285	315	350	1	0.05	2	0.10
Shawville	260	310	350	390	2	0.10	4	0.20
Ste-Agathe des Monts	270	310	345	380	2	0.10	4	0.20
Ste-Anne de Bellevue	310	365	400	440	2	0.10	4	0.20
St-Canut	280	330	370	310	2	0.10	—	—
St-Felicien	220	255	285	310	2	0.10	3	0.15
Ste-Foy	385	460	520	660	3	0.15	—	—
St-Hubert	310	365	400	440	2	0.10	4	0.20
St-Hubert de Temiscouata	410	505	585	660	4	0.20	5	0.30
St-Hyacinthe	270	310	345	380	2	0.10	3	0.15
St-Jean	310	365	405	450	2	0.10	3	0.15
St-Jérôme	285	330	365	400	2	0.10	4	0.20
St-Jovite	255	295	325	360	2	0.10	4	0.20
St-Lambert	315	365	400	440	2	0.10	4	0.20
St-Laurent	315	365	400	440	2	0.10	4	0.20
St-Nicholas	365	435	495	550	3	0.15	4	0.20
Sutton	305	360	405	450	2	0.10	3	0.15
Tadoussac	400	495	570	640	5	0.30	6	0.40
Temiscaming	240	285	315	350	1	0.05	3	0.15
Thetford Mines	280	335	370	410	2	0.10	3	0.15
Trois Rivières	330	390	435	480	2	0.10	3	0.15
Thurso	305	360	405	450	2	0.10	4	0.20
Val d'Or	240	285	315	350	1	0.05	3	0.15
Valleyfield	310	365	405	450	2	0.10	—	—
Varennes	300	360	405	450	2	0.10	3	0.15
Verchères	330	390	435	480	2	0.10	3	0.15
Verdun	315	365	400	440	2	0.10	4	0.20
Victoriaville	260	310	350	390	2	0.10	3	0.15
Ville d'Anjou	315	365	400	440	2	0.10	—	—
Ville-Marie	300	360	410	450	1	0.05	2	0.10
Waterloo	260	310	350	390	2	0.10	3	0.15