BRIDGE MANAGEMENT SYSTEM WITH INTEGRATED LIFE CYCLE COST OPTIMIZATION

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

In recent years, infrastructure renewal has been a focus of attention in North America and around the world. Municipal and federal authorities are increasingly recognizing the need for life cycle cost analysis of infrastructure projects in order to facilitate proper prioritization and budgeting of maintenance operations. Several reports have highlighted the need to increase budgets with the goal of overcoming the backlog in maintaining infrastructure facilities. This situation is apparent in the case of bridge networks, which are considered vital links in the road network infrastructure. Because of harsh environments and increasing traffic volumes, bridges are deteriorating rapidly, rendering the task of managing this important asset a complex endeavour. While several bridge management systems (BMS) have been developed at the commercial and research level, they still have serious drawbacks, particularly in integrating bridge-level and network-level decisions, and handling extremely large optimization problems.

To overcome these problems, this study presents an innovative bridge management framework that considers network-level and bridge-level decisions. The initial formulation of the proposed framework was limited to bridge deck management. The model has unique aspects: a deterioration model that uses optimized Markov chain matrices, a life cycle cost analysis that considers different repair strategies along the planning horizon, and a system that considers constraints, such as budget limits and desirable improvement in network condition. To optimize repair decisions for large networks that mathematical programming optimization are incapable of handling, four state-of-the art evolutionary algorithms are used: Genetic algorithms, shuffled frog leaping, particle swarm, and ant colony. These algorithms have been used to experiment on different problem sizes and formulations in order to determine the best optimization setup for further developments.

Based on the experiments using the framework for the bridge deck, an expanded framework is presented that considers multiple bridge elements (ME-BMS) in a much larger formulation that can include thousands of bridges. Experiments were carried out in order to examine the framework's performance on different numbers of bridges so that system parameters could be set

to minimize the degradation in the system performance with the increase in numbers of bridges. The practicality of the ME-BMS was enhanced by the incorporation of two additional models: a user cost model that estimates the benefits gained in terms of the user cost after the repair decisions are implemented, and a work zone user cost model that minimizes user cost in work zones by deciding the optimal work zone strategy (nighttime shifts, weekend shifts, and continuous closure), also, decides on the best traffic control plan that suits the bridge configuration. To verify the ability of the developed ME-BMS to optimize repair decisions on both the network and project levels, a case study obtained from a transportation municipality was employed. Comparisons between the decisions provided by the ME-BMS and the municipality policy for making decisions indicated that the ME-BMS has great potential for optimizing repair decisions for bridge networks and for structuring the planning of the maintenance of transportation systems, thus leading to cost savings and more efficient sustainability of the transportation infrastructure.

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To my Father, Mother, and Sisters

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Chapter 1

Introduction

1.1 General

Civil Infrastructure Systems, e.g., roadways, bridges, buildings, and water/sewer networks play essential roles in the economy of nations, and their value in most countries is significant. In North America, for example, the total value of the infrastructure systems is estimated to be $33 trillion (Vanier 2001). The yearly average expenditure on the infrastructure system is estimated to be $53 and $303 billion in Canada and the United States (USA), respectively. Therefore, the sustained operation of these infrastructure assets is crucial.

A large percentage of existing infrastructure assets are deteriorating due to age, harsh environmental conditions, and insufficient capacity (Bordogna, 1995). In 2001, the American Society of Civil Engineers (ASCE) (2001) published a report card on the condition of the United States infrastructure systems. The report examined trends and assessed the progress and decline of America's infrastructure. Twelve infrastructure categories were given an overall grade of D+, with some areas close to a failing grade. In 2003, ASCE released a progress report which indicated that none of the 12 categories demonstrated any significant improvement (Figure 1.1) (ASCE, 2003). The condition of the categories of roads, transit and energy has continued to decline, with no improvement in the condition of bridges, schools, or aviation. In 2003, it was estimated that a $1.6 trillion investment is needed to bring the condition of infrastructure facilities to acceptable levels, compared to $1.3 trillion in 2001. In 2005, the ASCE published an updated progress report with 3 additional categories, none of which demonstrated any significant improvement. In fact, the overall average condition declined to D, and the same level of investment would still be needed to improve the infrastructure systems to an acceptable condition (ASCE, 2005). Out of this $1.6 trillion, $358 billion is needed just for roads, bridges, and highways.

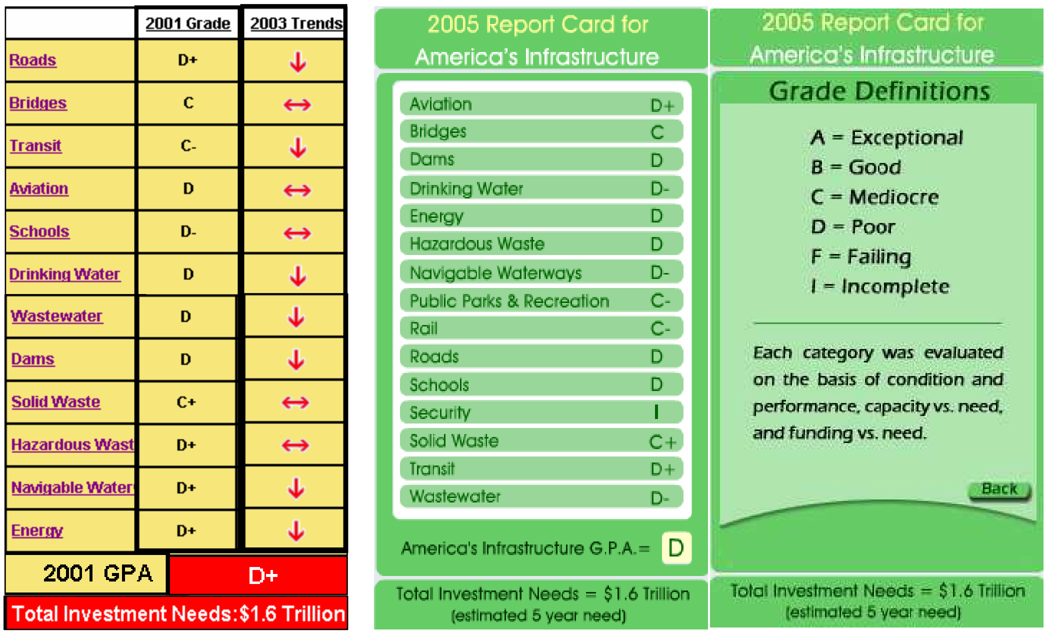


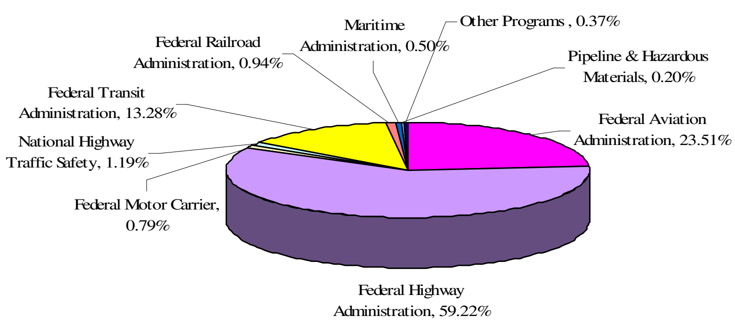
Figure 1.1: ASCE Report Card on the US Infrastructure (ASCE, 2003; ASCE, 2005)

As in USA, many of the infrastructure assets in Canada require large investments. According to Vanier and Danylo (1998), Canadian cities are required to spend $12 to $15 billion every year for maintaining and rehabilitating their infrastructure systems. Currently, the shortfall in the amount required to return these assets to acceptable conditions is estimated at $44 billion.

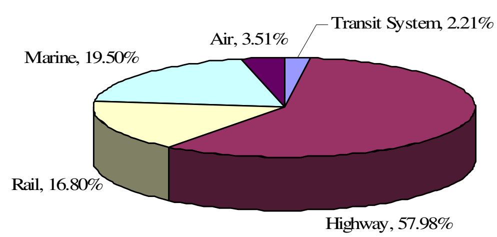
Due to the large size and cost of infrastructure networks, maintaining such networks is a challenging but crucial task, particularly in light of the limited budgets available for infrastructure maintenance. Consequently, municipalities and transportation agencies are under increasing pressure to develop new strategies for managing public infrastructure assets in a way that ensures long-term sustainability under constrained budgets. This chapter includes a brief discussion about bridges as an important infrastructure asset, followed by a discussion of the motivation, objectives, and methodology of the present research.

1.2 Bridges: Important Infrastructure Assets

Transportation networks are the most visible and expensive infrastructure assets. Such networks include roads, bridges, railways, marinas, and airports. Figure 1.2 (a) shows the distribution of the US Department of Transportation's (USDOT) budget for its administrative sectors (USDOT, 2006). It can be seen that the Federal Highway Administration (FHWA), which is concerned mainly with highways and bridges, consumes more than half (59%) of the US DOT budget. Similarly, in Canada, in the fiscal year 2005, the highway division consumed about 58% of the transportation budget (Transportation in Canada, 2005) (Figure 1.2 b). A recent report from the Canadian federal, provincial and territorial deputy ministers of transportation shows that Canada's roads and highways need $66 billion over the next 10 years in order to overcome the infrastructure gap between the requirements and services provided (Toronto Star, 2005).



a- US DOT budget distribution



b-Transportation investments in Canada

Figure 1.2: Budget Distribution for the US and Canada (USDOT, 2006; Transportation in Canada, 2005)

Bridges are considered to be vital links in any roadway network. Complete or partial failure to maintain these links paralyses the overall performance of the roadway network and causes excessive public and private losses. Therefore, bridge networks need to be managed in a way that ensures their uninterrupted performance throughout their design life. The total number of bridges in the US is about 590,750; 27.1% are structurally deficient or functionally obsolete, which means that they are either closed or restricted to light vehicles because of deteriorated components. It will cost about $9.4 billion a year for 20 years to eliminate all bridge deficiencies (ASCE, 2005). The increase in funds needed for bridges is very apparent from the highway statistics; Figure 1.3 shows the increase in funds required for bridge projects for 1997 – 2001 (USDOT, 2001). The distribution of the funds required for bridge programs by improvement type is illustrated in Figure 1.4 (USDOT, 2005). The same situation is evident in Canada: according to the National Research Council of Canada Institute for Research in Construction (NRC-IRC, 2000), about 40% of all bridges in Canada are older than 35 years, and most of them are in urgent need of replacement or rehabilitation. Lounis (1999) estimated that the deferred maintenance backlog in bridges was about $10 billion. From these statistics, it is clear that municipalities and departments of transportation are facing an increasing challenge in optimally allocating extremely limited budgets.

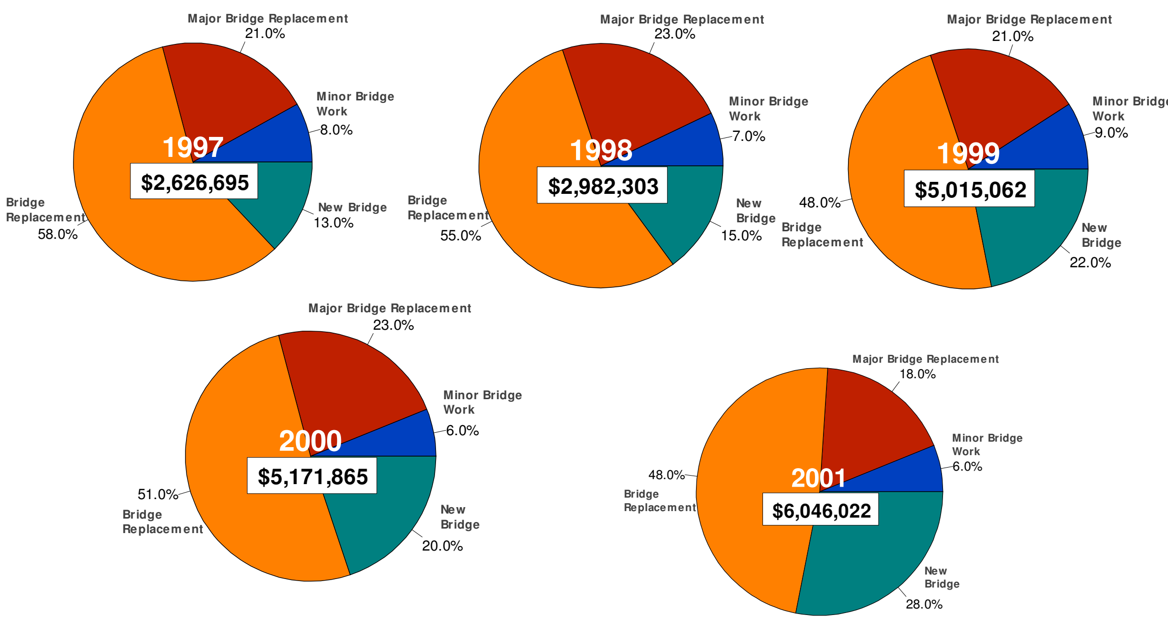


Figure 1.3: Increase in Funds Required for Bridges: 1997-2001 (USDOT, 2001)

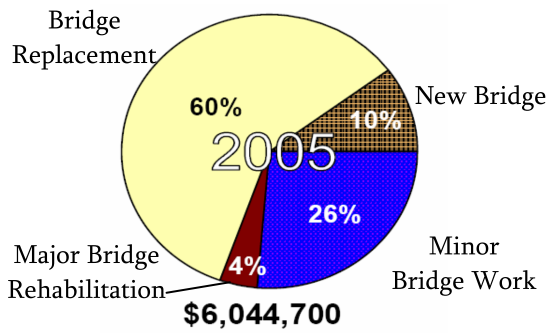


Figure 1.4: Distribution of US Federal Funds for Bridge Projects by Improvement Type (USDOT, 2005)

1.2.1 Bridge Management Systems (BMSs)

Because the task of managing thousands of highway bridges has become increasingly critical in the past few decades, tools have been developed to help government agencies. Bridge Management Systems (BMS) are designed to manage a network of bridges under the constraints of limited budget and resources. Many BMSs have been introduced in the literature to address three aspects of bridge management: assessing bridge conditions, modelling future deterioration behaviour, and the decisions to maintain, repair, or rehabilitate (MR&R) decision. Although much of the literature covers the first two aspects, few studies have been directed at optimizing the decisions related to the maintenance or repair of bridges.

The literature describes BMSs that have been developed to support either network-level decisions for prioritizing bridges for maintenance purposes, or project-level decisions for selecting the appropriate repair strategy for bridge elements. These two aspects are interrelated, but they have been treated separately in most BMSs, which can lead to non-optimal decisions. Thompson et al. (2003b) highlighted one of the important advances in BMS: the recognition of the importance of project-level decisions to complement network-level decisions. However, incorporating project-level details into network-level analysis complicates life cycle cost analysis (LCCA) and renders traditional optimization tools as incapable of dealing with the large formulation involved, particularly with large networks of bridges.

1.3 Research Motivation

The goal of this research was to develop a comprehensive framework for a BMS. The focus is on formulating practical LCCA and optimizing the repair decisions at both the network and project levels. The research has been motivated by the aspects discussed in the following subsections.

1.3.1 The Need for Practical Life Cycle Cost (LCC) Models

Civil infrastructure systems represent huge investments for both governments and taxpayers. The life cycle benefits of these investments must be maximized in order to ensure that the society's needs are optimally met. Frangopol et al. (2001) stated that additional research is required in order to develop a better life cycle so that the costs and benefits can be quantified. The ASCE's policy recommendations in a report titled "better infrastructure assets" encouraged the use of LCCA principles for evaluating the total costs of infrastructure projects (FHWA, 2002). The best practice in LCCA calls for including all costs incurred throughout the life of a bridge. Two types of costs should be considered: the agency costs (maintenance and repair costs) and user costs (costs incurred by the public) (FHWA, 2002). Recently, researchers have been advocating the incorporation of user costs into the analysis, in order to enhance the validity of the BMS results.

Life cycle cost analysis should support both network-level and project-level analysis. Currently, most BMSs focus on network-level analysis (Wilson et al., 1997). For example, Pontis software analyzes the funds required to maintain a given level of performance throughout the network (Pontis, 2001). However, Pontis does not appear to be effective at project-level analysis (Wilson et al., 1997). This thesis incorporates both the network-level and the project-level into the decision-making process. This enhancement has been added partly in response to a call by the National Cooperative Highway Research Program (NCHRP) in 2004 to develop new BMS models for network-level and project-level multi-objective optimization that can suit the performance criteria defined by all users (NCHRP, 2004).

1.3.2 The Need for Non-Traditional Optimization Tools

One of the greatest obstacles to the development of efficient LCCA optimization models is the inadequacy of traditional mathematical optimization tools to handle large-scale problems, which is the case in bridge networks. The problem is more complicated when both project-level details and optimizing network-level decisions are considered. Consequently, new tools derived from evolutionary algorithms (EAs), such as genetic algorithm (GA) and shuffled frog leaping (SFL) are good candidates for research. In recent years, EAs have become increasingly popular in science and engineering and have proven to be capable of arriving at near-optimal solutions for large-scale problems (Hegazy, 1999a and b; Leu and Yang, 1999; Mawdesley and Al-Jibouri, 2003). Experimenting with EAs for infrastructure life cycle cost optimization is an important element in this research.

1.3.3 The Need for a Comprehensive BMS Framework

Although various researchers have dealt with individual aspects of bridge management system (BMS) components such as deterioration models, condition assessment, and life cycle cost analysis, a comprehensive framework is still needed that will integrate these aspects in a practical manner. In the development of this framework, all the important factors that affect the analysis, including alternative maintenance strategies and other practical constraints such as budget limits need to be considered (FHWA, 1995).

1.4 Research Objectives

The objective of this research is to develop a comprehensive bridge management system using evolutionary algorithms to optimize life cycle costs at both the network and project levels. The system represents a tool for transportation agencies and decision makers in optimizing bridge maintenance plans and repair strategies over a number of years within budget limits and other related agency constraints so that feasible and practical plans can be determined.

The principle objectives of the present research are the following:

- Investigate bridge components that require detailed maintenance strategies, examining their deterioration processes, and their effect on the bridge condition rating.
- Determine the appropriate deterioration models described in the literature, and develop an improved Markov chain deterioration model.
- Develop a detailed life cycle cost analysis model for bridges that considers bridge elements and their deterioration behaviour, as well as different repair and rehabilitation strategies. Practical constraints are formulated with both network-level and project-level details.
- Examine different evolutionary algorithm techniques (e.g., GA) in order to optimize the decisions for prioritizing the repair of bridges and elements in large scale bridge networks.
- Experiment with large-scale optimization problems to determine the best objective function and the best problem formulation for handling thousands of bridges at the same time.
- Utilize the suitable optimization technique(s) to set up and implement a life cycle cost optimization model that prioritizes bridges and their elements for maintenance plans, according to limited available resources and practical constraints.
- Develop a model for estimating the user cost benefits gained from implementing repair decisions.
- Develop a computer prototype for the new BMS framework for integrating all previous developments in a user-friendly automated environment.
- Experiment with the proposed framework through a real-case study of a bridge network.

The proposed model is employed to determine cost-effective bridge repair strategies and their time of execution while maintaining acceptable bridge condition rating under different constraints. Although the proposed model focuses mainly on bridge management systems, it can also be adapted for other types of infrastructure assets, such as pavement, buildings, and water/sewer networks.

1.5 Research Methodology

The methodology for achieving the objectives of the study is illustrated in Figure 1.5. The following are brief descriptions of each step:

1. **Review of the Existing Models**: An extensive survey of the literature is carried out in order to examine existing bridge management models. Based on the review, the limitations of the available models and suggestions for improvement are identified. The most appropriate condition rating, deterioration models, and cost models are selected to be the subcomponents of the proposed BMS framework.

2. **Bridge Deck Management System (BDMS)**: After the practical aspects of different maintenance/repair costs, variable discounted rates, and user costs are considered, an LCC model is developed. The model is developed only for bridge decks. The model integrates both network-level and project-level decisions. A non-traditional evolutionary algorithm (EA) optimization technique is developed. Different EAs are used to be experimented with the model in order to reach the best technique to be used in further developments. Different problem formulations for handling large-scale problems are examined. Based on individual models, a comprehensive framework for a bridge deck management system framework is devised. Once a prototype has been completed, an example of a bridge network is presented in order to validate the system results and demonstrate its functionality for municipalities and transportation agencies.

3. **Multi-Element Bridge Management System (ME-BMS):** A bridge management system that considers multiple elements of the bridge is developed. The elements considered are: deck, overlay, joints, bearings, superstructure, substructure, and finishing. As well, the model integrates both the network-level and project-level decisions in an optimization model to enable the determination of the optimal repair decisions for both levels. The ME-BMS accounts for the costs incurred by the users because of the bridge deficiencies and estimates the benefits gained because of the application of the repair decisions. After the repair actions are decided, the model then estimates the user cost during the work

zone. A prototype is developed and an example application is then presented in order to demonstrate the capabilities of the model.

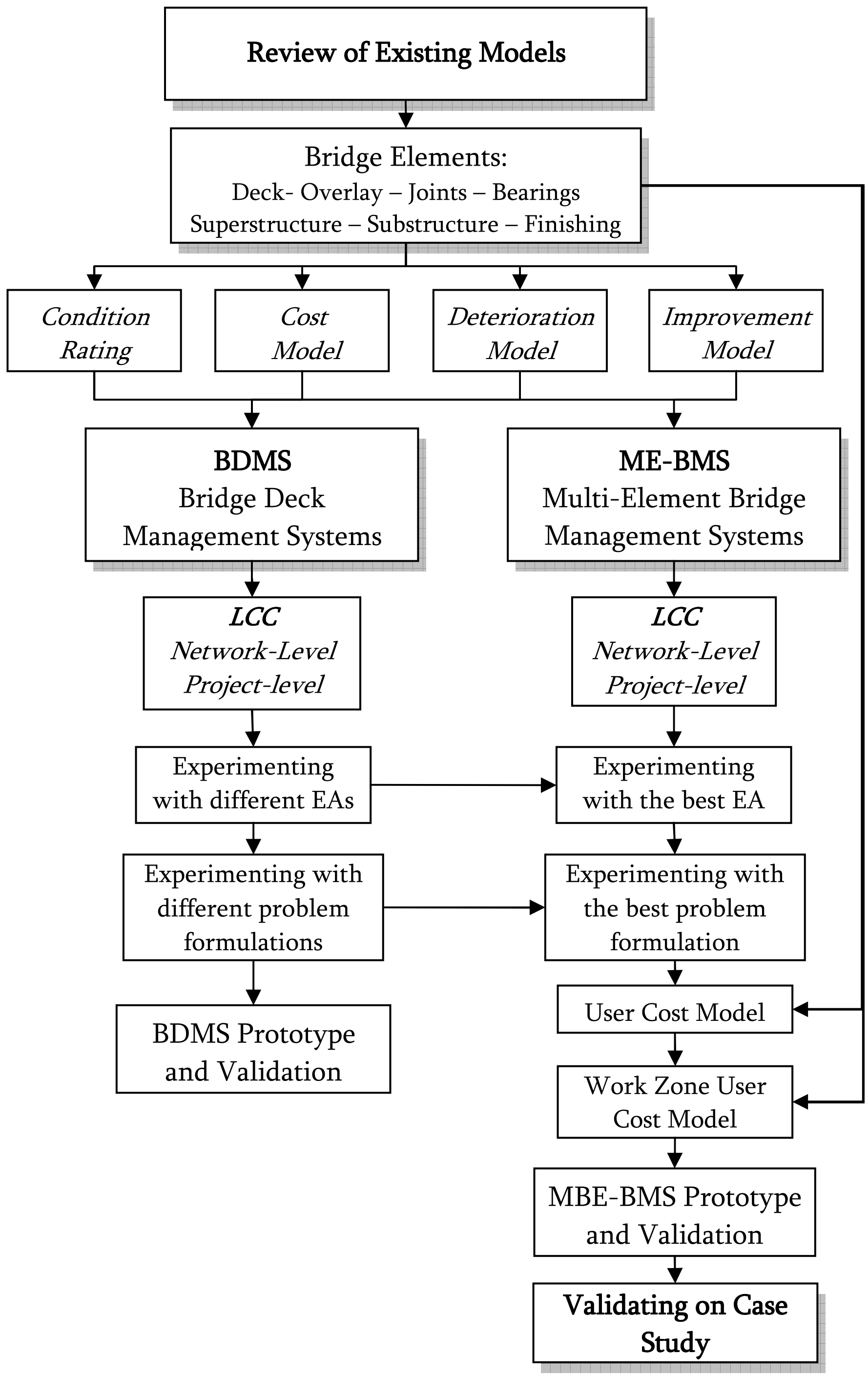


Figure 1.5: Schematic Diagram for Research Methodology

4. **Case Study and Validation**: A network of bridges from a department of transportation (DOT) is used as a case study. The results of the ME-BMS are then compared with the DOT repair decisions for this network of bridges.

1.6 Thesis Organization

The reminder of the thesis is organized as follows:

Chapter 2 introduces a detailed review of the previous work in the area of bridge management systems. The basic components of any BMS should include a condition assessment, deterioration models, cost models, improvement models, and a life cycle cost analysis model. A review of these components is presented along with a description of recent developments in these areas. The capabilities and limitations of the existing BMS models are then discussed.

Chapter 3 describes an initial BMS framework developed for bridge decks (BDMS). A detailed description of BDMS components is presented. Several evolutionary algorithms are used to experiment with the developed framework, and the best algorithm is then selected for further experimentation. Different problem formulations for overcoming the size of the problem are also introduced, and the best formulation is then tested using different objective functions.

Chapter 4 presents an expanded BMS framework that includes multiple bridge elements (ME-BMS). In this formulation, seven major elements are considered: deck, overlay, joints, bearings, superstructure, substructure, and finishing. For each bridge element different, different components of the ME-BMS are presented that include: a deterioration model, a cost model, and an improvement model. An optimization model is developed to optimize the repair decisions on both the project and network levels.

Chapter 5 presents the development of a user cost model that estimates the impact of repair decisions on the benefits gained with respect to user costs. The user cost model is then incorporated in the project-level and network-level formulation. To assist bridge engineers in optimizing work zone strategies, a work zone user-cost model is developed in order to minimize the interruption time for the users while the work zone is in effect.

Chapter 6 focuses on the validation for the proposed ME-BMS framework. This chapter presents a real-life case study collected form a department of transportation (DOT). The case study is used to validate the model's performance and compare its results to the decisions that are predicted to be made by the DOT's engineers.

Chapter 7 summarizes the research work, highlights its contributions, and gives recommendations for future research.

Chapter 2

Literature Review

2.1 Introduction

Bridge management is the process by which agencies monitor, maintain, and repair deteriorating systems of bridges with available resources. The development of bridge management systems (BMSs) has been necessitated by the large imbalance between the need for extensive repairs or replacements in a large bridge network and the limited budget available to municipalities and agencies for implementing the required repairs. A BMS process results in a set of decisions for allocating limited funds to a network of bridges over a number of years in order to maximize the network's performance and minimize the life cycle cost (LCC).

In this chapter, a detailed review is presented of the components of a BMS including condition-rating methods, element-deterioration models, a life cycle cost analysis (LCCA), and maintenance, repair, and rehabilitation decisions (MR&R).

2.2 The History of Bridge Management

In 1967, the Silver Bridge between Point Pleasant, WV and Callipolis, OH collapsed, then on June 28, 1983, a section of the Mianus River Bridge catastrophically failed due to the instantaneous fracture of a pin and hanger connection. This failure resulted in several fatalities and disrupted commerce in north-eastern US for several months. No systematic maintenance programs were yet in place for monitoring the condition of bridge networks (Czepiel, 1995).

To address this problem, the Federal Highway Administration (FHWA) created the national bridge inspection program (NBIP), which ordered every state to catalogue and track the condition of bridges on principal highways. The data collected as part of the NBIP were submitted after each inspection period and maintained by the FHWA in the national bridge inventory (NBI) database. The intention was to repair bridges before deterioration reached a critical state. Since the 1980s, interest in the development of BMSs has increased at both the state and the federal levels. In 1985, the national cooperative highway research program (NCHRP) initiated a program with the objective of developing a model for an effective BMS. In the late 1980s, the FHWA with the support of several state departments of transportation sponsored the development of the Pontis system (Pontis, 2001). In 1991, the Intermodal Surface transportation efficiency act (ISTA) recognized the need for the preventive maintenance of infrastructure. ISTA mandated that each state department of transportation (DOT) to implement a BMS that maximizes the use of resources for maintenance planning.

2.3 Components of a Bridge Management System

A BMS is defined as a rational and systematic approach to organizing and carrying out all the activities related to managing a network of bridges, including optimizing the selection of maintenance and improvement actions in order to maximize the benefits while minimizing the LCC (Hudson et al., 1992). Bridge management is the means by which a bridge network is cared for from conception to the end of its useful life (Ryall, 2001).

A BMS assists decision makers at all levels in selecting optimum solutions from an array of cost-effective alternatives. The purpose of a BMS is to combine management, engineering, and economic input in order to determine the best actions to take on a network of bridges over time (AASHTO, 2001). A BMS, also, helps engineers and decision makers determine when and where to spend bridge funds, to enhance safety and preserve the existing infrastructure.

Hudson et al. (1992) stated that the activities of a BMS should define the condition of the bridge, allocate funds for maintenance and improvement action, prioritize bridges for improvement actions, identify bridges for posting, find cost-effective alternatives for each bridge, account for actual bridge expenditures, track minor maintenance, inspect bridges, and maintain an appropriate database of information. To perform these functions, the American association of state highway and transportation officials (AASHTO) g*uidelines for bridge management systems* suggest that a BMS should include the following basic components: data storage, cost models, deterioration models, and optimization models (AASHTO, 2001) (Figure 2.1). Ryall (2001) has also, suggested that the modules for any BMS should be inventory, inspection, maintenance, and finance.

The heart of a BMS is a database derived from the regular inspection and maintenance activities. The integrity of a BMS is directly related to the quality and accuracy of the bridge inventory and physical condition data obtained through field inspections (AASHTO, 1994). Information such as the bridge name (ID), the location, and the construction are stored. These data are considered the starting point for the system: drawings, maintenance records, and surveys are reviewed. The database and inventory allow bridge managers to be fully informed about the bridge stock under their control so that they can make informed decisions about future maintenance and repair activities. The next sections present a brief discussion of condition-rating models, deterioration models, cost models, and MR&R decisions.

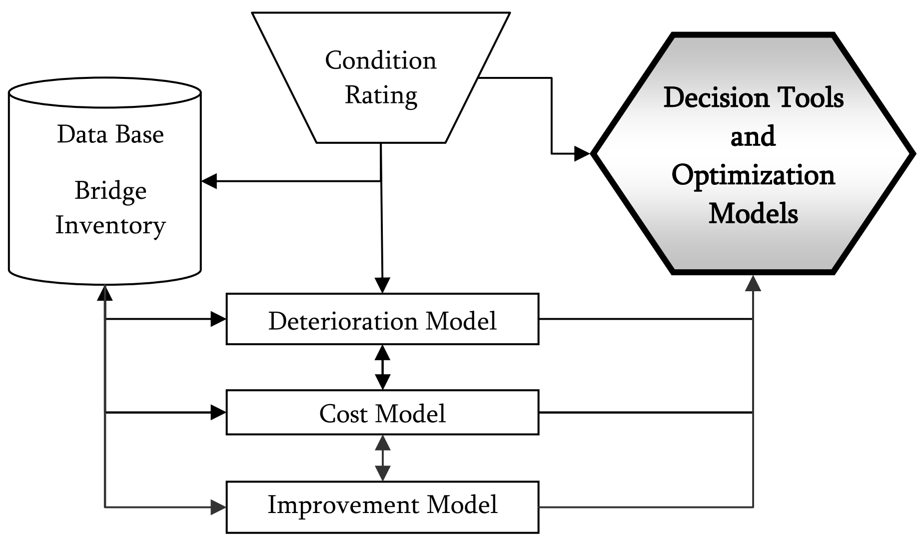


Figure 2.1: Basic Components of a BMS (AASHTO, 2001)

2.4 Condition Rating Systems for Bridges

Condition ratings are adopted to describe the existing condition of the bridge, compared to its condition at the time of construction. Usually, the condition of the bridge is assessed by means of an inspection. The regular inspection of bridges is essential for alerting bridge engineers to the deterioration of the bridge for a variety of reasons: vehicle accidents or damage, fracture, or material breakdown. Inspections also enable bridge engineers to determine future maintenance requirements. Since experience and technical expertise are important in the inspection process, an inspection is usually carried out by a professional engineer or, at least is supervised by a professional engineer. Each bridge is unique; its form and layout dictate the focus of the inspection (Ryall, 2001). Inspection categories vary depending on the frequency of the inspection and the details required. Narasimban and Wallbamk (1998) have listed categories of inspection, as shown in Table 2.1.

Table 2.1: Inspection Categories (Narasimban and Wallbamk, 1998)

Inspection Type	Interval	Remarks
Superficial	When needed	Cursory inspection, no standard report
General	2 years	Visual inspection from ground level
Principal	6 years	Close visual inspection, all defects recorded
Special	When needed	Detailed testing of a particular area
Joint	On completion of construction	New structures
Initial Principal	At the end of the maintenance period	New structures
Underwater	6 years	Part of the principal inspection
Scour	When needed	Special inspection
Paint survey	When needed	-----

Bridge inspection involves checking the materials and the physical condition of the deck, superstructure, and substructure components. Consequently, an accurate condition assessment must include both the severity of the deterioration or disrepair and the extent to which it is widespread in the component being inspected. According to Aktan et al. (1996), the condition-rating process can be summarized in measuring the extent of damage and deterioration, determining the effect of that damage or deterioration on the condition of the facility, setting a scale of parameters that describe the condition of the facility as a whole, and compare the existing damage or deterioration with the previous records of the condition of the component. One of the recent advances in the field of inspection relates to visual inspection; Hammad et al. (2006) presented a mobile model-based bridge life cycle management system (MMBLMS). This system is linked to a 4D model of the required bridge to be inspected so that different events throughout the life cycle of the bridge along with a suitable level of details can be recorded on mobile computers.

Different countries have developed different ways within their BMSs to provide an assessment of the condition of a bridge in an attempt to prioritize them within the constraints of the repair work necessary and limited budgets. The most popular bridge condition rating has been developed by the FHWA (FHWA, 1995). In general, the condition rating can be categorized as bridge ratings and component ratings. The literature on condition ratings is reviewed in the following subsections.

2.4.1 Overall Bridge Rating

Bridge condition rating systems apply to the assessment of the whole bridge. For example, in Japan, the condition of bridges is assessed according to one of five deterioration levels (Liu et al., 1997; Yokoyama et al., 1996) as given in Table 2.2. The degree of deck deterioration is given a value from 0 to 1, with 1 being the most critical condition.

The AASHTO (1994) reported that each highway bridge should be rated at two load levels the load factor (capacity rating) and the working stress methods (inventory rating). The capacity rating determines the maximum permissible loads to which a structure may be subjected, and the inventory rating determines the load level for the safe utilization of an existing structure for an indefinite period of time. The bridge rating is too general for describing the condition rating. As a result, condition rating is usually conducted at the element level.

Table 2.2: Japanese Condition Rating (Liu et al., 1997)

Deterioration Level	Deterioration Degree	Deterioration Condition Description
I	0.8-1.0	Potentially hazardous
II	0.6-0.8	Obvious deterioration and may need detailed inspection
III	0.4-0.6	Aggravated deterioration and may need further inspection
IV	0.2-0.4	Minor deterioration
V	0.0-0.2	Like new

2.4.2 Individual Element Rating

The second type of condition-rating system is the element condition rating performed at the element level. The bridge is divided into several sub-elements such as the deck, superstructure, and substructure. An example of sub-element categorization of concrete bridges was presented by Furuta et al. (2006); the six elements considered in the analysis were the upper part of pier, the lower part of pier, the shoe, the girder, the bearing section of floor slab, and the central section of floor slab. The following is a review of component condition-rating systems.

Minor et al. (1988) have presented subjective ratings that summarize the condition of bridge components into four general categories: good, fair, poor, and critical, as shown in Table 2.3.

In the US, the national bridge inventory (NBI) requires condition ratings for only three major bridge structural components: the deck, the superstructure, and the substructure, The FHWA (1995) has presented the commonly used bridge-rating system has a scale from 0 to 9. The scale of this condition rating indicates the urgency of an impending loss of structural integrity, but provides little information about the type and location of the possible failure (Turner et al., 1994). In the FHWA system, it is assumed that bridges are usable until the rating is reduced to a value of 3. Table 2.4 illustrates the FHWA condition ratings. Minor et al. (1988) have classified the FHWA numerical ratings: “7, 8, or 9” represents “Good” conditions; “5 or 6” means “Fair”; “3 or 4” stands for “Poor”; and “0, 1, or 2” represents “Critical” conditions.

Table 2.3: Subjective Rating Systems (Minor et al., 1988)

Good	The element or component is in new condition
Fair	The element or component is in need of minor repair
Poor	The element or component is in need of major repair and is deteriorated or damaged to the extent that the structural integrity is affected. Immediate repair is required for the member
Critical	The element or component is not performing the function for which it was intended

Table 2.4: FHWA Bridge Condition Rating (FHWA, 1995)

Rating	Description
N	Not applicable
9	Excellent condition or new condition: no noteworthy deficiencies
8	Very Good condition: no repair needed
7	Good condition: some minor problems; minor maintenance needed
6	Satisfactory condition: some minor deterioration; major maintenance needed
5	Fair condition: minor section loss, cracking, spalling, or scouring for minor rehabilitation; minor rehabilitation needed
4	Poor condition: advanced section loss, deterioration, spalling or scouring; major rehabilitation
3	Serious condition: section loss, deterioration, spalling or scouring have seriously affected primary structural components; immediate rehabilitation needed
2	Critical Condition: advanced deterioration of primary structural elements for urgent rehabilitation; bridge may be closed until corrective action is taken
1	Imminent failure condition: major deterioration or section loss present; bridge may be closed to traffic but corrective action can put it back into light service
0	Failed condition: out of service and beyond corrective action

In an effort to overcome some of the drawbacks of the NBI condition rating, the FHWA and AASHTO have developed the commonly recognized (CoRe) element condition rating. This system consists of 108 standardized elements, for example, 12 = Bare Concrete deck, 14 = concrete deck protected with overlay, 101 = unpainted steel web/girder. Each bridge would contain an average of about 10 elements. The CoRe elements have been implemented by Pontis software

(Thompson and Shepard, 2000) for five condition states: protected, exposed, attacked, damaged and failed for which each condition sate corresponds to a percentage of damaged areas.

Hearn (1998) presented a new approach for condition rating in the US that defines the condition states as five stages of service life for the commonly recognized (CoRe) elements. Table 2.5 indicates the five stages of service life for a sample bridge element, in this case a painted steel element. A simple description of these stages is provided in Table 2.6 (Hearn and Shim, 1998).

Table 2.5: Service Life stages (Hearn, 1998)

	Service life stages				
	1	*2*	*3*	*4*	*5*
Stages of service life	Protected	Exposed	Vulnerable	Attacked	Damaged
Painted steel element	Good Paint	Failing Paint	Staining	Surface Corrosion	Section Loss

Table 2.6: Service Life Stages (Hearn and Shim, 1998)

Condition State	Description
Protected	No deterioration process active. No aggressive agent present. No loss in protection against aggressive agent.
Exposed	No deterioration process active. No aggressive agent present. Lack of protection against aggressive agent.
Vulnerable	No deterioration process active. No aggressive agent present. Deterioration may become active soon.
Attacked	Deterioration process is active.
Damaged	Element is measurably or visibly damaged.

New York (NY) City has developed its own rating system (Yanev, 1997), in which all components in all spans are inspected at least once every two years and are rated as follows: 7 = New, 5 = functioning well, 3 = not functioning as designed, and 1 = failed. The even numbers 6, 4, and 2 denote intermediate conditions. Thirteen bridge elements are used in this system and are assigned relative weights, as listed in Table 2.7. Field observations about some of these elements are presented in

Table 2.8. The overall bridge condition rating (BCR) can then be calculated from the element ratings as follows:

$$BCR = \frac{\sum (Component\ rating \times Weight)}{\sum Weights} \tag{2.1}$$

Table 2.7: Element Weights in the NY Rating System (Yanev, 1997)

	Component	Weight
1	Bearings	6
2	Back wall	5
3	Abutments	8
4	Wing walls	5
5	Piers	8
6	Primary members	10
7	Secondary members	5
8	Deck	8
9	Curb	1
10	Wearing surface	4
11	Bridge seats	6
12	Sidewalks	2
13	Joints	4

Table 2.8: Field Observations in the NY Rating System (Yanev, 1997)

Primary Members	Steel and concrete deteriorate at a nearly constant rate from new 7 to 1 in approximately 30 years.
Bridge Deck	Decks with separate overlay have a useful life of 40 years without joints and 30 years with joints.
Bridge Seats, Bearings, Piers, Sidewalks	Ratings drop from 7 to 4 (3 for bearings) in less than 5 years. Thereafter, there is a slower rate of declining to 1 after 30 years.
Joints	Joints begin to fail after 10 years although experience suggests even worse performance in the field.

A Japanese study has presented an evaluation method for the degree of damage to reinforced concrete bridges. The damage rating for RC decks may be classified into five categories that correspond to the magnitude of the crack density on the deck surfaces: the crack length per unit surface (m/m²), as shown in Table 2.9 (Dogaki et al., 2000). The degree of deterioration D_c of RC decks is expressed in terms of crack density C_d as

$$D_c = \frac{C_d}{10} \tag{2.2}$$

Table 2.9: Damage Ranking for RC decks (Dogaki et al., 2000)

Deteriorating State of RC Decks			Need for Repair
Damage Rank	*Deterioration Degree (D_c)*	*Crack Density (C_d) (m/m²)*	
I	0.0 — 0.3	0 — 3	Conditioned (No Rehabilitation)
II	0.3 — 0.6	3 — 6	Possible Rehabilitation
III	0.6 — 0.8	6 — 8	Rehabilitation or Upgrading
IV	0.8 — 0.9	8 — 9	Rehabilitation, Upgrading, or Replacement
V	0.9 —	9 —	Most Severe (Upgrading or Replacement)

Brodsky et al. (2006) stated that the Moscow bridge management system assess the bridge elements based on five-point scale, as shown in Table 2.10. The scale shows the estimated percentage of wear and the type of repair associated with each condition.

Table 2.10: Classification of Condition Categories in Moscow Bridge Management System (Brodsky et al., 2006)

Condition	Assessment	Wear	Type of required repair
1	Good	Less than 20%	Cleaning, scheduled maintenance
1.5	Not very good	20 – 40 %	Preventive maintenance
2	Poor	40 – 60 %	Current (local) repair
2.5	Very Poor	60 – 80%	Major repair
3	Unacceptable	80 – 100%	Replacement or restoration repair

2.5 Bridge Deterioration Models

Bridge deterioration is the process of decline in the condition of the bridge resulting from normal operating conditions (Abed-Al-Rahim and Johnston, 1995), excluding damage from such events as earthquakes, accidents, or fire. The deterioration process exhibits the complex phenomena of physical and chemical changes that occur in different bridge components. What makes the problem more complicated is that each element has its own unique deterioration rate (Thompson, 2001a). Accurately predicting the rate of deterioration for each bridge element is, therefore, crucial to the success of any BMS.

In the late 1980s, deterioration models for bridge components were introduced in order to predict the future condition of infrastructure assets as a function of their expected service condition. Deterioration models in Infrastructure Management Systems (IMSs) were first developed for Pavement Management Systems (PMSs). Deterioration models in PMS differ from those in BMS because of the differences in construction materials, structural functionality, and the types of loads carried. In addition, safety is more important in bridges than in pavements. Despite of the dissimilarities in the deterioration models for pavement and bridges, the approaches to developing pavement deterioration models for PMSs have been employed in the development of bridge deterioration models in BMSs.

In a study conducted at the transportation systems center (TSC), Busa et al. (1985) examined the factors affecting the deterioration of a bridge's condition. The study concluded that the top-ranking factors that affect deterioration include age, average daily traffic, the environment, the bridge design parameters, and the quality of the construction and materials used.

According to the FHWA's Bridge Management System report (1989a), most studies of deterioration rates tend to predict slower declines in condition ratings after 15 years. The report included results from a regression analysis of NBI data for the deterioration of structural conditions. For example, the results suggest that the average deck condition rating declines at the rate of 0.104 points per year for approximately the first 10 years and 0.025 points per year for the remaining years. In addition, the overall structural condition declines at a value of 0.094 per year for 10 years and 0.025 per year thereafter. These results suggest that the condition will not fall below 6 until after 60 years, which is not the case in real life: bridges deteriorate at a much higher rate. In another study, the estimated average deterioration of decks was about 1 point in 8 years and 1 point in 10 years for the superstructure and substructure, respectively. A simple description of the deterioration process over time is given in Figure 2.2. In general, deterioration models can be categorized into four main categories: mechanistic models, deterministic models, stochastic models, and artificial intelligence (AI) models.

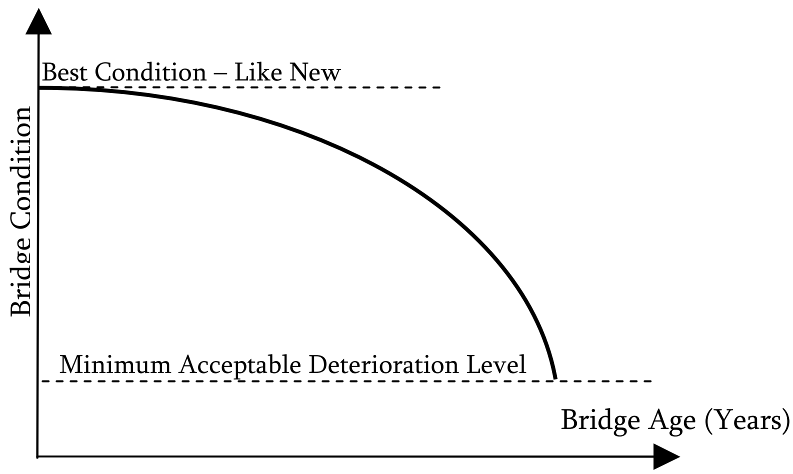


Figure 2.2: Bridge Deterioration

2.5.1 Mechanistic Models

Mechanistic models are detailed models that describe the specific deterioration mechanisms of particular bridge components. These models are usually effective at the project level but not at the network level (Kayser and Nowak, 1989). The mechanism of the corrosion process for the superstructure of steel bridges has been developed by Sobanjo (1991). The following expression predicts the deterioration:

$$C = At^{B} \tag{2.3}$$

where C = average corrosion penetration, t = time in years, and A, B = constants.

Miyamoto et al. (1999) used load-carrying capacity and durability to predict bridge deterioration. The load-carrying capacity is defined as the bridge's performance based on the load-carrying capacity of the bridge member, whereas durability is defined as the ability of the bridge member to resist deterioration. The scores for the load-carrying capacity and durability are ranked on a scale of 0 to 100 (a newly built bridge). As the bridge deteriorates, the score decreases and finally drops to 0, indicating that the bridge should no longer be in service and requires immediate action.

Yet, as reported by Stukhart et al. (1991), most of these models have not been tested in practice and none of the DOTs uses such models. In addition of being unreliable for the development of BMSs, it is difficult with the use of these models to incorporate the various variables affecting the deterioration process.

2.5.2 Deterministic Models

Deterministic models are dependent on a mathematical or statistical formula for the relationship between the factors affecting bridge deterioration and the measure of a bridge's condition. The output of such models is expressed by deterministic values (i.e., there are no probabilities involved) that represent the average predicted conditions. The models can be categorized as using straight-line extrapolation, regression, and curve-fitting method (Morcous, 2000). The different types of deterministic methods are discussed below.

Straight-Line Extrapolation: The simplest condition-prediction model is based on straight-line extrapolation; this method can be used to predict the material condition rating (MCR) of a bridge given the assumption that traffic loading and maintenance history follow a straight line. The method requires only one condition measurement to be carried out after construction; an initial condition can be assumed at the time of construction and a second condition is determined at the time of the inspection. The straight-line extrapolation is used because of its simplicity (Shahin, 1994). Although this method is accurate enough for predicting short-term conditions, it is not accurate for long periods of time. In addition, the straight line method can not predict the rate of deterioration of a relatively new bridge, or of a bridge that has undergone some repair or maintenance.

Regression: Regression models are used to establish an empirical relationship between two or more variables: one dependent variable and one or more independent variables. Each variable is described in terms of its mean and variance (Shahin, 1994). Several forms of regression models are presented in the literature, including linear and non-linear ones.

2.5.3 Stochastic Models

The theory of stochastic processes is now being increasingly used in applications in engineering and other applied sciences. The general concepts of stochastic processes can be found in Srinivasan and Mehta (1978). The use of stochastic models has contributed significantly to the field of modelling infrastructure deterioration because of the high uncertainty and randomness involved in the deterioration process. The most commonly used stochastic technique for infrastructure deterioration is the Markov chain model.

Markov Chains: One of the most popular stochastic techniques obtained from operation research is the Markov decision process (MDP). This process has been used to develop stochastic deterioration models for different infrastructure facilities. Markovian bridge deterioration models are based on the concept of defining states in terms of bridge condition ratings and obtaining the probabilities of a bridge condition changing from one state to another (Jiang, 1990). Details about Markov chains can be found in Appendix B.

Based on the FHWA condition rating for the deterioration in the condition of the Indiana Department of Highway bridges (IDOH), Jiang (1990) and Jiang et al. (1988) have developed a performance prediction model by using the Markov chain,. In this model, a transition probability matrix was developed for three main bridge components: the deck, superstructure, and substructure. The transition probability matrices take into account the type of structure (steel or concrete), the effect of age (assuming that the rate of deterioration differs with age), and the highway type (interstate or other). The drawback of this study is that it does not consider other factors affecting the deterioration process such as traffic density and climate.

In Pontis, Markov chain is utilized in the development of the CoRe element deterioration model. The model incorporates five condition states for each element. To include the factors that affect the deterioration, Pontis classifies each element of a bridge into one of four categories of environment: benign, low, moderate, or severe. Each environment represents a different level of the impact of the external factors on the performance of the element over time, and a deterioration matrix is assigned for each element in each environment (Thompson et al., 1998).

It should be noted that the transition matrix (and accordingly, the deterioration behaviour) is greatly affected by the service condition (or the environment) to which the bridge element is exposed. In an interesting study by Morcous et al. (2003), they attempted to describe clearly the service conditions associated with the four environmental categories described in the Pontis system: benign, low, moderate, and severe. Genetic algorithms are used to arrive at the best of the four environmental categories: one that describes a given combination of the service parameters listed in Table 2.11. Once the category is known, then the transition matrix associated with it is used to predict the deterioration.

Table 2.11: Service Parameters Affecting Deterioration (Morcous et al., 2003)

Parameter	Class	Description
Highway Type	1	Express and national
	2	Regional and collector
	3	Local and others
Region	1	Eastern
	2	Northern
	3	Central
	4	Western
Average Daily Traffic	1	<5000
	2	>=5000
% of Truck Traffic	1	<10%
	2	>=10%

Although Markovian models have been employed in many advanced BMSs such as Pontis and Bridigit, great advances in modelling bridge deteriorations have been achieved with their use, they are still based on assumptions and have some limitations:

- Markovian models assume that past conditions have no effect on predicted ones (Madanat et al., 1997).

- Markovian models assume discrete transition time intervals, a constant bridge population, and stationary transition probabilities (Collins, 1972).
- It is quite difficult for Markovian models to consider the interactive effects among the deterioration mechanisms of different bridge components (Cesare et al., 1992).
- The transition probabilities are estimated in terms of subjective engineering judgement and require frequent updating when new data are obtained (Tokdemir et al., 2000).

2.5.4 Artificial Intelligence Deterioration Models

The area of artificial intelligence (AI) is comprised of several different techniques that have been utilized in a variety of applications during the last few decades. Artificial neural networks (ANNs), case based reasoning (CBR), and machine learning (ML) are examples of AI techniques that have been recognized as powerful tools for solving engineering problems.

The feasibility of using ANNs in modelling bridge deterioration has been investigated by Sobanjo (1997). A multi-layer ANN was utilized to relate the age of the bridge superstructure (in years) to its condition rating (a numeric value from 1 to 9). The network configuration used in this study is depicted in Figure 2.3. The inspection records for 50 bridge superstructures were utilized to train and test the network; 75% of the data were used for training, while the remaining data were used for testing. The use of this ANN resulted in 79% of the predicted values were with a 15% prediction error.

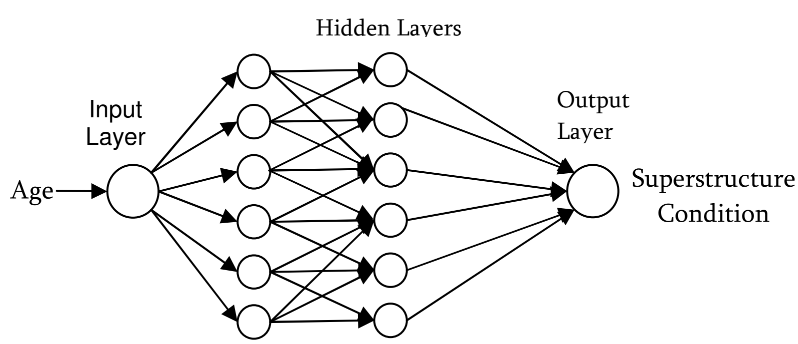


Figure 2.3: Multi-layer Neural Networks (Sobanjo, 1997)

In more detailed AI model, Tokdemir et al. (2000), using age, traffic, and geometrical and structural attributes as explanatory variables, predicted a bridge sufficiency index (SI) ranging from 0 to 100. Testing the performance of the developed ANN resulted in an average percentage of correct solutions of 33.5% and 62.5% with a prediction error of 3% and 6%, respectively. Two of the difficulties associated with using ANN models are as follows:

- The determination of an efficient ANN architecture is carried out in an ad hoc manner and does not follow clear rules (Boussabina, 1996; Hua, 1996).
- ANNs work well when the input and output variables are numerical values. The conversion to numbers may lead to the loss of information that was contained in the original representation (Arditi and Tokdemir, 1999).

2.5.5 After-Repair Deterioration

It is very important that any BMS be able to estimate the future conditions of bridges after a specific repair has been performed. It was recorded in the literature that the rate of deterioration of rehabilitated bridges is greater than that of newly constructed bridges. It was, also, noticed that rehabilitated bridges do not revert back to their best condition (Yanev and Xiaomong, 1993). However, currently, most BMSs assume that the rate of deterioration after repair is the same as that in effect when the bridge was constructed. Bolukbasi et al. (2006) recently investigated the rate of deterioration of reconstructed steel decks for highway bridges in Illinois. Figure 2.4 shows the comparison of the rates of deterioration for new bridge decks and those for reconstructed decks. The study concluded that a reconstructed deck has at least a 25% shorter life span than new decks. Although Bolukbasi et al. (2006) quantified the rate of deterioration for bridge decks after improvement; they included only one type of improvement: deck replacement. The study needs to be expanded to include other improvement types as well as other bridge elements.

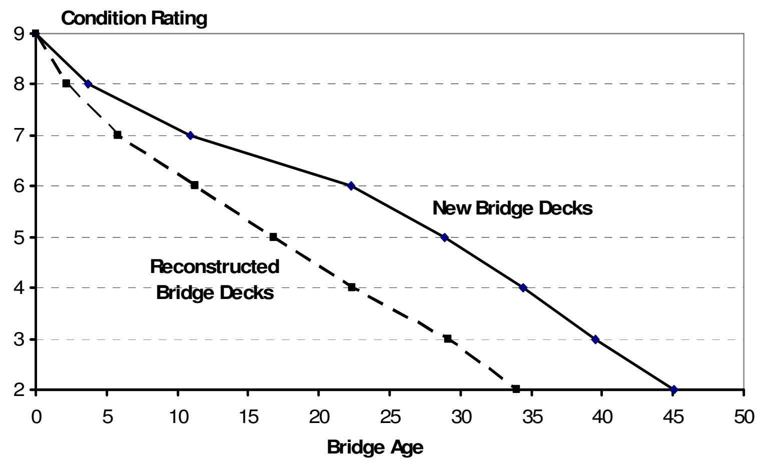


Figure 2.4: Deterioration of New and Constructed Bridge Decks (Bolukbasi et al., 2006)

2.6 Cost Models

The cost of maintenance, repair and rehabilitation (MR&R) in BMSs can be expressed either as a unit cost or as a percentage of the cost of the initial or replacement of the bridge. An example of an MR&R unit cost is presented by Saito and Sinha (1990) with respect to bridge deck repairs, for which the repair costs are expressed in dollars per square foot of deck area (Table 2.12). An example of percentage MR&R costs is given in Seo (1994), in which the cost of the repair depends on the repair intensity (light, medium, or extensive) and on the bridge component (deck, superstructure, or substructure) (Table 2.13).

Table 2.12: Repair Unit Cost (Saito and Sinha, 1990)

Rehabilitation Category		Unit Cost ($/ft^2)
1	Deck Overlay	$32.28
2	Deck Widening	$69.48
3	Deck Replacement and Widening	$72.70
4	Major Reconstruction	$27.57
5	Deck Replacement	$30.19
6	Superstructure Replacement	$35.23

Table 2.13: Cost of Major Components for Rehabilitation Intensities (Seo, 1994)

Intensity	Deck	Superstructure	Substructure
Light	28%	49%	26%
Medium	65%	74%	63%
Extensive	100%	100%	100%

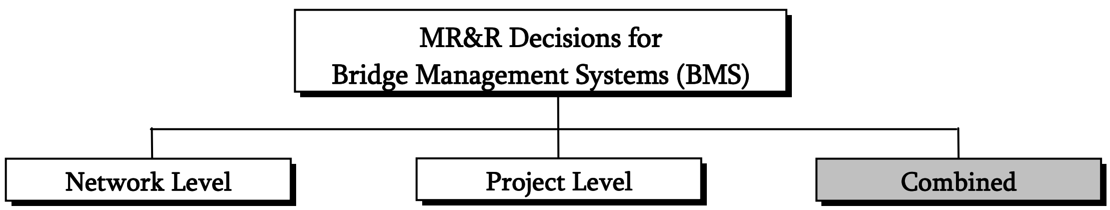
2.7 Maintenance Repair and Rehabilitation Decisions in BMSs

Deciding on the priorities for carrying out the activities for the maintenance, repair, and rehabilitation (MR&R) of bridges is the most challenging task in BMSs. The cost of MR&R consumes most of the available funding for bridge improvements. Therefore, the budget for these activities should be carefully allocated, particularly when the life cycle cost (LCC) is considered. Setting priorities for MR&R activities is a multi-attribute decision-making problem which requires simultaneous evaluation at both the network level (i.e., which bridge to repair), and the project level (i.e., which repair strategy for a given bridge).

2.7.1 Network-Level versus Project-Level Decisions

One of the main aspects that need to be considered in MR&R decisions is the practical constraints on the network level and the project level. The prioritization of bridges for repair is considered a network-level decision, while the selection of repair methods for an individual bridge is considered a project-level decision. At the project level, the focus is mainly on repair strategies, the cost of the repair, and the improvement expected from the repair. Ideally, both the network and project levels are complementary; they should be used together in BMSs (Thompson et al., 2003b). The output from the project level is detailed cost estimates for possible strategies for repairing various bridges. These can then be used to make network-level decisions related to prioritizing the bridges and determine the allocation of the budget.

Dealing with network and project levels separately will lead to a non-optimal decision. In the literature, BMSs have been developed to support either the network level or project level, and only to a lesser extent to support both of them. At the Network level, Li et al. (1998) developed a network level BMS prototype; the model produces a list of prioritized bridges which gives higher priority ratings to bridges with a greater need for maintenance and rehabilitation. At the project level, a Finnish project-level BMS uses the recommendations from the network-level BMS to decide on a repair strategy for individual bridges based on a life cycle cost analysis (Soderqvist and Veijola, 2000). LEfforts related to incorporating both the network level and the project level have been increasing in recent years (Figure 2.5), yet the incorporation of project level into the network level complicates the life cycle cost analysis and makes traditional optimization tools insufficient to deal with the large problem size. Figure 2.5 presents a brief summary of the research efforts in developing BMSs, with a brief summary of their advantages and disadvantages.



	Network Level	Project Level	Combined
Description	- Focuses on overall bridge network. - Prioritizes bridges for repair purposes using weights or cost-benefit analysis. - May consider budget limits. - May consider multi-year planning - May use LCC	- Focuses on individual bridge. - Suggests best repair methods for all bridge components. - Usually done in isolation from network analysis. - May use LCC	- Tries to combine both network-level & project-level decisions. - Use life-cycle cost analysis. - Current trend in BMS.
Examples	- Li et al., 1998.	- Soderqvist and Veijola, 2000. - Reel and Conte, 1994.	
Comments	- Does not consider individual project needs; thus, decisions may not be optimal. - Approximations needed to simplify analysis (salvage value, user cost).	- No consideration for execution constraints. - Isolated from network level analysis; thus, decisions may not be optimal.	- **May not consider frequent repairs.** - **No consideration for execution constraints.** - **Frequent failure of mathematical optimization due to large problem size.** - **Full integration is complex.**
Techniques	- Priority Ranking, - Optimization + LCCA	- Benefit/Cost ration - Optimization, - AI + LCCA	- Combined

Figure 2.5: Network-Level versus Project-Level BMS (Hegazy et al., 2004)

2.8 Network-Level Decisions

Prioritization methods for selecting bridges for repair range from subjective decisions based on engineering judgement to complex optimization techniques. Prioritization methods can be grouped into the following types: priority ranking (e.g. sufficiency rating (SR), level-of-service (LOS), deficiency rating, and incremental-benefit-cost B/C analysis), mathematical optimization, and AI technique.

2.8.1 Priority-Ranking Techniques

In North America, several attempts have been made to develop BMSs that are based on priority ranking techniques for selecting bridges for MR&R actions. Many decision makers consider the rule of "Choosing projects with the worst conditions" to be rational and therefore adopt it when they are prioritizing which bridges to select for repair. However, this rule does not maximize the benefits or reduce the life cycle cost, so BMSs based on this rule do not guarantee optimal solutions (Jiang, 1990). Ranking on the subjective basis of engineering judgement is acceptable for young and small networks of bridges. This subjective prioritization, however, is not suitable for a large network of bridges (Mohamed, 1995). Priority ranking techniques are based on calculating a value for each bridge and then sorting all bridges in descending order of their indices. Starting with the bridge with the highest ranking index, projects are carried out until the available funds are exhausted. Although such techniques provide good solutions, they are not optimal (Mohamed, 1995). Alternatives for priority ranking at the network level are introduced below.

Condition and sufficiency-rating system: Condition-rating models are used to sort the bridges according to their relative importance in the network. The most important bridges appear at the top of the priority list. The term "important" reflects the type, location, and condition of each bridge. Maintenance actions are assigned to the bridges based on the available budget. This method still does not provide an optimal allocation of the budget (Mohamed, 1995).

The sufficiency-rating (SR) approach is widely used by agencies and recommended by the FHWA as a priority-ranking technique to determine the eligibility of bridges for replacement or rehabilitation. The SR method calculates a numerical value as an indicator of whether the bridge can remain in service. The results of this analysis are expressed as a percentage on a scale from 0 to 100, with 100 representing completely sufficient bridge and 0 representing a deficient or insufficient bridge. Bridge deficiencies are described as one of two categories: structurally deficient or functionally obsolete (Xanthakos, 1996). The drawbacks of the SR method are that it is based on standards for load capacity and bridge width. Based on this concept, relatively narrow bridges that have a low capacity are assigned low sufficiency ratings, although these bridges may be in good condition and adequate for service. The SR method also overlooks the Average Daily Traffic (ADT) and user cost in the decision making. The SR is also unable to provide a repair strategy for each bridge.

Level-of-service-deficiency rating: Another type of priority ranking is the level-of-service-deficiency rating (LOS), which has been proposed as a way of overcoming the disadvantages of the SR system (Johnston and Zia, 1983). This approach recognizes that priorities should be set according to the degree to which a bridge is deficient in meeting the public's needs. To evaluate a bridge in meeting its intended function, three characteristics are used: load capacity, clear deck width, and vertical roadway clearance. Although, the LOS rating has proved to be superior to condition and sufficiency rating, it still has drawbacks. The LOS rating does not have the ability to determine the recommended action (i.e., ignoring the project level, or determining whether major maintenance, rehabilitation, or replacement is needed). Secondly, it can not predict the optimal timing for any repair alternative (Mohamed, 1995).

Benefit/Cost Ratio: The benefit/cost (B/C) ratio is defined as the benefit gained by moving from one repair to another more expensive divided by the associated extra costs. The benefits include those for both the agency and the user. Agency benefits are defined as "the present worth of future cost savings to the agency because of bridge expenditures" (FHWA, 1989b). User benefits are considered in terms of cost reductions or savings to the user because of an improvement. The first implementation of the B/C ratio method was for a project-level decision, in which comparing different repair alternatives can be analyzed. A computer model was developed to extend the B/C ratio from the project level to the network level; the model allocates funds for bridges at the network level. The application of an incremental B/C technique is recommended for a system with a small number of bridges. Alternatives are selected in descending order of their B/C ratios until the budget is exhausted.

Farid et al. (1993) reported that the B/C ratio is difficult to use for estimating user costs and for predicting future conditions. The B/C ratio also assumes that the benefits gained from an improvement action are constant, whether the projects are undertaken in the present or at any other time within the analysis period, which assumption is incorrect. The B/C ratio can be used to compare different improvement actions for the same bridge. Although the B/C technique can provide good solutions, it can not guarantee the optimal allocation of funds (Mohamed, 1995).

2.8.2 Mathematical Optimization Techniques

Although mathematical optimization techniques have been implemented successfully at the project level, they fail to incorporate network-level constraints. In an attempt by AL-Subhi et al. (1989) to extend mathematical optimization techniques to include network-level decisions, an optimization model called OPBRIDGE was developed for the North Carolina Department of Transportation. The model optimizes the budget allocation for the bridge network by minimizing the overall reductions in the annual costs for all bridges. The prioritization is set for each year separately through the use of an integer-linear programming formulation. The constraints used were the budget, the LOS, and the minimum allowable condition rating. The drawbacks of this method are the limited number of bridges that can be handled. The performance evaluation of the bridge network using reliability index is presented in Liu and Frangopol (2005c and 2006b). Life-cycle, failure, and user costs are conflicting criteria in decision analysis for bridge networks, Liu and Frangopol (2006a) presented a novel approach to consider these conflicting criteria in a multi-objective optimization; however, the presented model can not handle large-scale networks. To balance between keeping the deteriorated bridges connected and minimize maintenance cost, Liu and Frangopol (2005a) presented a model based on probabilistic approach in order to keep the highway network connected.

2.9 Project-Level Decisions

A Project-level decision determines the MR&R strategy associated with repair cost, and the optimal timing for performing the repairs. In the literature, different approaches for project-level decisions have been presented. Project-level decisions can be categorized according to the following techniques: Benefit/Cost ratio (B/C), LCC mathematical optimization, and AI techniques.

Benefit/Cost ratio (B/C): The B/C ratio technique has been used successfully at the project level to compare repair strategies. The benefit gained for each repair strategy is estimated for each individual bridge. The repair strategy with the highest benefit is then selected. The drawback of this technique is the fact that network-level constraints are ignored, e.g., budget limits.

Mathematical Optimization Techniques: Mathematical models allow the manipulation of the trade-off between the objectives and the constraints so that an optimal solution can be reached. Jiang (1990) used integer-linear programming to formulate the optimization model for the Indiana Department of Transportation (INDOT). Three key rehabilitation activities were considered: deck reconstruction, deck replacement, and bridge replacement. Each activity is represented a zero-one variable: "1" if the activity is selected and "0" otherwise. The model divides the decision problem into stages; each year is considered a stage. At each stage, the Markov chain technique is used to predict the future bridge condition, and integer-linear programming is used to maximize the effectiveness of the network. The only constraints in this model are the budget limits and the fact that only one activity can be undertaken. As the bridge age increases, the condition rating gradually decreases from the new-condition rating. As shown in Figure 2.6, the area between the performance curves indicate old condition and the new one represents the condition improvement that can be expected if the rehabilitation or replacement activity is undertaken. To consider user costs, the average daily traffic (ADT) is multiplied by the expected area of improvement (ΔA_i). This value is considered a measure of improvement that can be experienced by the users or vehicles on the bridge. Traffic safety conditions and the impact of a bridge on a community are two other factors affecting the decision. The effectiveness of the system is defined by the following:

$$E_i = ADT_i \times \Delta A_i(\alpha) \times (1 + C_{safe_i}) \times (1 + X_{impc_i}) \tag{2.4}$$

where E = the effectiveness gained by bridge i if activity a is selected; α = the improvement activity; a = 1 - deck reconstruction, 2 – deck replacement, 3 - bridge replacement; ADT = the average daily traffic; C_{safei} = the traffic safety index for bridge I; and X_{mpci} = the community impact of bridge expressed in terms of detour length.

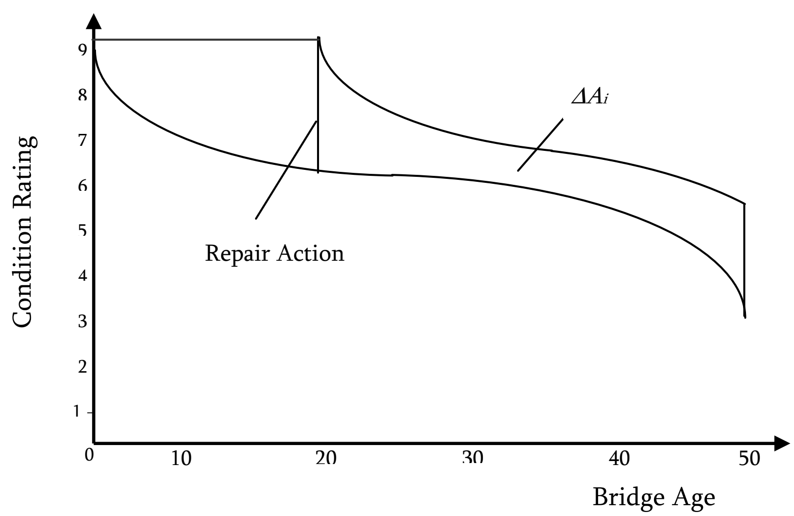


Figure 2.6: Area of a Performance Curve Obtained by Rehabilitation (Jiang, 1990)

However, the drawbacks of such a model are that one activity can not be undertaken more than once on one bridge in (T) years that is no multiple visits are considered; if the bridge is not considered in a specified year, the cost of rehabilitation should be increased in the coming years; the application of the integer linear programming technique at each stage does not provide an optimal solution for a large number of decision variables for multiple number of years; the system's effectiveness is represented only by the users' benefits while the agency cost is ignored; the model assumes that the effectiveness of carrying out an improvement action depends only on the condition of the bridge and the accumulated costs due to delaying the action are not considered; and the implementation of integer-linear programming can not provide a solution for more than 1000 bridges (Mohamed, 1995). The application of probability and uncertainty is presented in Liu and Frangopol (2004 and 2005b) where the bridge maintenance planning is decided based on the probabilistic performance prediction and multi-objective combinatorial for bridge decks.

Artificial Intelligence (AI): AI techniques have been devised to solve the shortcomings of the priority ranking and mathematical models: they make it easier to define more than one constraint and optimize the time required for maintenance. Another advantage of AI models is their ability to optimize a network of bridges that have different alternatives for improvements on the planning horizon. A great deal has been invested in examining the application of AI techniques in BMSs as is detailed in the following subsections.

Artificial Neural Networks (ANNs): Mohamed et al. (1995) studied the use of an ANN for selecting bridge repair strategies based on minimizing the benefit loss. The objective function is

$$Minimize \quad Z = \sum_{t=1}^{T} \sum_{B=1}^{N} \sum_{A=0}^{m(t,B)} BL(t,B,A)\ .\ X(t,B,A) \qquad (2.5)$$

Where Z = the total benefit loss, T = the analysis period, N = the total number of bridges, $m\ (t,B)$= the number of improvement alternatives for bridge B in year t, $BL(t,B,A)$= the amount of benefit loss if alternative A for bridge B was chosen in time t, and $X(t,B,A)$ = 1 if alternative A for bridge B is chosen in time t and 0 otherwise.

The input to the ANN model was the benefit loss (BL) and initial cost (IC) of each repair alternative for each bridge and the available budget. The output was a zero-one selection, i.e., the model selected a specific alternative for the current year or not, based on a trained neural network. The drawbacks of such a model are the fact that it ignores the practical constraints in the optimization at the network level, and that the model must know the BL and the IC for each repair strategy for each bridge.

2.10 Combined Network-Level and Project-Level Decisions

In recent years, several attempts have been made to integrate network-level and project-level constraints in the decision making of BMSs. Most of these attempts have used GA technique. The following is a brief review of the advantages and disadvantages of these efforts.

Genetic algorithms (GA): Liu and Hammad (1997) presented the application of the mutli-objective optimization of bridge decks rehabilitation. The objective function was to minimize both the total LCC and the average degree of deterioration weighted by the bridge deck area. The total rehabilitation cost (C) was determined by

$$Minimize\ C = \sum_{i=1}^{N} \sum_{t=1}^{T} [(1+r)^{-t}\ .c\,.s(i)\,.n(i,t)] \tag{2.6}$$

where N = the number of bridges, T = the length of the planning period, r = the discount ratio, c = the unit area cost of rehabilitation, $s(i)$ = the deck area of bridge i, and $n(i,t)$ = 1 if a rehabilitation cost is calculated or 0 otherwise.

In the GA coding, the string bits of “doing nothing” and “undertaking rehabilitation action” are defined by the binary values of 0 and 1. The study shows that the use of a GA was successful in optimizing bridge deck rehabilitation plans. The shortcomings of this model, however, are that only one repair alternative is included and that only the deck rehabilitation is considered; the rest of bridge components are ignored. In addition, the user cost during the rehabilitation process was not included in the optimization formulation.

Miyamoto et al. (1999) utilized GA to minimize the repair cost and maximize the quality index. The output of the model consisted of different maintenance plans for the bridge network. In this model, the number of repair alternatives is also limited, and the user costs are overlooked in the optimization formulation.

Dogaki et al. (2000) presented a GA model for planning the maintenance of reinforced concrete decks. The deterioration model was given by a probability-based transition matrix. The evaluation of the degree of deterioration of the deck slab was based on the crack density. The objective function was to minimize the maintenance cost and maximize the benefit derived from the maintenance. The constraints considered in this model were detours, traffic capacity, the possibility of widening of the bridge width, traffic constraints, and the importance of the bridge. The model includes the LCC, the user cost, and the environmental cost. However, this model deals only with deck repair/rehabilitation plans, while other bridge components are neglected. The model also ignores the number of visits per bridge through the planning horizon.

Furuta et al. (2006) proposed the concept of multi-objective bridge maintenance planning optimization. In this research, three objective functions were considered: the life cycle cost (LCC), the service life, and the safety level. The target was to minimize the LCC while maximizing the service life and safety level using a multi-objective genetic algorithm (MOGA). A case study of 10 concrete bridges with similar piers and floor plans was considered. The oldest bridge in the case study was two years old. The proposed model was able to arrive at several near-optimal maintenance plans in order to assist bridge engineers in their decision making. However, the network used for testing the MOGA was relatively small (only 10 bridges), and with larger number of bridges, the problem is more complicated. Frangopol and Liu (2007) present the application of multi-objective optimization for safety and life cycle cost for civil infrastructure; also, Neves et al. (2006a; b) used multi-objective optimization for different bridge maintenance types.

2.11 Commercial Bridge Management Systems

Most Bridge Management systems in the USA were developed prior to 1991. Pontis and Bridgit are two very well known BMSs. Other countries have developed their own BMSs. The following is a review of existing BMSs and their unique features.

2.11.1 Pontis

In 1992, the first version of Pontis (Latin for bridge) was completed under the auspices of the FHWA (Thompson, 1993). PONTIS consists of five modules: a database module, a prediction module, a condition states and feasible action module, a cost module, and a network optimization module. The database module includes all the bridges in the network, and each bridge is divided into constituent elements. The deterioration module predicts future bridge conditions using the Markov approach (Thompson et al., 1998). The cost module estimates repair and user costs.

In Pontis, the prioritization of bridges is carried out sequentially for two types of repair strategies; the first is maintenance, repair, and rehabilitation (MR&R), which improves the condition of the bridge. The second is improvement actions, which improve the level-of-service (LOS) of the bridge. All bridge projects are ranked by their incremental benefit/cost ratios, and those bridges above the budget limit are carried out. The rest of the list will be analyzed again and prioritized for future years. This procedure is repeated throughout the required analysis period. Pontis has the advantage of being the first complete software application developed for bridge management systems. However, the following are some of its drawbacks:

- Pontis network prioritization module differentiates between two sets of actions within the same class: major rehabilitation and replacement projects, and improvement projects. The rehabilitation and replacement projects should be analyzed in conjunction with the improvement projects because both have the same effect on the bridge network with respect to both the agency costs and on the user costs. The separation between the two leads to the user costs being ignored (Mohamed, 1995).
- Pontis uses the incremental benefit/cost method to rank the recommended bridge projects. This method does not insure that funds are put to the best possible use (Ryall, 2001).
- Dividing a bridge into sections in order to choose the best action for each section may be suitable for pavement management, but dividing a bridge into elements in order to choose the best action for each one does not result in a good, co-ordinated solution (Mohamed, 1995).

2.11.2 Bridgit

Bridgit is a bridge management system developed jointly in 1985 by NCHRP and national engineering technology corporation (Hawk, 1999). It is very similar to Pontis in terms of modeling and capabilities. The advantage of Bridgit is its ability to define and distinguish between specific protections systems for components when determining feasible options. However, the disadvantage of Bridgit is the same for Pontis since they use almost the same prioritization approach.

2.11.3 Ontario Bridge Management System

In 1998, the Ontario Ministry of Transportation (MTO) decided to develop a new system for bridge management: Ontario bridge management system (OBMS). The inspection of elements is performed biennially and includes the recording of the type, severity, and extent of deterioration. The major elements included in OBMS are abutments, approaches, barriers, beams, bracing, coatings, culverts, decks, embankments, foundations, joints, piers, retaining walls, sidewalks, signs, and trusses (Thompson et al., 2003a). Each element has four possible condition states: excellent, good, fair, and poor.

The project level begins with the identification of the needs with respect to individual elements, as determined in recent inspections. Based on the condition of the element, a knowledge-based model identifies a number of feasible treatment alternatives. For each possible treatment, the Markov deterioration model predicts the element's condition at the end of the analysis period. Each possible combination of treatment alternatives for the elements is considered a potential project alternative. The number of project alternatives is then narrowed through the use of the benefit/cost analysis and a knowledge-based model that incorporates engineering and economic points of views. The benefits of a project alternative are assessed in terms of the reduction in the social costs of the life cycle achieved by implementing the project rather than choosing the do-nothing alternative (Thompson et al., 2001b; Thompson at al., 1999a).

At the network level, OBMS finds the set of projects that maximizes the benefit within the budget constraints. The network analysis provides a summary of the predictions about network-wide performance at any given funding level.

Thompson et al. (2003a) mentioned that OBMS has not yet been fully implemented by the municipalities since the network-level module has not been fully developed. In addition, the user cost is not currently considered in the model. Interviews with municipal bridge engineers have revealed that OBMS is used as storage for bridge network data and as a tool for tracking network-wide performance, while repair decisions are still made using traditional techniques

2.12 Summary and Conclusions

In this chapter, a review of the previous work on BMS components and MR&R decisions has been presented. The existing techniques for making MR&R decisions are classified into network-level decisions, project-level decisions, and combined network- and project-level decisions.

The literature survey revealed the components most suitable for integration into the present study. The FHWA condition-rating system was found to be the most popular and accepted rating system for assessing the condition of different bridge elements. The Markov deterioration model is the most accurate and popular deterioration model in the BMS, since it captures the uncertainty in the deterioration process. To evaluate the total costs on the planning horizon, combined network- and project-level LCCA is the best method for evaluating and analyzing all the costs incurred throughout the life of the bridge.

A main difficulty in the prioritization of a network of bridges is the large number of bridges and the number of repair alternatives for each bridge in each year through the planning horizon. Another difficulty is the limited budget for meeting different network- and project-level constraints. Most of the existing models deal separately with the project level and network level, leading to non optimal solution. Heuristic techniques are used for the prioritization of bridges. Although the solutions these techniques provide are good, they are not necessarily optimal. Mathematical techniques can arrive at better solutions, but the complexity of the mathematical computations efforts and the inability of these techniques to handle a large bridge inventory render them inadequate for the prioritization of bridges. The literature describes AI techniques that have been used and tested for the prioritization of bridges. However, most of the existing models have not integrated the project level and the network level in the optimized decisions. In their problem formulation, these models, also fail to incorporate the practical constraints faced by the transportation agency.

The present research focuses on the development of a BMS framework to assist bridge engineers in arriving at an optimal decision for managing their bridge networks, taking into consideration both network-level and project-level constraints.

Chapter 3

Bridge Deck Management System (BDMS)

3.1 Introduction

Bridge decks are considered the most vulnerable element in a bridge. A harsh environment, an increase in traffic volume, and aging are the main reasons for rapid bridge deck deterioration. As a result, every 10 to 15 years, bridge decks have to be replaced at a cost of about 30% to 50% of bridge rehabilitation budget. In light of limited available funds, the increase in deteriorated bridge decks and in the cost of maintenance, have led to the development of bridge deck management systems.

This chapter presents a simplified framework for bridge deck management system (BDMS) that considers both network-level and project-level decisions. To deal with the primary challenge of large problem size, different problem formulations are examined and experimented with using non-traditional optimization techniques based on evolutionary algorithms. The experiments were carried out using different numbers of bridges in order to represent the complexity of the problem.

3.2 BDMS Components

The components of the BDMS that incorporates both project-level and network-level decisions include the main components presented in Figure 3.1. As shown in Figure 3.1, several constraints should be taken into account in a bridge management system (BMS) including available technology, governmental, political, user, project, and network constraints (Hegazy et al., 2004). An effective BMS should be able to consider all practical constraints imposed on the decision making process for bridge repairs, not only at the project and network levels but also on the user, government, and municipality as well. A detailed discussion of the different models used in the BDMS is presented in the following section.

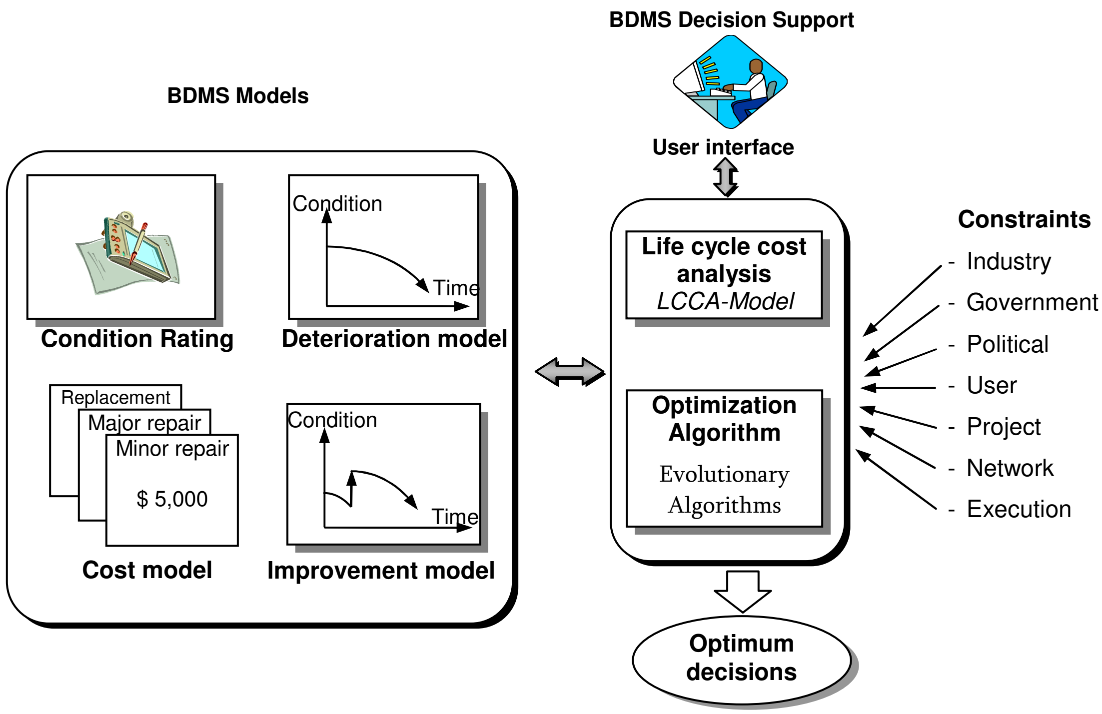


Figure 3.1: Components of the Bridge Deck Management System

3.3 BDMS Models

The following models are integrated and linked with the developed BDMS:

Bridge condition rating: Condition ratings are used to describe the existing condition of a bridge. The condition rating used in the proposed BDMS was developed by the FHWA (1989a), which uses a scale from 0 to 9 for bridge elements, in which 9 corresponds to the best condition (like new). The range from 0 to 9 is sufficiently wide to describe a suitable range of deck conditions. It is assumed that bridges are serviceable until the rating reaches a value of 3 (non-serviceable) (Table 3.1).

Table 3.1: Condition Rating (FHWA, 1998)

Rating	Description
N	Not applicable
9	Excellent condition, new condition: no noteworthy deficiencies
8	Very good condition: no repair is needed
7	Good condition: some minor problems for minor maintenance
6	Satisfactory condition: some minor deterioration for major maintenance
5	Fair condition: minor section loss, cracking, spalling, or scouring for minor rehabilitation; minor rehabilitation is needed
4	Poor condition: advanced section loss, deterioration, spalling or scour for major rehabilitation; major rehabilitation is needed
3	Serious condition: section loss, deterioration, spalling or scouring have seriously affected primary structural components; immediate rehabilitation is needed
2	Critical condition: advanced deterioration of primary structural elements; for urgent rehabilitation. The bridge may be closed until corrective action is taken
1	Imminent failure condition: major deterioration or section loss; bridge may be closed to traffic but corrective action may put it back into light service
0	Failed condition: out of service and beyond corrective action

Deterioration Model: A BMS requires a deterioration model that estimates the future decline in the condition of the bridge so that an appropriate rehabilitation strategy can be selected (Sobanjo, 1997). In this research, one of the most common models, the Markovian deterioration model, is used to predict future bridge conditions (Jiang et al., 1988). The Markov deterioration model calculates the future condition of the bridge using a transition probability matrix (TPM), as shown in Equation 3.1. The TPM has seven rows and seven columns representing the probabilities of moving from one condition to another in one-year intervals (i.e., to deteriorate from condition 9 to condition 3). It is assumed that within one year, the deck can either remain in its current condition or worsen by one level; therefore, each row of the matrix has two values only to represent the probability of the deck remaining in its current condition, and the probability of its moving to the next worse condition (the summation of both probabilities equals 1.0) (Jiang et al., 1988). For example, as shown in the TPM presented in Equation 3.2, if the current condition is 6 (6^{th} column and 6^{th} row), then the deck has a 40% probability of remaining in its current condition and a 60% probability to move to condition 5. Details about the Markov chain process and the use of a TPM to calculate a predicted condition at different ages are included in Appendix B.

$$
P = \begin{array}{c} \\ 9 \\ 8 \\ 7 \\ 6 \\ 5 \\ 4 \\ 3 \end{array}
\begin{array}{c}
\begin{array}{ccccccc} 9 & 8 & 7 & 6 & 5 & 4 & 3 \end{array} \\
\begin{bmatrix}
P_{11} & P_{12} & 0 & 0 & 0 & 0 & 0 \\
0 & P_{22} & P_{23} & 0 & 0 & 0 & 0 \\
0 & 0 & P_{33} & P_{34} & 0 & 0 & 0 \\
0 & 0 & 0 & P_{44} & P_{45} & 0 & 0 \\
0 & 0 & 0 & 0 & P_{55} & P_{56} & 0 \\
0 & 0 & 0 & 0 & 0 & P_{66} & P_{67} \\
0 & 0 & 0 & 0 & 0 & 0 & P_{77}
\end{bmatrix}
\end{array}
\tag{3.1}
$$

$$
P = \begin{array}{c} \\ 9 \\ 8 \\ 7 \\ 6 \\ 5 \\ 4 \\ 3 \end{array}
\begin{array}{c}
\begin{array}{ccccccc} 9 & 8 & 7 & 6 & 5 & 4 & 3 \end{array} \\
\begin{bmatrix}
0.85 & 0.15 & 0 & 0 & 0 & 0 & 0 \\
0 & 0.52 & 0.48 & 0 & 0 & 0 & 0 \\
0 & 0 & 0.70 & 0.30 & 0 & 0 & 0 \\
0 & 0 & 0 & 0.40 & 0.60 & 0 & 0 \\
0 & 0 & 0 & 0 & 0.50 & 0.50 & 0 \\
0 & 0 & 0 & 0 & 0 & 0.25 & 0.75 \\
0 & 0 & 0 & 0 & 0 & 0 & 1.00
\end{bmatrix}
\end{array}
\tag{3.2}
$$

In the present research, the two common deck types (steel and reinforced concrete) are considered, with each type having its own set of Markov-based deterioration models. Within each type, two Markov matrices have been set up to model deck deterioration under either a moderate or a severe operational environment. A moderate operational environment means that the bridge is located on a secondary highway, and the average daily traffic (ADT) is less than 10,000 vehicles. A severe environment, on the other hand, means that the deck is located on a major highway, the average daily traffic (ADT) is greater than 10,000 vehicles per day, and the deck is exposed to a large number of freezing cycles and many days of below-zero temperatures.

For a steel deck under severe operational environment, Figure 3.2 shows the Markov matrix and the deterioration curve which was determined based on the calculation of the predicted condition at different ages, as discussed in Appendix B. In this study, the initial values in the

Markov matrices for the deck deterioration models are taken as the generic TPMs proposed by Jiang (1990), which are based on a detailed study of bridges in Indiana, USA.

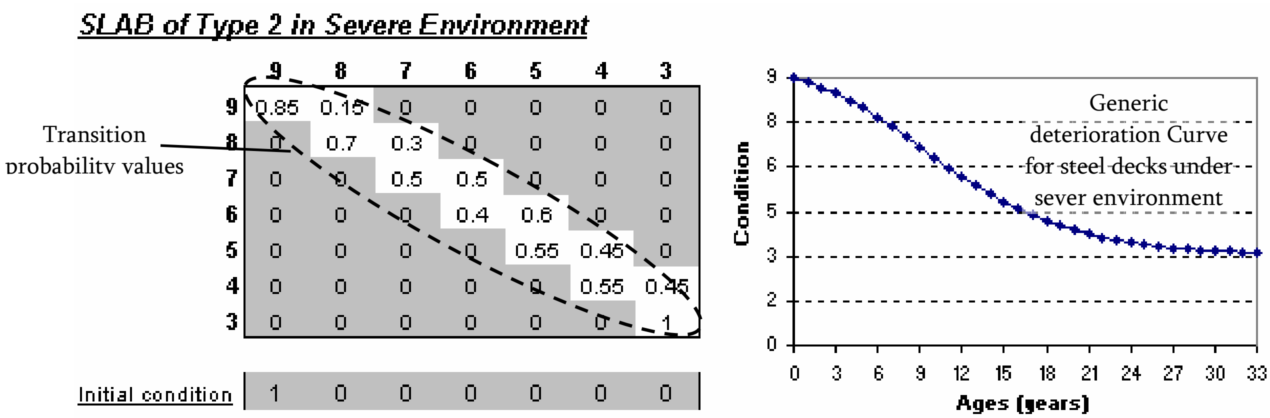


Figure 3.2: A Markov Deterioration Model for a Steel Deck in a Severe Environment

Because the deterioration curve in Figure 3.2, and all those proposed by Jiang (1990), is generic and does not represent the operational environment of a specific bridge deck, the present study proposes a mechanism for customizing the generic Markov matrix values for a specific deck using the historical condition data of that deck as collected through inspection. Figure 3.3 shows the Markov matrix customization process for an example of a concrete deck under a severe operational environment. The figure shows two actual condition measurements for a specific deck at year 6 (6.6) and at year 12 (4.9). Using these actual condition measurements, an optimization process was performed to modify the generic TPM to suit these data as follows:

Objective function: minimize the total error between the Markov-generated deterioration curve and the historical data (k) collected through inspection:

$$Min(T\_Error) = \sum_{i=1}^{k} Error_i \tag{3.2}$$

Variables: Diagonal probability values P_{ii} for the transition matrix.

Constraints: Variable range is 0 to 1 (maximum probability is 100%):

$$0 \le P_{ii} \le 1 \tag{3.3}$$

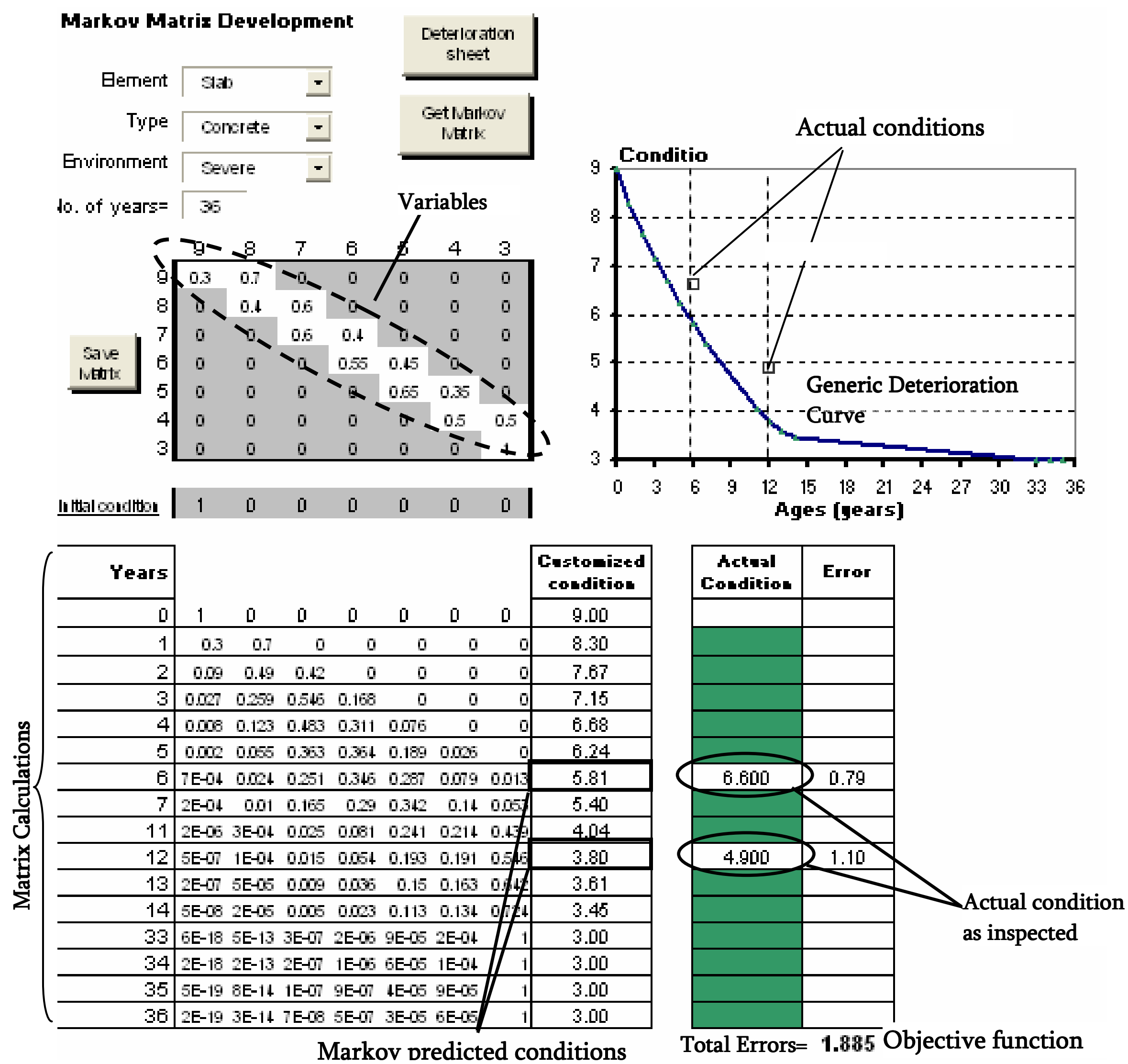


Figure 3.3: Deterioration Matrix Customization

The first experiments with a simple optimization problem used Excel's solver utility that employs simplex, and branch and bound techniques. Because of the highly non-linear nature of the relationships involved, the solver was not capable of producing a solution. Alternatively, a non-traditional optimization tool based on genetic algorithms (Evolver) was used as a powerful random search method. Evolver also is an Excel-add-in program that proved suitable for solving problems for which mathematical optimization techniques fail (Elbeltagi et al., 2005). Using Evolver, the process minimizes the total error by determining modified TPM values. Figure 3.4 shows the modified Markov deterioration matrix with the customized deterioration curve close to the actual condition values.

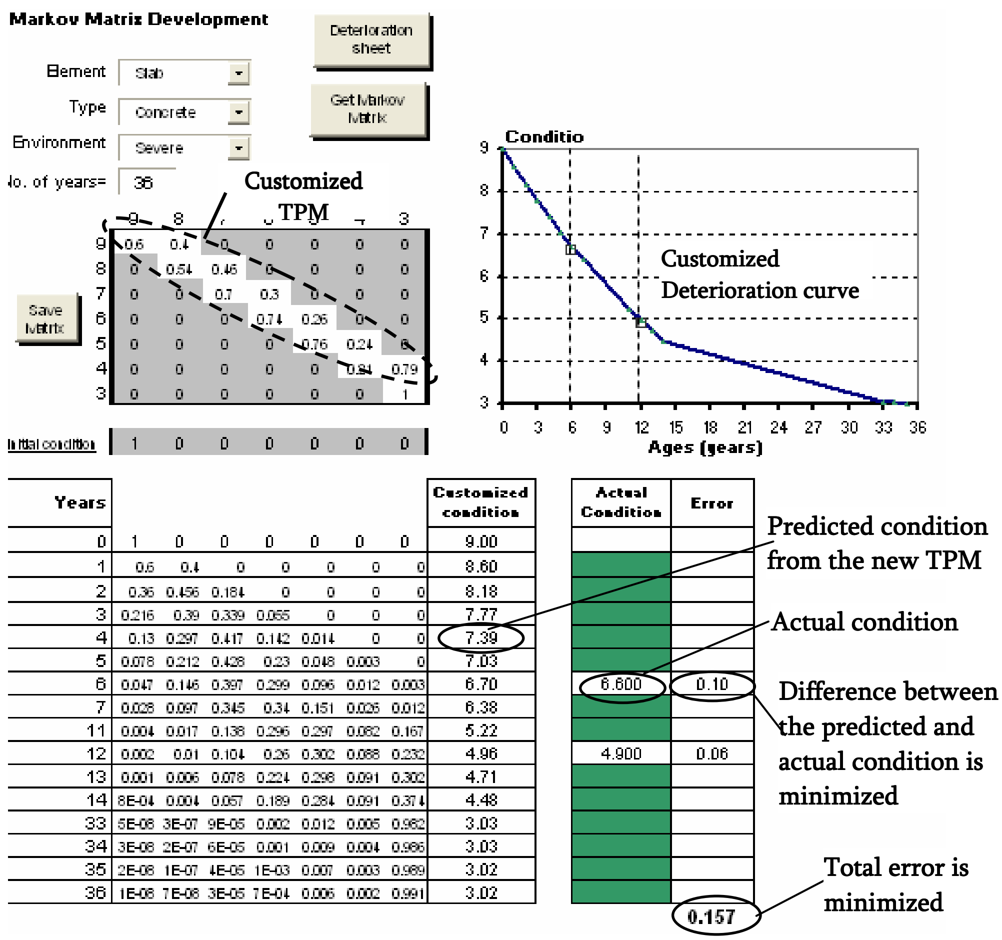


Figure 3.4: Optimized Markov Deterioration Matrix

Once the user is satisfied with the new matrix, the matrix can be stored and linked to the BDMS, to be used later in the life cycle cost analysis. It should be noted that the process of generating customized deterioration models for specific bridge components is not limited to bridge decks. Rather, it was designed to be used for all other bridge elements. This feature facilitates the development of the multi-element bridge management system described in Chapter 4.

Repair Cost Model: In the proposed BDMS model, three repair options are used for bridge decks. According to Seo (1994), repair costs can be estimated as a percentage of the initial (or total replacement) cost: light repair, medium repair, and extensive (full replacement) repair. Light repairs are intended to restore the deck surface and include patching, sealing, and cleaning of debris. Medium repairs, on the other hand, involve strengthening or increasing the thickness of the bridge deck, and thus, may require partial closure of the bridge. Extensive repairs involve deck replacement which requires a complete closure of the bridge to traffic. In the present model, the repair costs associated with the three repair options are estimated to be 28.5%, 65%, and 100%, respectively as suggested by Seo (1994). However, the user has the flexibility of changing these values through the life cycle cost analysis.

Improvement Model: It is important that the impact of each repair option on the condition of a bridge deck be analyzed. Table 3.2 shows estimated repair improvements as represented by Seo (1994). The improvement values are graphed in Figure 3.5. For example, to raise the condition of the bridge deck from 3 to 5, a medium repair should be selected, while to raise it to condition 7, extensive repair should be selected.

Table 3.2: The Impact of Repair Options on the Condition of Bridge Decks

Condition Rating		Condition Rating before Repair		
		3, 4	5, 6	7,8
Condition Rating after Repair	3,4	Light	-----	-----
	5, 6	Medium	Light	-----
	7, 8	Extensive	Medium	Light

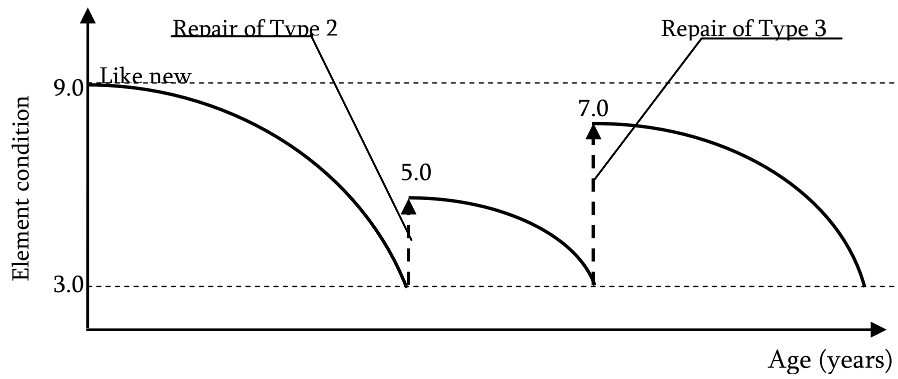


Figure 3.5: Condition Rating Improvement Model

3.3.1 Life Cycle Cost Analysis

Once a network of bridge decks with their deterioration models, the repair alternatives, and their improvement models have been defined, the proposed BDMS can incorporate a life cycle cost analysis module to determine the optimum priority list of which bridge decks should be repaired and the most cost-effective repair method.

To set up the optimization problem, an objective function is constructed by summing the present values of the annual cost of repairs for all bridge decks (Equation 3.4). The objective function is to minimize the total life cycle cost (TLCC) while maintaining an acceptable bridge condition:

$$Min\, TLCC = \frac{1}{(1+r)^t} \sum_{t=1}^{T} \sum_{i=1}^{N} (C_{ti}) \tag{3.4}$$

where C_{ti} = the repair cost of bridge i at time t; r = the discount rate, T = the number of years, and N = the number of bridges. In addition to constructing the objective function, the proposed BDMS accounts for the following constraints (other constraints related to execution and resource limitations are proposed in Elbehairy and Hegazy, 2004):

1. The yearly repair costs should be ≤ yearly budget limits:

$$\sum_{i=1}^{N} C_t \leq (AB)_t \tag{3.5}$$

2. The condition rating for any individual bridge deck ≥ 3 (or a pre-defined user desirable value):

$$BDCR_{i=1}^{N} \geq min\,Cond \tag{3.6}$$

3. The overall network condition rating (NCR) ≥ the pre-defined user desirable value:

$$NCR \geq User\ defined \tag{3.7}$$

4. The repair method used in a specific year for a specific bridge = user-forced value:

$$Repair\ method = User\ value \tag{3.8}$$

5. The number of repair visits to a specific bridge can be constrained to a user-desirable maximum number:

$$Number\ of\ \ visits = User\ desired\ Value \tag{3.9}$$

Once the objective function and the constraints for optimizing repair decisions are defined, it is important to determine the optimization technique to be used. Initial experiments conducted to optimize the transition probability matrix (TPM) presented in section 3.3, revealed that mathematical optimization techniques failed to optimize the TPM values. Therefore, with the large network of bridges and the highly non-linear formulation included in the decision support system, the use of non-traditional optimization techniques based on evolutionary algorithms was recommended as discussed in the following section.

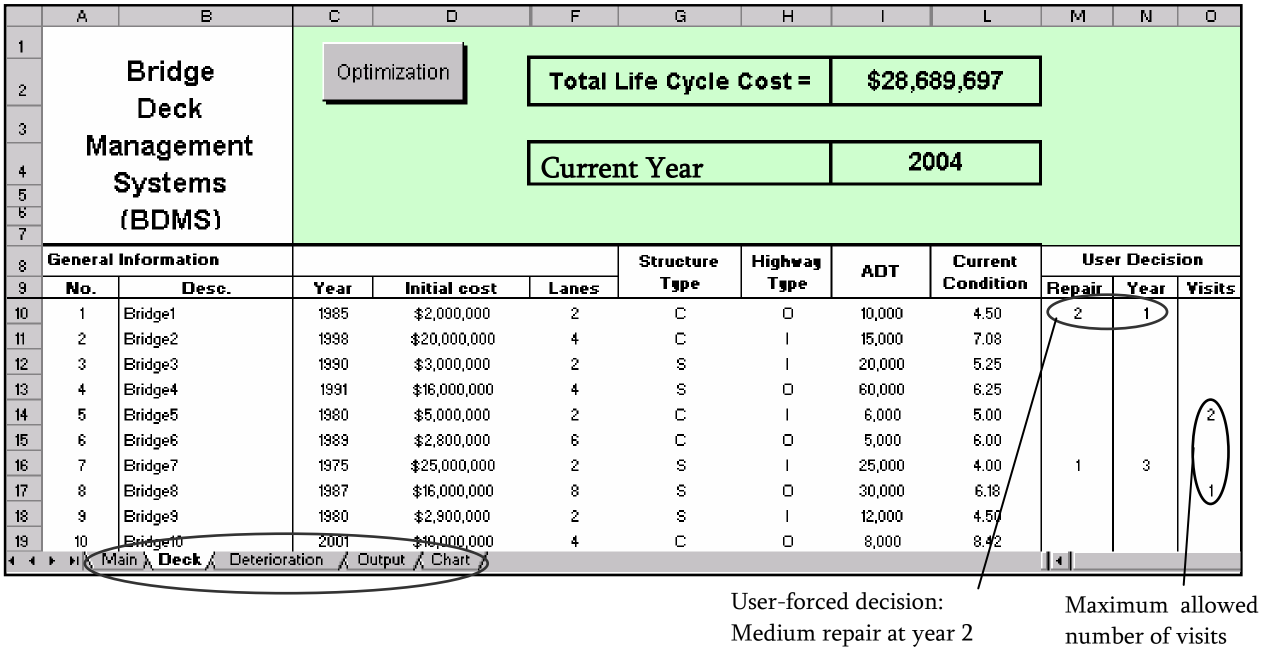
3.3.2 Evolutionary Optimization Algorithms

The difficulties associated with using mathematical optimization techniques on large-scale problems have contributed to the development of alternative solutions. Linear programming and dynamic programming techniques, for example, often fail (or reach local optimum) in solving NP-hard problems with a large number of variables and non-linear objective functions (Lovbjerg, 2002). To overcome these problems, researchers have proposed evolutionary-based algorithms to search for near-optimum solutions. Genetic algorithms (GA) are a well-known example of evolutionary algorithms that have been used to solve complicated optimization problems. Recently, a new breed of evolutionary algorithms has been developed, such as shuffled frog leaping (SFL), ant colony optimization (ACO), and particle swarm optimization (PSO). Appendix A includes more details about these evolutionary algorithms. Experiments using these EAs with the proposed BDMS are discussed in Section 3.5.

3.4 BDMS Prototype and Implementation

The proposed bridge deck management system was implemented on a commercial spreadsheet program (Excel). The developed application includes different forms and worksheets. The data for a network of bridges are input to the BDMS, as shown in Figure 3.6. Each row represents one bridge, for which the input, output, and calculations are represented in the columns. For each bridge, the input is the construction year, the initial cost, the deck type (steel or concrete), the highway type (interstate or other), the average daily traffic (ADT), the width, the length, and the inspected condition (current condition). The user can force a desirable repair decision by defining the repair type and year of repair. This feature provides the flexibility of catering to the technical/environmental/political constraints associated with a specific repair type in a specific year. An additional flexible option in the BDMS model is that, to reduce traffic disruption, the number of repair visits to an individual bridge can be constrained to a user-desired maximum number of visits.

As shown in Figure 3.6, column "L" includes the current condition of the bridges. The bottom left hand corner of Figure 3.6 shows the different spreadsheets that are included in the BDMS application, including a spreadsheet that incorporates the Markov chain deterioration calculations for predicting the future condition of each bridge through the 5-year planning horizon based on the current condition value.



Bridge Deck Management Systems (BDMS)

Optimization

Total Life Cycle Cost =	$28,689,697
Current Year	2004

General Information									User Decision		
No.	Desc.	Year	Initial cost	Lanes	Structure Type	Highway Type	ADT	Current Condition	Repair	Year	Visits
1	Bridge1	1985	$2,000,000	2	C	O	10,000	4.50	2	1	
2	Bridge2	1998	$20,000,000	4	C	I	15,000	7.08			
3	Bridge3	1990	$3,000,000	2	S	I	20,000	5.25			
4	Bridge4	1991	$16,000,000	4	S	O	60,000	6.25			
5	Bridge5	1980	$5,000,000	2	C	I	6,000	5.00			2
6	Bridge6	1989	$2,800,000	6	C	O	5,000	6.00			
7	Bridge7	1975	$25,000,000	2	S	I	25,000	4.00	1	3	
8	Bridge8	1987	$16,000,000	8	S	O	30,000	6.18			1
9	Bridge9	1980	$2,900,000	2	S	I	12,000	4.50			
10	Bridge10	2001	$10,000,000	4	C	O	8,000	8.42			

Figure 3.6: Main Worksheet Showing User Input for the BDMS

3.4.1 Basic LCCA Presentation

The simplest form for representing the LCCA variables in the BDMS is shown in Figure 3.7. Each bridge is arranged in a separate row, and five columns are set to hold the values for the problem variables in the five-year planning horizon. These values represent indices for one of the four repair options mentioned earlier. In this representation, the variables are the repair decisions for all the bridge decks throughout the five-year planning horizon. As shown in Figure 3.7, a number 1 assigned for year1 of bridge1 means that this bridge is selected for repair in the first year (network-level decision) and that the selected repair strategy is type 1 (project-level decision). Similarly, a number 2 in the column for year 5 means that bridge1 will be repaired again in the fifth year using repair type 2. It is noted that in this basic problem formulation, the number of variables involved is $N \times T$, and each variable can take an integer value from 0 to 3, corresponding to one of the repair options. The solution structure for this representation is shown in Figure 3.8.

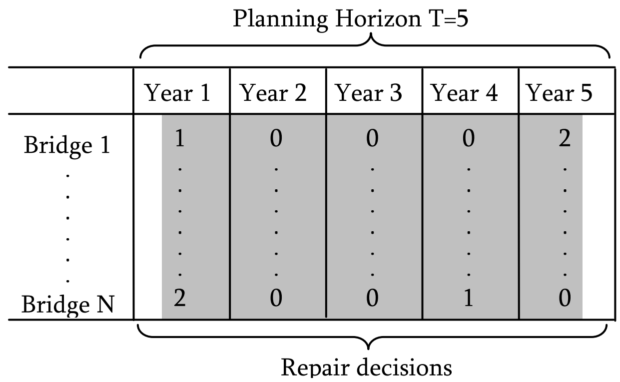


Figure 3.7: Basic BDMS Representation and Variables

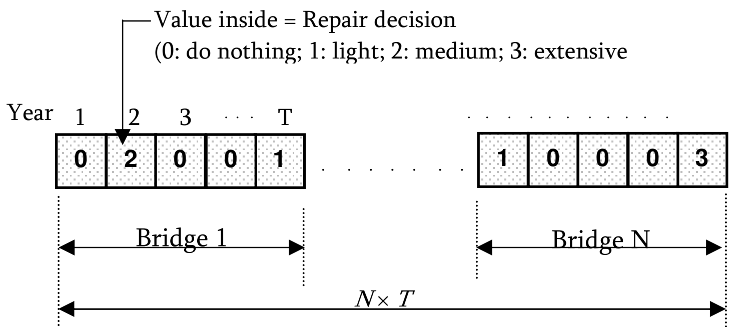


Figure 3.8: Solution Structure for BDMS

Once the data for the bridges are input, the user starts the optimization by defining the optimization constraints as shown in the user form illustrated in Figure 3.9. Network-related constraints (e.g., minimum overall rating for the network = 6.5 and minimum rating for individual bridges = 4.5) and organization-related constraints (e.g., yearly budget limit, yearly discount rate, and the percentages of full replacement associated with the different repair options) are then fixed during the optimization process; however, the user can change these values and re-optimize in order to examine the sensitivity of the results to budget limits, for example.

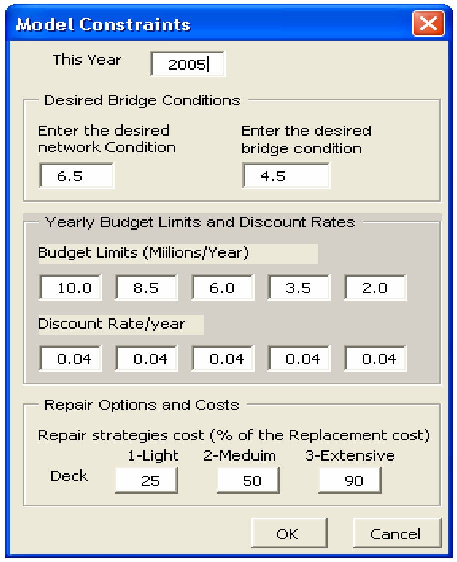
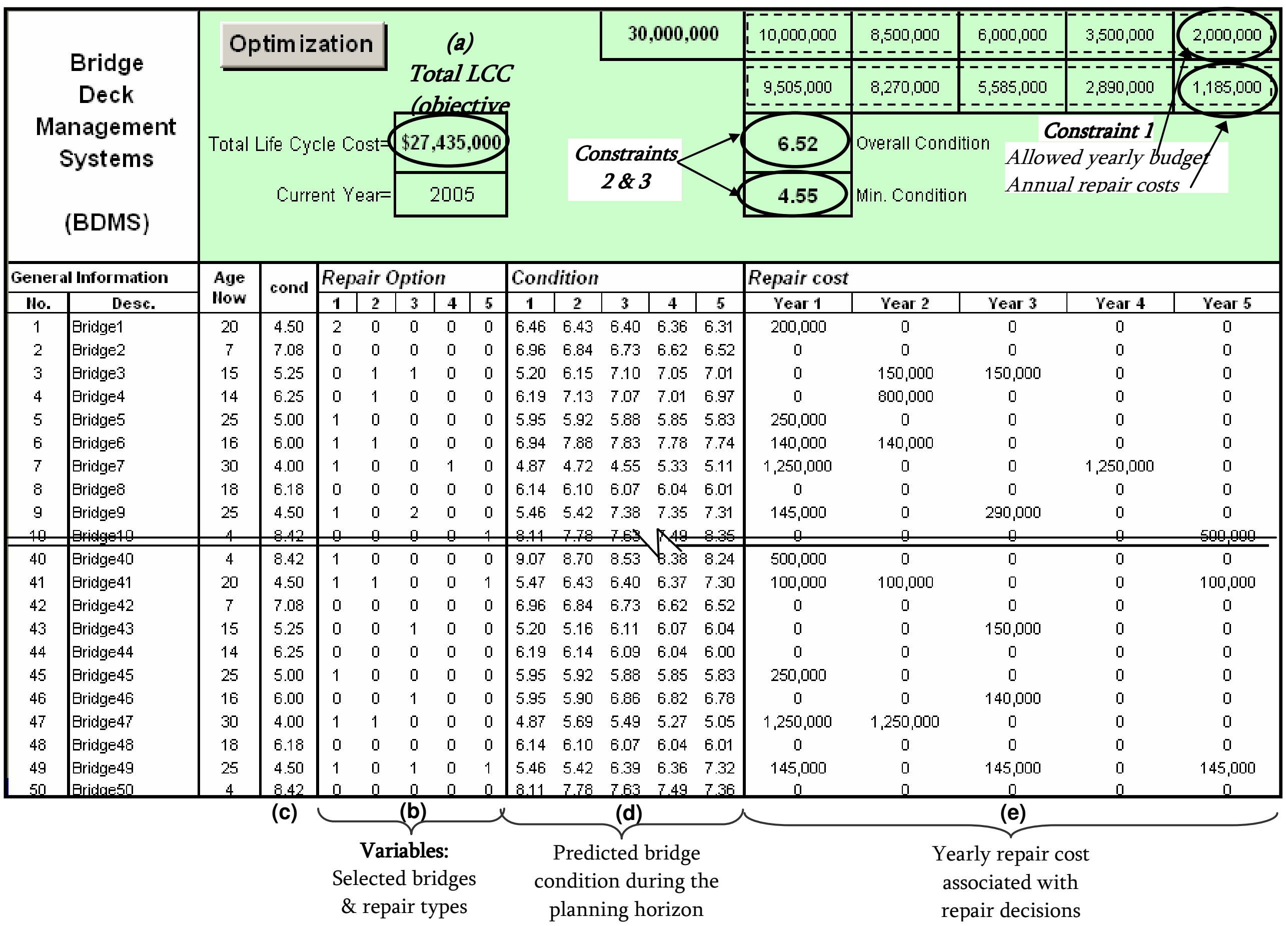


Figure 3.9: Optimization Constraints for a Network of Bridge Decks

Once the constraints are set, the evolutionary process starts and continues until a pre-set stop criterion is reached. A sample output for a network of 50 bridges is shown in Figure 3.10. Part (a) of the figure shows the cell for the TLCC, which is linked by formulas to all the other parts of the model (TLCC reached minimum of $27,435,000). Part (b) shows the cells associated with the variables of the model (five variables for each bridge). The values inside these cells represent the repair decisions (0, 1, 2, or 3) for each year of the five-year planning horizon. The deck condition ratings before and after the repair are shown in parts c and d, respectively. For example, bridge 2 which had a relatively good condition rating before the optimization (7.08), is not selected for repair (decision indices are zeros in all years). Accordingly, its condition deteriorates in the following years (part (d) of Figure 3.10). Other examples of bridges that started with low condition ratings are bridges 1 and 9 (both were 4.5 before optimization). Accordingly, the cheapest repair strategies are shown in part (b) of Figure 3.10, with multiple repairs along the planning horizon (i.e., with no constraint on the number of visits). Part (e) of Figure 3.10 also shows the repair costs associated with the repair decisions. For example, the repair decision for bridge1 at year1 is to perform medium repair, therefore the repair cost is estimated to be $200,000 (based on the percentages defined in Figure 3.9). The allowable yearly budget and the resulting annual repair costs are shown at the top part of Figure 3.10. It should be noted that the resulting annual repair costs are less than the budget limits. The overall network condition is 6.52, which is greater than the constraint value entered by the user (6.5, Figure 3.9). Similarly, all individual bridges show a rating in each year that is higher than the constraint value (4.5, Figure 3.9). As shown in Figure 3.10, the developed BDMS is transparent and has many flexible and practical features. The user can manually input a repair decision, and the model instantaneously presents the implications in terms of cost, bridge condition, and the overall network condition.



General Information		Age Now	cond	Repair Option					Condition					Repair cost				
No.	Desc.			1	2	3	4	5	1	2	3	4	5	Year 1	Year 2	Year 3	Year 4	Year 5
1	Bridge1	20	4.50	2	0	0	0	0	6.46	6.43	6.40	6.36	6.31	200,000	0	0	0	0
2	Bridge2	7	7.08	0	0	0	0	0	6.96	6.84	6.73	6.62	6.52	0	0	0	0	0
3	Bridge3	15	5.25	0	1	1	0	0	5.20	6.15	7.10	7.05	7.01	0	150,000	150,000	0	0
4	Bridge4	14	6.25	0	1	0	0	0	6.19	7.13	7.07	7.01	6.97	0	800,000	0	0	0
5	Bridge5	25	5.00	1	0	0	0	0	5.95	5.92	5.88	5.85	5.83	250,000	0	0	0	0
6	Bridge6	16	6.00	1	1	0	0	0	6.94	7.88	7.83	7.78	7.74	140,000	140,000	0	0	0
7	Bridge7	30	4.00	1	0	0	1	0	4.87	4.72	4.55	5.33	5.11	1,250,000	0	0	1,250,000	0
8	Bridge8	18	6.18	0	0	0	0	0	6.14	6.10	6.07	6.04	6.01	0	0	0	0	0
9	Bridge9	25	4.50	1	0	2	0	0	5.46	5.42	7.38	7.35	7.31	145,000	0	290,000	0	0
10	Bridge10	4	8.42	0	0	0	0	1	8.11	7.78	7.63	7.49	8.35	0	0	0	0	500,000
40	Bridge40	4	8.42	1	0	0	0	0	9.07	8.70	8.53	8.38	8.24	500,000	0	0	0	0
41	Bridge41	20	4.50	1	1	0	0	1	5.47	6.43	6.40	6.37	7.30	100,000	100,000	0	0	100,000
42	Bridge42	7	7.08	0	0	0	0	0	6.96	6.84	6.73	6.62	6.52	0	0	0	0	0
43	Bridge43	15	5.25	0	0	1	0	0	5.20	5.16	6.11	6.07	6.04	0	0	150,000	0	0
44	Bridge44	14	6.25	0	0	0	0	0	6.19	6.14	6.09	6.04	6.00	0	0	0	0	0
45	Bridge45	25	5.00	1	0	0	0	0	5.95	5.92	5.88	5.85	5.83	250,000	0	0	0	0
46	Bridge46	16	6.00	0	0	1	0	0	5.95	5.90	6.86	6.82	6.78	0	0	140,000	0	0
47	Bridge47	30	4.00	1	1	0	0	0	4.87	5.69	5.49	5.27	5.05	1,250,000	1,250,000	0	0	0
48	Bridge48	18	6.18	0	0	0	0	0	6.14	6.10	6.07	6.04	6.01	0	0	0	0	0
49	Bridge49	25	4.50	1	0	1	0	1	5.46	5.42	6.39	6.36	7.32	145,000	0	145,000	0	145,000
50	Bridge50	4	8.42	0	0	0	0	0	8.11	7.78	7.63	7.49	7.36	0	0	0	0	0

Figure 3.10: Sample Output for the Proposed BDMS

3.5 Experimenting with Different Evolutionary Algorithms

Using the visual basic for application (VBA) Macro programming language of Microsoft Excel, the genetic algorithms (GA), shuffled frog leaping (SFL), ant colony optimization (ACO), and particle swarm optimization (PSO) algorithms (discussed in Appendix A) were coded and integrated into the developed BDMS. Each algorithm is used to optimize the repair decisions for a network of bridges. Experiments were carried out using different numbers of bridges: 10, 50, and 100 represented different sizes of bridge networks. Ten trial runs were performed for each number of bridges using all four algorithms.

The performance of the presented algorithms was compared using four criteria: the percentage of success (i.e., how many times out of 10 trials was the system able to provide a solution without violating the condition constraints on both the project and network levels); the best solution obtained (i.e., the least TLCC); the average solution (i.e., the average value of the TLCC for all successful trials); and the average processing time for all successful trials). In all experiments, the system stopped when the value of the objective function (TLCC) did not improve after 10 consecutive iterations. The parameter settings used in the experiments for the four EAs are shown in Table 3.3.

Table 3.3: EA Parameter Settings

Algorithm	Population	Parameters
GAs	100	Crossover = 0.8; Mutation = 0.08; Number of generations = 500
PSO	100	Iterations = 100; Maximum velocity = 2
ACO	40	$\alpha = 0.5$; $\beta = 1$; $\rho = 0.4$; $R = 10^8$; Iterations = 100
SFL	200	Number of memeplexes = 10, Number of frogs per memeplex = 20, and Number of iterations per memeplex = 20

The results of applying the four EAs to different number of bridges (10, 50, and 100) are given in Table 3.4. For the experiments with large networks of bridges (50 and 100 bridges), the networks were constructed by copying the 10-bridge network several times. Thus, the solution obtained from the 10-bridge experiment was used as a reference to measure the success of the larger networks.

The results presented in Table 3.4 show that in the case of 10 bridges, the GA and the SFL algorithm were able to obtain solutions that satisfy all the constraints in all trial runs (100%

success), while the PSO algorithm achieved 80% success and the ACO algorithm achieved only 60%. With the increase in the number of bridges to 50, the GA was able to achieve only 80% success compared to 100% success using the SFL algorithm, also, the success rate for the PSO and ACO algorithms was only 50% and 40%, respectively.

Table 3.4: Four EAs Experiments Results

Algorithm	Comparison criterion	Number of bridges		
		10	50	100
Genetic algorithms (GA)	% Success	100	80	20
	Best cost ($)	$6,073,333	$44,866,000	$98,346,667
	Average TLCC ($)	$6,833,333	$46,910,833	$99,031,111
	Time (hr:min:sec)	00:02:16	00:49:02	02:17:40
Particle Swarm (PSO)	% Success	80	40	10
	Best cost ($)	$6,533,000	$45,426,000	$95,717,000
	Average TLCC ($)	$7,720,000	$47,655,000	$95,717,000
	Time (hr:min:sec)	00:05:46	01:19:55	02:16:54
Ant Colony (ACO)	% Success	60	40	0
	Best cost ($)	$6,873,000	$44,866,000	-
	Average TLCC ($)	$7,725,000	$47,345,000	-
	Time (hr:min:sec)	00:02:26	01:30:24	-
Shuffled Frog Leaping (SFL)	% Success	100	100	80
	Best cost ($)	$5,733,000	$30,126,000	$67,206,333
	Average TLCC ($)	$5,956,000	$31,638,000	$67,903,111
	Time (hr:min:sec)	00:01:37	00:26:06	01:28:34

A comparison of the results of the objective function revealed that the SFL algorithm resulted in the lowest TLCC of all the algorithms. The SFL algorithm, also, required the least processing time to achieve the stopping criterion for the 10 and 50 bridge networks. The same trend was noticed with the 100-bridge network in which the SFL algorithm outperformed all the other algorithms. As shown in Table 3.4, as the number of bridges increased, the processing time increased exponentially and the problem complexity increased substantially. Based on the results presented in Table 3.4, the ACO and PSO algorithms were discarded and not used in further experiments.

3.6 Achieving the Best Optimization Performance

The developed GA and SFL algorithm were tested against two commercial GA software systems (Evolver, 2002 and Gene Hunter, 2003), which are Excel add-in programs. Experimenting with both systems showed that the developed GA performs as well as the commercial software. The benefit of the developed GA code as opposed to the commercial programs, however, lies in its flexibility in accommodating any adjustments to the algorithm to suit the problem at hand.

The experiments using the developed GA and SFL algorithm on the basic formulation (Figure 3.7) were unsatisfactory in terms of the success rate and the processing time (Table 3.4), and the following observations can be made about the performance of both algorithms:

- The large number of variables involved in the basic formulation for a 50-bridge network took a substantial amount of time (about one hour) to improve solutions. This effect occurred because the genes of all the population members had randomly generated values that represent random repairs (with associated costs). Thus, all starting solutions in the population were excessively violating the budget constraints, and many evolutionary cycles are required in order to meet the stopping criterion.
- Although the TLCC (sum of the yearly expenditures) was reduced during the evolutionary process and was nearing the desired total budget limit, the yearly distribution of the expenditures violated the yearly budget limit, particularly for the first year.
- The best solutions obtained still violated the minimum desirable condition (4.5) for some of the individual bridges.
- The SFL algorithm performed better than GA because of its use of a step term to adjust and refine solutions (i.e., deeper local search). In the GA, the crossover exchanges large portions of the parent chromosome, which causes slower refinement of the solutions, particularly with a small mutation rate.

Additional experiments were used to improve the performance of both algorithms for this typical infrastructure problem. These experiments were structured as follows, and discussed in the following subsections (Elbehairy et al., 2006b):

1. Examine other objective functions and decide on the best one to use with the five-year optimization model.
2. Develop a pre-processing function to avoid violating the minimum desirable condition for each bridge.
3. Adjust the initial solutions by examining the effect of changing the percentage of non-zero values.
4. Determine the best values for the parameters of each algorithm.
5. Examine the model on a year-by-year optimization.

3.6.1 Experimenting with Different Objective Functions

The experiments conducted in this section were carried out on the basic formulation which is to optimize the five-year planning horizon. In addition to minimizing the TLCC, two other objective functions were experimented with and the constraints were modified accordingly, for the 50-bridge network case. In order to force the optimization to avoid violating the yearly budget, the first objective function was set up to minimize the budget error, which is the sum of the absolute difference between each year's repair cost and the allowed budget, and to obtain the maximum network improvement for the cost, and the second objective function was to maximize the overall network condition rating. The best performance in terms of processing time and solution quality was obtained by minimizing the total budget error. Maximizing the overall network condition consistently over-allocated repair money to earlier years thus, violating the yearly budget limit and resulting in unfeasible solutions.

3.6.2 Pre-processing of solutions

Once a suitable objective function was selected to compare the performance of GA and SFL algorithm, several experiments were then carried out using different numbers of bridges: 50, 100, 200, and 400. With the increase in the number of bridges, the number of variables also increased.

Due to the random nature of the evolutionary process, one of the difficult constraints to meet is that each bridge needs to maintain a condition above the desirable limit of 4.5 in all years. To overcome this problem, a pre-processing function was added to the GA and SFL code. The pre-processing function is simple and does not change the process; rather, it may make minor adjustments, if necessary, to some of the no-repair (i.e., zero) values of any solution generated during the evolutionary process (population members, offspring members, and frogs). The function checks the consequent conditions associated with the initial values of a solution, then forces a repair (changes the zero value to a 1) for any bridge that has a condition lower than the minimum acceptable level in any year. This process ensures that repair funds are spent first on the must-repair bridges, then randomly on the remaining bridges. It also ensures that this constraint is not violated during the optimization.

3.6.3 Adjusting the Initial Solutions

Because bridge management problems involve strict budget limits, only a small proportion of the bridges are expected to receive repairs. Therefore, the final solution string is expected to have many zeros, which is not the case in the totally random manner in which initial solutions (population members and frogs) are generated. Thus, a simple approach for speeding the evolutionary process is to generate each initial solution with all zeros except a percentage of random non-zero values (this percentage can be roughly estimated as the ratio of available budget to the total repair need). To examine the validity of this approach and to determine the most suitable percentage for each algorithm, different percentages of non-zero values (10%, 20%, 40%, 55%, 70%, and 85%) were introduced into the initial population of chromosomes and frogs, and were experimented with for the 50-bridge network. Based on the results shown in Figure 3.11, the lowest error was achieved with the use of 70% and 20% non-zeros for the GA and SFL algorithm, respectively.

Further experiments using the 70% and 20% non-zeros with networks of 50, 100, 200, and 400 bridges were carried out, and the results are shown in Figure 3.12. Ten trial runs were performed for each case, using the minimum-error objective function. The results in Figure 3.12 shows that with the use of 20% non-zeros in the chromosomes and frogs, the error obtained from the SFL algorithm was lower than that of the GA, while with the use of 70% non-zeros, the GA resulted in lower error compared to that from the SFL algorithm. This indicates that with the use of proper percentages of non-zeros in the chromosomes and frogs, it is possible to achieve better performance.

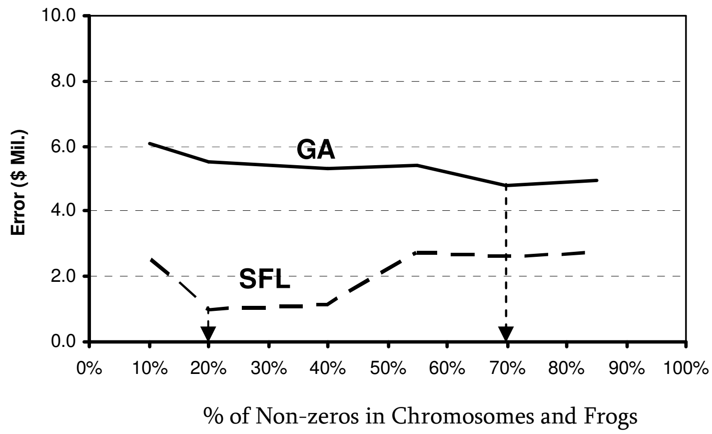


Figure 3.11: Effect of Non-zeros in Initial Chromosomes and Frogs for the BDMS

3.6.4 Determining the Best Parameter Values

After initial experimentation, the best GA parameters were set as follows: crossover probability = 0.8; mutation probability = 0.08; population size = 100; and number of generations = 500. In addition to setting the values of the algorithms' parameters, the use of the solution pre-processing procedure and the 70% non-zero value for the population members is used. The criterion for stopping the optimization was also set to no improvement in the objective function for 10 consecutive generation cycles (10 × 500 generations).

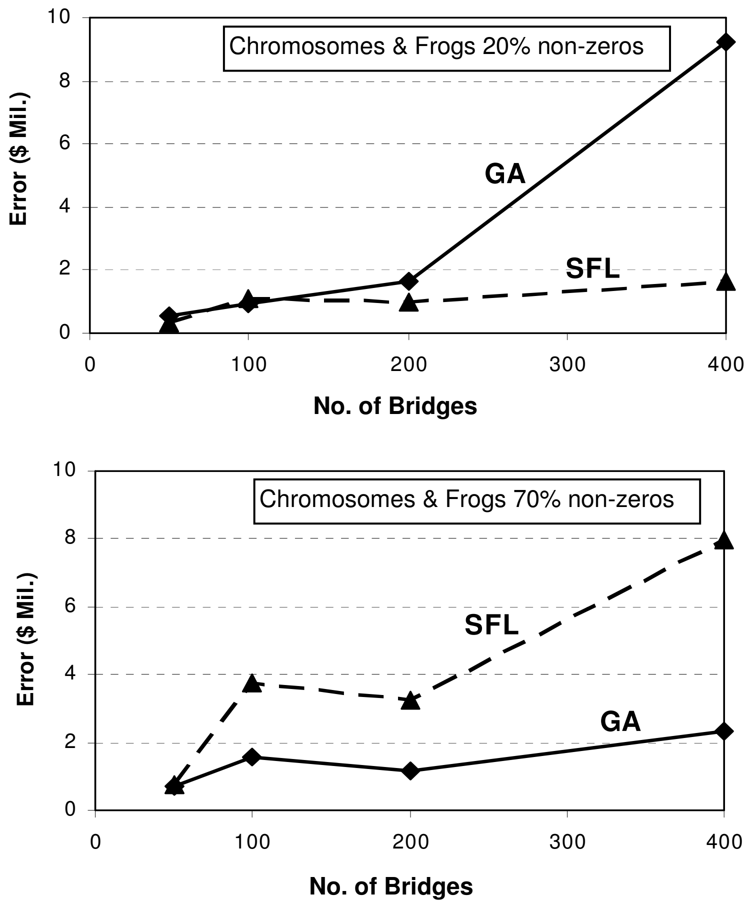


Figure 3.12: Performance of the GA and SFL algorithm using Non-zeros in Initial Solutions

For the SFL algorithm, the initial parameter settings were those suggested by Elbeltagi et al. (2005), which were found to work efficiently for the problem at hand: population size = 200 frogs; memeplexes = 20; and iterations = 10 per memeplex. Based on preliminary experiments, one parameter, the maximum step size, however, was reduced from 2 to 1 in order to improve the SFL algorithm performance. This step was added to the use of the solution pre-processing procedure and the 20% non-zero value for the frogs. The SFL criterion for stopping the optimization was also set to no improvement in the objective function for 10 consecutive shuffling cycles (10 × 20 × 10 generations). Based on these best settings for the two algorithms, Figure 3.13 and the top two sections of Table 3.5 show the best performance achieved for both the GA and SFL algorithm with different numbers of bridges. The SFL algorithm showed a performance very close to and slightly better than that of the GA.

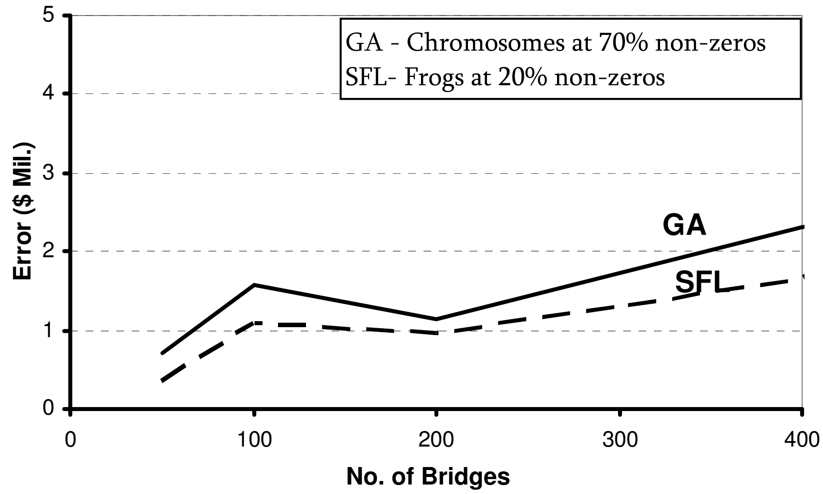


Figure 3.13: Best performance of the GA and SFL Algorithms

3.6.5 Examining a Year-by-Year Optimization

The results in Table 3.5 clearly show that the network condition is reduced slightly in proportion to the problem size. Because of municipalities' desire to maximize their return on the repair dollar, the five-year formulation (basic formulation, Figure 3.7) was not suitable with an objective function that maximizes the network condition. presents a year-by-year formulation that considers each year individually in five consecutive optimizations, with the objective function being to maximize the overall network condition, and only one constraint: the sum of repair costs for each year is within that year's budget limit. Thus, each of the five optimizations is much smaller and can logically maximize the network's return on the repair investment made every year. The year-by-year strategy was then experimented with for the different-sized networks with the pre-processing procedure set at fully random values of the population members. The results of this strategy show a substantial improvement in the network condition (third section of Table 3.5). In addition, no noticeable difference was observed between the results of the GA and the SFL algorithm.

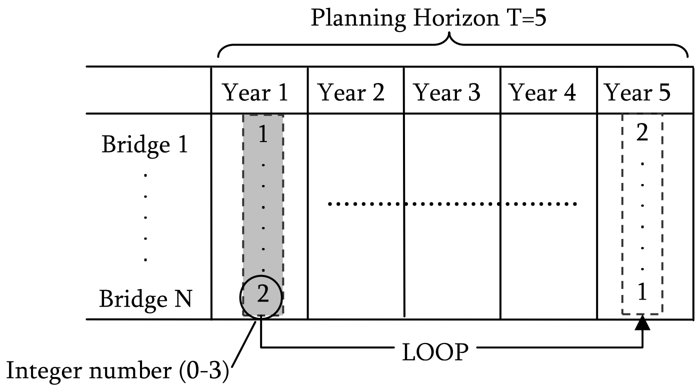


Figure 3.14: Year-by-Year Formulation

Table 3.5: Results of Optimization Experiments for the BDMS

No. of Bridges	Budget Limit	Total Repair Cost	Sum of Budget Errors	Network Condition	Optimization Time (min.)
Results of Genetic algorithms - one Five-Year Optimization (Minimize budget error)					
50	$30,000,000	$29,910,000	$356,666	6.13	35
100	$60,000,000	$59,651,111	$784,444	6.11	39
200	$120,000,000	$119,844,444	$571,111	6.08	64
400	$240,000,000	$239,712,000	$1,156,000	6.08	108
Results of Shuffled Frog Leaping – one Five-Year Optimization (Minimize budget error)					
50	$30,000,000	$30,026,667	$173,333	6.11	12
100	$60,000,000	$60,263,333	$543,333	6.10	23
200	$120,000,000	$119,960,000	$480,000	6.08	37
400	$240,000,000	$239,980,000	$826,666	6.07	74
Results of Genetic algorithms - five Year-by-Year Optimizations (Maximize condition)					
50	$30,000,000	$29,633,333	$366,666	6.84	25
100	$60,000,000	$59,733,333	$266,666	6.82	25
200	$120,000,000	$119,926,667	$73,333	6.71	25
400	$240,000,000	$239,860,000	$140,000	6.57	50

3.7 Discussion of Results

A comparison of the results for the different network sizes is possible because the 50, 100, 200, and 400-bridge networks are multiples of a single 10-bridge network. Therefore, the optimization experiments on the la rger networks had a defined solution against which the optimization performance could be judged.

The results of using the GA and the SFL algorithms illustrated in Table 3.5 show that each algorithm can perform better with its parameters set up properly. The best results in Figure 3.13 and Table 3.5 also show that the two algorithms are consistent in producing results that correspond to the objective function used. Both algorithms could allocate the repair funds efficiently. The total repair cost in the third column of Table 3.5 is very close to the budget limit in the second column.

Based on the experiments, the most suitable optimization strategy for this typical infrastructure problem is a year-by-year strategy. This strategy was able to determine an overall network condition of 6.84 for the 50-bridge network (Table 3.5), which is higher than comparable values obtained by any trials with the single five-year optimization (the best result was 6.13). The year-by-year strategy, coupled with the use of the pre-processing function, also worked well for the larger networks that required additional processing time.

As shown by the slight degradation of the overall network condition as the network size increased (from 6.84 for 50 bridges to 6.57 for 400 bridges), the problem size still represents a challenge for optimizing bridge maintenance and repair decisions. The complexity of the problem substantially increases as the number of bridges increases and the solution space becomes too large. For example, in the case of 400 bridges, the number of possible solutions is 4^{2000}, which is relatively large. The problem is also expected to become even larger if the model is expanded to the case of multiple bridge elements (e.g., deck, substructure, and superstructure). Therefore, some strategies may need to be applied in order to reduce the number of possible solutions in the optimization.

3.8 Summary and Conclusions

A flexible and transparent bridge deck management system (BDMS) that integrates both project-level and network-level decisions was developed. Two evolutionary techniques, genetic algorithms (GA) and shuffled frog leaping (SFL) algorithm were used in the BDMS for optimizing maintenance and repair activities for bridge decks. Ten trial runs with different numbers of bridges were experimented with to evaluate the performance of both the GA and the SFL algorithm. The results of the experiments showed that both techniques are equally suitable for dealing with the problem at hand. The key issue is to determine the parameters of the optimization technique. Based on the experiments and the approaches used to improve the optimization performance, the best optimization strategy for this typical infrastructure problem is year-by-year optimization with the objective function to maximize network condition, coupled with the use of a pre-processing function to allocate repair funds first to must-repair bridges.

Chapter 4

Multi-Element Bridge Management system

4.1 Introduction

Built upon the framework presented in Chapter 3, a new model for managing bridge networks with multiple elements (ME-BMS) is presented in this chapter. The objective of the multi-element model is to arrive at optimum decisions for bridge-element repairs (project-level decisions) and to select the appropriate year for implementing the repairs (network-level decisions). The model development and implementation are presented along with an example application that demonstrates its practicality.

4.2 Considering Multiple Bridge Elements

The bridge deck management system (BDMS) presented in Chapter 3 integrates both project-level and network-level decisions and was shown to be flexible and transparent. However, a practical bridge management system should take other bridge elements (e.g., superstructure, substructure, and bearing) into consideration in the decision-making process. The BDMS worked very efficiently with large numbers of bridge decks; however, expanding the model to include other bridge elements complicates the life cycle cost analysis and makes the integration between the project level and the network level more complex. In the BDMS, the number of possible solutions was R^{NxT}, where R = the number of repair alternatives, N = the number of bridge decks, and T = the number of years. For example, for a network of 10 bridges with four repair alternatives and a five-year planning horizon, the number of possible solutions is 4^{50}, which is an enormous solution space for the model to search and arrive at a near optimal solution. However, if seven bridge elements are considered in the optimization process for the same example, the number of possible solutions is 4^{350}: the number of possible solutions increases exponentially with the consideration of additional elements. This problem size requires suitable adjustments to the formulation of the model to enable it to handle large scale problems.

4.3 Multi-Element Bridge Management Components

The components of a multiple elements bridge management system are similar to those used in the BDMS with modifications to include other bridge elements. For this study, seven bridge elements are considered: deck, superstructure, substructure, bearings, joints, overlay, and finishing. Figure 4.1 shows the components of the modified model that accounts for multiple elements:

- General BMS models (i.e., condition rating, time-dependent deterioration, repair cost, and repair-improvement).
- BMS constraints (e.g., industry, government, political, user (user-defined constraints), project, and network).
- ME-BMS decision support model: this includes the integration between the project-level and the network level decisions:
  - Project-level decision support model: an optimization model that determines for each bridge the best repair type for each element if the repair is done in year 1, year 2, …, year 5.
  - Network-level decision support model: an optimization model that uses the repairs of the project-level decision support and determines, at the network level, the best year to repair each bridge.
- User costs (discussed in Chapter 5): to estimate the impact of the repairs on the user costs.

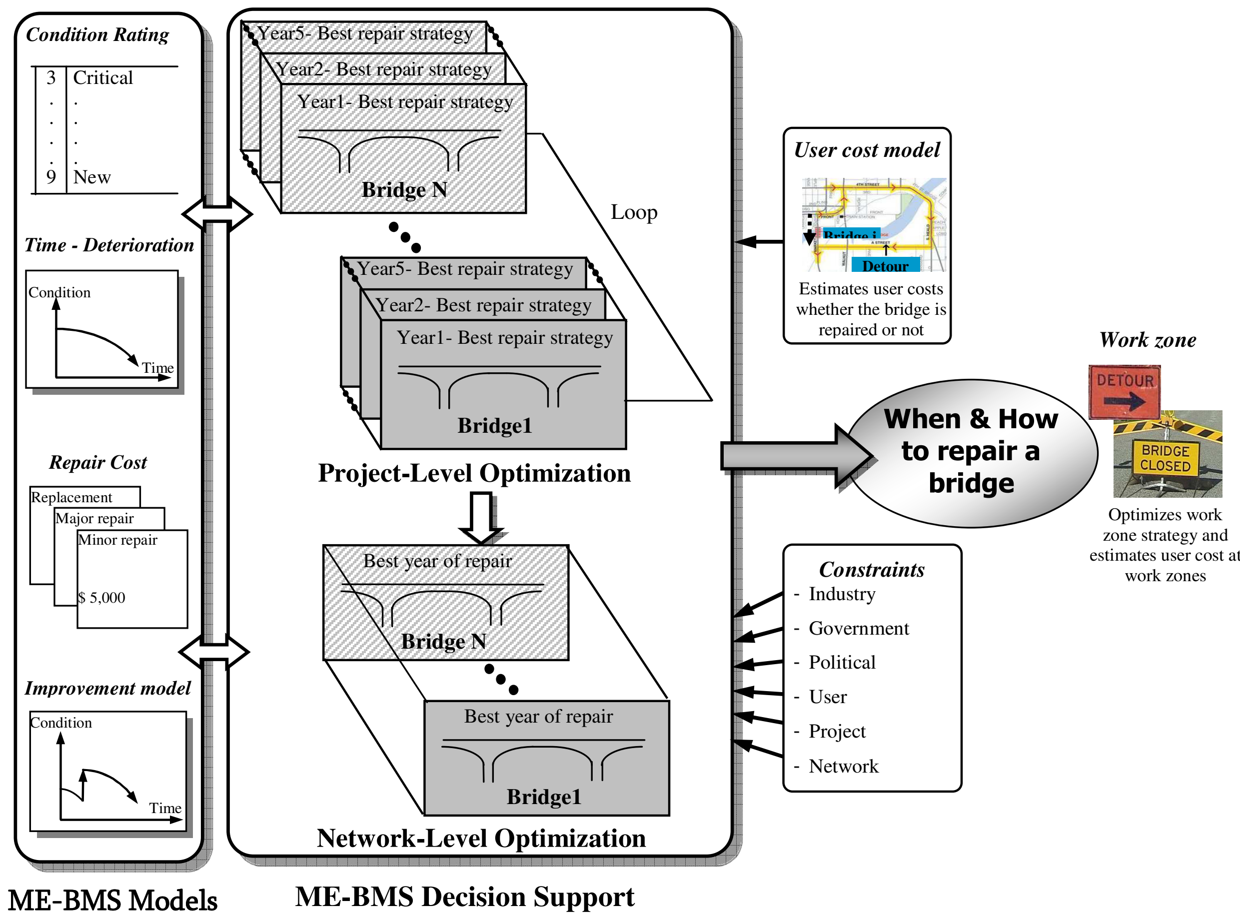


Figure 4.1: Multi-Element Bridge Management System Framework

It should be noted that the ME-BMS structured in Figure 4.1 has been designed in a manner that reduces the size of the problem, yet maintains the integration between network-level and project-level decisions. In this proposed design, project-level decisions are optimized to provide a wide range of the best repair options that the network level subsequently uses to optimize the timing of the repair. Each of the ME-BMS components shown in Figure 4.1 is discussed in the following subsections, with the constraints being introduced where appropriate. The project-level and network-level optimization models are introduced in the section of the ME-BMS decision support model that explains the concepts that led to their development, and they are then discussed and analyzed in detail individually.

4.4 ME-BMS General Models

The general bridge management system models used in the proposed ME-BMS framework shown on the left side of Figure 4.1 are the same ones mentioned in Chapter 3 for the BDMS, but with the changes described in the following subsections.

4.4.1 Element Condition Rating System

The condition rating system used in the ME-BMS is the same as that presented in Chapter 3 for the BDMS. A condition rating is given for each bridge element on a scale from 0 to 9 (best condition) (FHWA, 1998). The BDMS was dealing only with the deck, however, when dealing with multiple elements, an overall bridge condition rating (BCR) is then calculated using Equation 4.1, based on the weights given for each element (Yanev, 1997).

$$BCR = \frac{\sum (element\ condition\ rating\ x\ element\ weight)}{\sum weights} \tag{4.1}$$

In the present model, the weights associated with the bridge elements are those proposed by Yanev (1997) and given in Table 4.1. These element weights are considered fixed in the model and therefore are the same for all bridges in the network. The user, however, can change these weights according to the agency preferred values at any time during the analysis.

Table 4.1: Elements Relative Weights for ME-BMS (Yanev, 1997)

Element	Weight	Importance
Deck	7	18%
Overlay	4	10%
Joints	6	15%
Bearings	5	13%
Superstructure	8	20%
Substructure	7	18%
Finishing	3	8%
∑ weights	**40**	

4.4.2 Deterioration Model

In the present ME-BMS model, the method for defining the deterioration of the bridge elements is shown in Figure 4.2. Each element has up to 3 different types (e.g., the deck can be concrete or steel, or composite). For each element type, the deterioration is defined differently for a severe or moderate working environment. For the elements that have Markov deterioration (e.g., the deck, the superstructure, and the substructure), their transition probability matrices (TPMs) are as proposed by Jiang (1990). For the remaining bridge elements, the deterioration is assumed to be linear (no Markov deterioration models were found in the literature), based on the expected lifespan of the element. For example, as shown in Figure 4.2, a joint of type 1 has an expected life of 7 years under a severe working environment and 12 years under a moderate working environment. Thus the condition rating for element *i* at year *t* is estimated as follows:

$$CR_i = \left(9 - \frac{9-3}{life\ span} \times t \right) \tag{4.2}$$

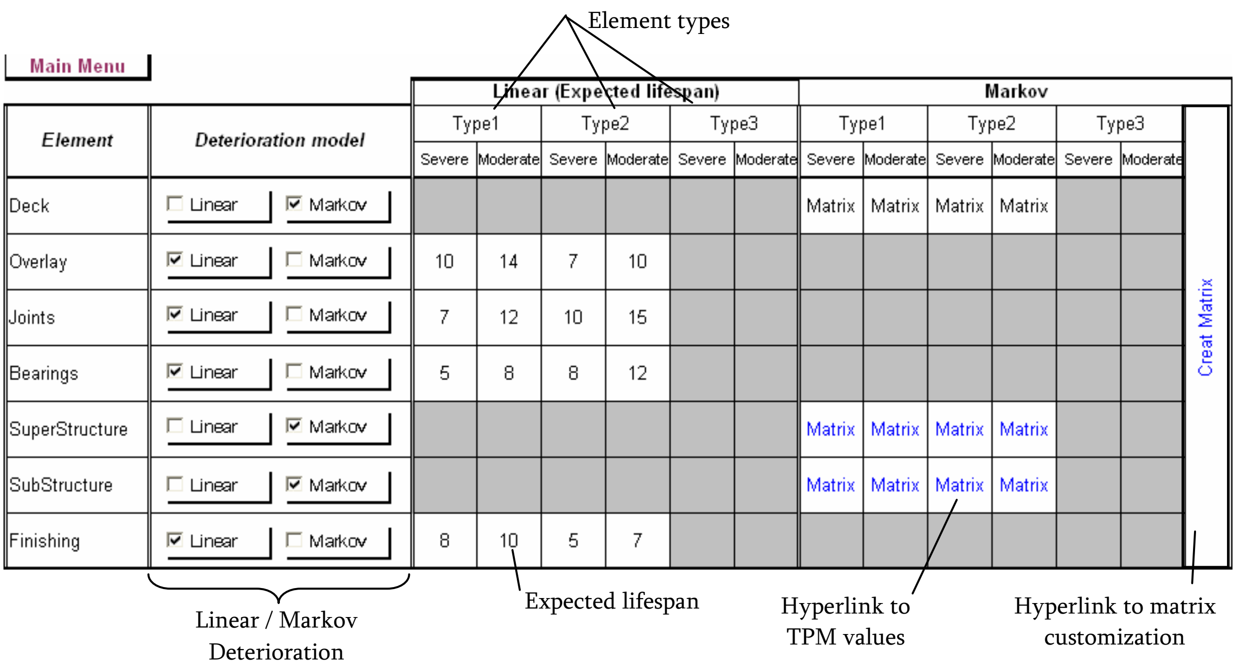


Figure 4.2: Deterioration Model for ME-BMS

Figure 4.2 shows that the deterioration implementation for the present ME-BMS is user friendly, with check boxes to facilitate quick user inputs. The cell to the far right of the figure also has a hyper link to activate the Markov transition probability matrix (TPM) customization model explained in Chapter 3.

4.4.3 Cost Model

Six repair options are proposed in the ME-BMS ranging from 0 (do nothing) or 1 (light repair) to 5 (extensive repair). The extent of the repair associated with each option is shown as a percentage in the second column of each section of Figure 4.3. For practical reasons, the repair strategy for each type of element is listed along with a rough estimate of the cost associated with each type of repair. For example, a deck element of type 1 (concrete) with a repair option of type 1 "crack sealing and patching" would cost \$50/m^2 (Figure 4.3).

Using the data in Figure 4.3, the total cost of repairing bridge i is calculated as follows:

$$RC_i = \sum_{j=1}^{7} C_{jmp} \times Size_j \tag{4.3}$$

where RC_i = the repair cost for bridge i, j = the bridge element, m = the repair option (0 - 5), p = the element type (type 1 or type 2), C_{jmp} = the unit cost of repairing element j using repair option m for type p, and $Size_j$ = the dimension or quantity of element j. For example, the size of the deck is its width multiplied by its length, while for the bearing; the size is the total number of bearings in the bridge. To illustrate the cost calculations, an example of a bridge with a concrete deck with a length and width equal to 60m and 20m, respectively, is considered. The bridge also includes three steel expansion joints. If the repair decisions are repair option 2 for the deck and repair option 3 for the joints, then the estimated repair costs are:

- Deck (60 m x 20 m x \$210) = \$252,000
- Joints (3 x 20m x \$1000) = \$60,000

Total cost = \$252,000 + \$60,000 = \$312,000

Repair Type	Repair Extent	Deck						Overlay					
		Type 1 - Concrete			Type 2 - Steel			Type 1 - Concrete			Type 2 - Asphalt		
		Repair Option	Cost	Unit	Repair Option	Cost	Unit	Repair Option	Cost	Unit	Repair Option	Cost	Unit
0	0%	Do nothing	$0		Do nothing	$0		Do nothing	$0		Do nothing	$0	
1	25%	Crack sealing	$50	m2	Paint (10% area)	$63	m2	Crack Sealing	$8	m2	Crack Sealing	$8	m2
2	35%	Replace 50% of Top concrete	$210	m2	Paint and repair (15% area)	$280	m2	Patch (25%)	$14	m2	Patch (25%)	$14	m2
3	45%	Replace 50% Top + Bottom concrete	$450	m2	Paint (25%)+ Replace (10%)	$585	m2	Patch (35%)	$41	m2	Patch (35%)	$34	m2
4	60%	Replace 50% Top reinforcement	$780	m2	Paint (35%)+ Replace (30%)	$960	m2	Replace (50%)	$54	m2	Replace (50%)	$45	m2
5	80%	Replace 50% top and bottom Reinf.	$1,280	m2	Paint (50%)+ Replace 50%)	$1,600	m2	Replace (75%)	$72	m2	Replace (75%)	$60	m2

Repair Type	Repair Extent	Joints						Bearings					
		Type 1 - Steel			Type 2 - Rubber			Type 1 - Steel			Type 2 - Neubrane		
		Repair Option	Cost	Unit	Repair Option	Cost	Unit	Repair Option	Cost	Unit	Repair Option	Cost	Unit
0	0%	Do nothing	$0		Do nothing	$0		Do nothing	$0		Do nothing	$0	
1	25%	Repair	$125	m	Patch	$125	m	Repair	$88	each	Repair	$88	each
2	35%	Replace	$420	m	Replace	$525	m	Replace	$525	each	Replace	$525	each
3	45%	Replace	$1,000	m	Replace	$1,000	m	Replace	$1,000	each	Replace	$1,200	each
4	60%	Replace	$1,500	m	Replace	$1,500	m	Replace	$1,500	each	Replace	$1,800	each
5	80%	Replace	$2,000	m	Replace	$2,000	m	Replace	$2,000	each	Replace	$2,400	each

Repair Type	Repair Extent	SupperStructure						SubStructure					
		Type 1 - Concrete			Type 2 - Steel			Type 1 - Concrete			Type 2 - Steel		
		Repair Option	Cost	Unit	Repair Option	Cost	Unit	Repair Option	Cost	Unit	Repair Option	Cost	Unit
0	0%	Do nothing	$0		Do nothing	$0		Do nothing	$0		Do nothing	$0	
1	25%	Patch	$88	m2	Paint	$88	m2	Patch	$88	m2	Paint	$88	m2
2	35%	Cover Repair	$525	m2	Repair	$525	m2	Cover Repair	$525	m2	Repair	$280	m2
3	45%	RFT. Replace	$1,000	m2	Replace	$1,200	m2	RFT. Replace	$1,000	m2	Replace	$600	m2
4	60%	Strengthen/Rehab	$1,500	m2	Replace	$1,800	m2	Strengthen/Rehab	$1,500	m2	Replace	$1,200	m2
5	80%	Replace	$2,000	m2	Replace	$2,400	m2	Replace	$2,000	m2	Replace	$2,000	m2

Repair Type	Repair Extent	Finishing					
		Type 1 - Class A			Type 2 - Class B		
		Repair Option	Cost	Unit	Repair Option	Cost	Unit
0	0%	Do nothing	$0		Do nothing	$0	
1	25%	Repair	$6	m2	Repair	$5	m2
2	35%	Replace	$25	m2	Replace	$16	m2
3	45%	Replace	$40	m2	Replace	$24	m2
4	60%	Replace	$60	m2	Replace	$42	m2
5	80%	Replace	$80	m2	Replace	$56	m2

Figure 4.3: Repair Costs for the Elements in the ME-BMS

4.4.4 Improvement Model

The basic premise of the condition rating improvement in the proposed ME-BMS is that the condition improves by an amount that corresponds to the repair type. For example, if an element is at condition 5 before repair and the decision is to have it repaired using repair option 2, then the condition rating after improvement will be 7 (5+2).

4.5 ME-BMS Decision Support System

To achieve project-level and network-level integration for the multi-element bridge management system without exploding the size of the optimization problem, the present framework has been designed to incorporate a two step sequential optimization for the project level and network level as shown in Figure 4.4.

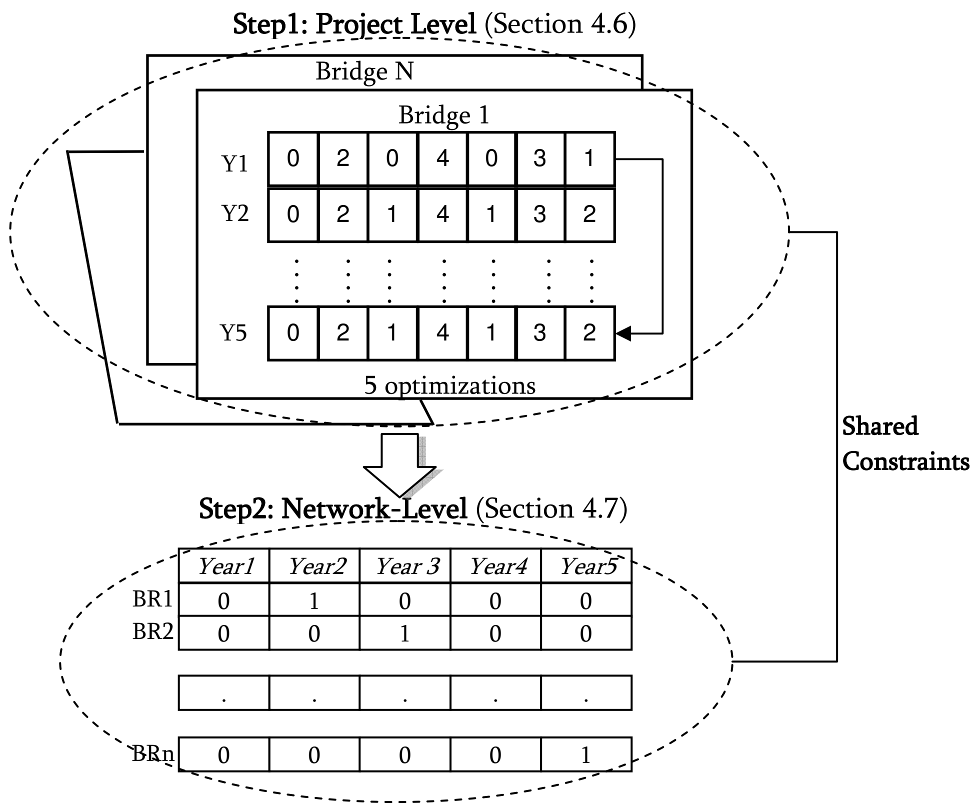


Figure 4.4: Sequential Optimization Design in the ME-BMS

In the first step, project-level optimization is conducted for each bridge individually one year at a time. As such, at this level the optimization size is reasonable (in terms of processing time and the variables involved) and can produce results that can be later used at the next step of network-level optimization. As show in the top part of Figure 4.4, each bridge is exposed to 5 optimizations, one for each year, to determine element repairs with the best benefit/cost if the repairs were to be carried out at each year. This would establish a set of optimal repair decisions for different years. The data are then used in the second optimization step (lower part of Figure

4.4) that determines the suitable year of repair for each bridge considering the whole bridge network. Details on the project-level and network-level steps are provided in the following sections.

4.6 Project-Level Decision Support

Project-level decisions represent the first step in the multi-element life cycle cost analysis; the model is built based on the definition of the deterioration models for all elements, as explained earlier. Given a network of bridges with known initial conditions for its elements, the deterioration and improvement models are capable of predicting the elements' conditions given a repair or no-repair strategy for any year. Each repair strategy has an associated repair cost, and also provides specific benefits in terms of the difference between the after-repair and the before-repair condition, and in terms of the reduction predicted in the user costs after performing the repair. Therefore, it is possible to construct an optimization problem to determine for the elements the best set of repairs that achieve the maximum benefit/cost ratio (B/C) and maximum user cost benefits if the repairs are to be carried out in a given year (user cost calculations are presented in detail in Chapter 5).

As an optimization problem, the objective function for the project level for bridge *i* at year *t* is to maximum the benefit/cost ratio (B/C), formulated as follows:

$$Project\text{ - }Level\ Objective = Max\left(\frac{BCR_R - BCR_C}{repair\ \ cost}\right) \tag{4.4}$$

where BCR_R = the after-repair bridge condition rating, BCR_C = the predicted before-repair condition rating, and *repair cost* = the total cost of the repairs for all the elements.

The present project-level optimization accounts for the following constraints in addition to the objective function:

1. The after-repair condition rating for any element *n* in bridge *i* at time *t* ≥ a pre-defined value (or is taken as 3, according to the FHWA):

$$ECR_n \geq User \quad Predefined \quad Value \tag{4.5}$$

2. The after-repair bridge condition rating (BCR_R) ≥ a pre-defined acceptable value (BCR_R is calculated using Equation 4.1):

$$BCR_R \geq User\ Acceptable\ Value \tag{4.6}$$

3. To add practicality to the project-level model, two logical constraints that respect the logical relationships between element repair decisions are considered:

   ▪ Slab and overlay: Usually, performing a repair in the slab is accompanied by the removal of the overlay on the part to be repaired. Therefore, the overlay repair decision index should be equal to or greater than that of the slab decision. For example, if the repair decision for the deck is repair option 3 and that of the overlay is 2, then the overlay repair decision should be modified to be repair option 3:

$$Overlay \quad decsion_{it} \geq Slab \quad decision_{it} \tag{4.7}$$

   ▪ Overlay and joint: A similar relationship exists between the overlay and the joint: if there is to be a repair in the joint, the repair option for the overlay should be greater than 0.

The variables in this optimization problem for bridge i at year t are the repair decisions for the seven bridge elements: deck, overlay, bearings, joints, superstructure, substructure, and finishing (Figure 4.5).

Five separate optimizations are carried out for each year in the planning horizon. A solution for the problem is structured as a string of seven elements, as shown in Figure 4.5. Each variable can be assigned an integer value from 0 to 5, corresponding to one of the repair options (0 = do nothing; 1 = light repair; 2, 3, and 4 = medium repairs; and 5 = extensive repair).

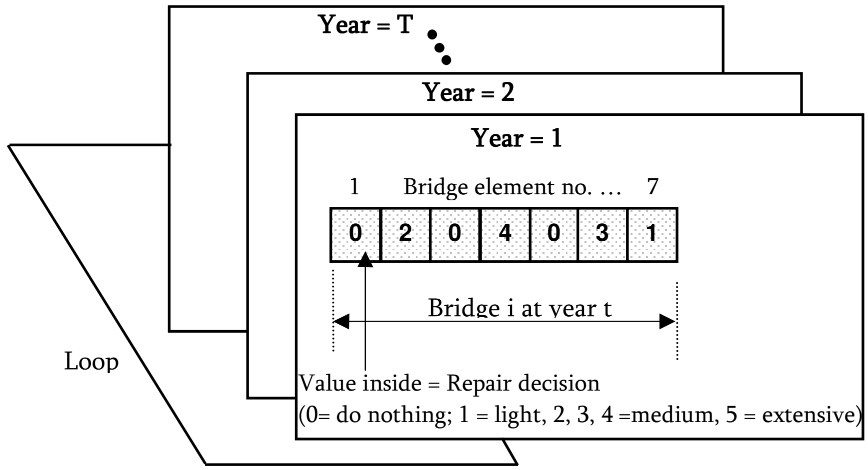


Figure 4.5: Solution Structure for the Project-level in the ME-BMS

4.6.1 Project-level implementation

The present project-level optimization was implemented on a commercial spreadsheet program (Microsoft Excel). The developed application includes forms and worksheets linked with the deterioration, repair cost, and improvement models. The data for the ME-BMS is as shown in Figure 4.6. For each bridge, the input is categorized as General Information (e.g., location, construction year, initial cost); Bridge Information which includes properties of the bridge (e.g., highway type: interstate or other, number of lanes, and structure type), traffic information (the average daily traffic (ADT), length of detour, percentage of trucks and the year of measuring the traffic), and information about the elements (e.g., width, length, and number of bearings and joints), and current condition rating (the condition rating for the seven elements as inspected and the bridge condition rating (BCR)).

Figure 4.7 shows the basic formulation and the variables involved. Each bridge is arranged in a separate row and seven columns for each year in the planning horizon are set to hold the values for the problem variables. These values represent indices to one of the six repair strategies mentioned earlier for each bridge element. Bridge elements are sorted as: deck, overlay, joints, bearings, superstructure, substructure, and finishing. For example, having number 1 assigned at year t of bridge i for element 1 means that the deck of this bridge is selected for repair using repair option 1 at year t, similarly, number 2 in the third column of year t means that the joints of bridge i is selected to be repaired using repair option 2.

General Information

No.	BR. Name	Decription/ location	Year	Initial cost
1	Bridge1	Highway 24 @5km	1985	$2,000,000
2	Bridge2	North of Waterloo	1998	$20,000,000
3	Bridge3		1977	$3,000,000
4	Bridge4		1991	$16,000,000
5	Bridge5		1980	$5,000,000
6	Bridge6		1989	$2,800,000
7	Bridge7		1975	$25,000,000
8	Bridge8		1987	$16,000,000
9	Bridge9		1980	$2,900,000
10	Bridge10		2001	$10,000,000

		Current Condition Rating							6.80
No.	BR. Name	Deck	Overlay	Joints	Bearings	Supper Structure	Sub Structure	Finishing	BCR condition Rating
1	Bridge1	9.00	6.00	6.00	6.50	7.50	6.00	5.50	6.93
2	Bridge2	8.00	5.97	6.25	6.75	7.93	6.00	6.50	6.95
3	Bridge3	6.00	6.00	6.00	6.00	6.00	7.00	5.75	6.13
4	Bridge4	7.00	7.50	6.25	8.00	7.50	7.50	7.50	7.28
5	Bridge5	5.50	5.00	5.00	8.25	9.00	7.25	5.50	6.68
6	Bridge6	8.00	6.00	6.00	6.00	6.00	6.00	6.50	6.44
7	Bridge7	9.00	4.50	5.50	5.50	6.00	4.50	5.00	6.01
8	Bridge8	8.00	6.50	6.00	6.50	7.00	7.50	7.00	7.01
9	Bridge9	5.00	4.00	5.25	5.00	8.00	6.25	4.50	5.69
10	Bridge10	9.00	9.00	9.00	9.00	9.00	8.50	8.50	8.89

Bridge information

Properties				Traffic				Elements information				
Lanes	D/UD	Structure	HighWay	AADT	%Trucks	Year	Detour (Km)	Width	Length	Bearings	Joints	Shoulder
4	divided	Concrete	Otherstate	50,000	0%	1990	0.2	7.0	50.0	6	4	3
4	undivided	Steel	Interstate	20,000	5%		0.5	10.0	30.0	6	3	2.5
2	divided	Steel	Otherstate	5,000	10%	1990	1.4	8.0	25.0	3	4	3.25
4	divided	Concrete	Interstate	30,000	12%	1991	1	15.0	30.0	7	3	3.5
2	divided	Steel	Interstate	6,000	10%	1995	1.2	6.0	20.0	5	2	3
6	divided	Steel	Otherstate	30,000	10%	1989	0.6	20.0	15.0	2	1	2
2	undivided	Concrete	Interstate	5,000	2%	2000	1	6.0	20.0	4	1	2.5
8	divided	Concrete	Interstate	50,000	5%		1.1	40.0	50.0	6	2	1.5
2	divided	Steel	Interstate	10,000		1990	0.5	7.0	28.0	8	3	3
8	divided	Steel	Interstate	90,000	10%		2.5	24.0	100.0	10	7	3

Figure 4.6: ME-BMS input data

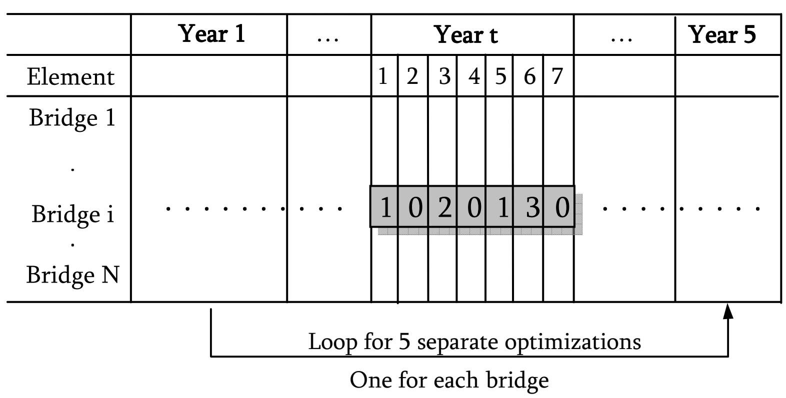


Figure 4.7: Representation of the Project-level optimization in the ME-BMS

Once the data for the bridges are input, the user starts the optimization by defining the optimization constraints. The basic constraint used in the project-level decision support model is to satisfy the predefined minimum element condition rating (Equation 4.5) and the minimum acceptable bridge condition rating (BCR) throughout the planning horizon (Equation 4.6). The user enters the values for the constraints in the form shown in Figure 4.8.

Once the constraints are set as shown in Figure 4.8, the optimization process starts and continues until no more improvement in the objective function (Equation 4.4) is reached.

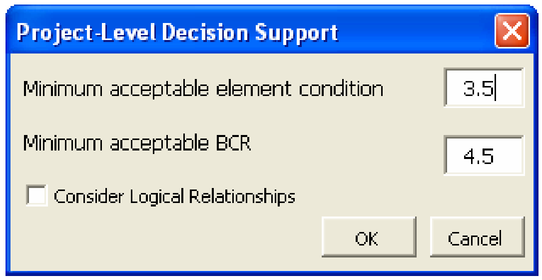


Figure 4.8: Project-Level Optimization Constraints

4.6.2 Experimentation with Different Optimization Techniques

To achieve the most efficient and fast technique for optimization, the project-level decision support model was used to experiment with various optimization techniques. The techniques considered were:

- Solver optimization linear optimization (Excel add-in software)
- Genetic algorithms (GA) (Evolver, Excel add-in software)

The comparison between the two techniques was based on two criteria: the average benefit/cost ratio (B/C) that resulted through the planning horizon and the time taken to complete the optimization loops for a network of 10 bridges in the five-year planning horizon. Table 4.2 shows the results of the experiments for the three techniques, it can be noted that the results using the GA have the highest average B/C and the shortest time. In experiments with larger networks, the GA outperformed the Solver technique. Therefore, the element repair decisions obtained by the GA were used later in the network-level analysis.

Table 4.2: Results of the Experiments for the Project Level

Method	Average B/C	Time 10 bridges – 5 years
Solver	14.26	1:12:23
GA	**14.47**	**0:50:53**

4.6.3 Project-Level Output

Sample output of a network of bridges for project-level decisions in a specific year is shown in Figure 4.9. Part (a) of Figure 4.9 shows a column that lists the value of objective function for each bridge in a separate row- benefit/cost ratio (B/C) (Equation 4.4). Part (b) shows the variables for the project-level model (seven variables for each bridge in each year). The values inside these cells represent one of the repair decisions (0, 1, 2, 3, 4, or 5). The element repair costs and element condition rating after repairs are shown in parts c and d, respectively.

The results show that logical repair decisions are produced by the model. For example, bridge 10 which has a high condition rating before the optimization (Figure 4.6), has none of its elements selected for repair (repair decisions are zeros for all elements). On the other hand, for bridge 9, which has a low condition rating for the overlay (condition rating was 4 before optimization, Figure 4.6), it was decided to perform a repair of type 2 (part (b) of Figure 4.9) in order to raise the condition rating to 6 (part (d) of Figure 4.9). Part (c) shows the repair costs associated with the repair decisions; for example, for the same bridge element, it is estimated that it will cost $10,780$ to perform the decided repairs. Part (e) shows the bridge condition rating (BCR), which is calculated based on the deteriorated or improved element condition ratings in part (d) and using the weights illustrated in Table 4.1 (Equation 4.1). The results shown in Figure 4.9 are for only one year (first year in the analysis); the same procedure is carried out for every year in the planning horizon.

BR. Name	B/C-06	Element Repair Decision 2006: Deck	Overlay	Joint	Bearing	Super	Sub	Finish
Bridge1	23.15	0	2	0	2	0	1	1
Bridge2	4.89	0	1	0	1	0	2	0
Bridge3	26.23	0	2	0	1	0	2	1
Bridge4	13.65	0	1	1	1	0	1	1
Bridge5	11.01	0	2	1	0	0	1	1
Bridge6	16.27	0	0	1	2	0	1	0
Bridge7	10.46	0	1	0	2	0	1	1
Bridge8	7.29	0	2	0	2	0	1	0
Bridge9	27.35	0	2	1	2	0	1	1
Bridge10		0	0	0	0	0	0	0

BR. Name	Element Repair Cost 2006: Deck	Overlay	Joint	Bearing	Super	Sub	Finish
Bridge1	$0	$7,875	$0	$3,150	$0	$5,600	$4,688
Bridge2	$0	$12,000	$0	$1,313	$0	$20,160	$0
Bridge3	$0	$5,880	$0	$788	$0	$10,080	$3,500
Bridge4	$0	$7,500	$15,625	$1,313	$0	$6,300	$9,375
Bridge5	$0	$15,120	$13,500	$0	$0	$613	$6,750
Bridge6	$0	$0	$11,250	$4,200	$0	$1,969	$0
Bridge7	$0	$9,000	$0	$10,500	$0	$8,925	$11,250
Bridge8	$0	$16,170	$0	$7,350	$0	$7,000	$0
Bridge9	$0	$10,780	$5,500	$5,250	$0	$2,100	$4,813
Bridge10	$0	$0	$0	$0	$0	$0	$0

BR. Name	Element Deterioration 2006: Deck	Overlay	Joint	Bearing	Super	Sub	Finish	BCR 2006
Bridge1	8.81	8.00	5.25	8.50	7.34	7.00	6.50	7.42
Bridge2	7.79	6.97	4.96	7.75	7.72	8.00	5.38	7.12
Bridge3	5.92	8.00	5.10	7.00	5.92	9.00	6.75	6.66
Bridge4	6.89	8.50	7.25	9.00	7.34	8.50	8.50	7.82
Bridge5	5.40	7.00	6.00	7.13	8.91	8.25	6.50	7.08
Bridge6	7.86	4.71	7.00	8.00	5.87	7.00	5.38	6.72
Bridge7	8.88	5.50	4.75	7.50	5.89	5.50	6.00	6.43
Bridge8	7.87	8.50	4.71	8.50	6.88	8.50	5.20	7.23
Bridge9	[illegible]	6.00	6.25	7.00	7.89	7.25	5.50	6.47
Bridge10	8.81	7.71	8.10	7.88	8.84	8.34	6.70	8.26

(a) B/C

(b) **Variables:** Element repair decision

(c) Repair Costs associated with decisions

(d) Element condition rating after repair

(e) BCR

Figure 4.9: Sample Output of the Project-level Decision Support Model

4.7 Network-Level Decision Support

The network-level decision support system has been developed to support managers who wish to optimize the allocation of funding for a network of bridges and to decide on the best timing for the repairs. The decisions about repairs to the bridge elements that result from the project-level decision support are a key input for the network-level decision making process. The variables are the years the bridges are selected to be repaired (Figure 4.10). As shown in the representation of Figure 4.10, the variables are binary; for example, the values shown indicate that bridge 1 is selected to be repaired in year 1, while bridge n is selected to be repaired in year 4. For these network-level decisions, the associated project-level decision is known and the consequent after-repair bridge condition rating (BCR_R) for each bridge is also automatically known.

	Year 1	Year 2	Year 3	Year 4	Year 5	
Bridge 1	1	0	0	0	0	$\sum = 1.0$
.	.	.	.	.	.	
.	.	.	.	.	.	
.	.	.	.	.	.	
.	.	.	.	.	.	
Bridge N	0	0	0	1	0	$\sum = 1.0$

Selected bridges for repair

Figure 4.10: Network-Level in the ME-BMS

To determine a suitable objective function, the conclusions from the extensive experimentation described in Chapter 3 are utilized. A year-by-year GA optimization strategy with an objective function for maximizing the network condition rating is therefore used at the multi-element network-level analysis. Thus, the objective function is to maximize the network condition rating (NCR) as follows:

$$Max(NCR) \tag{4.8}$$

where NCR is the average of all the after-repair condition ratings for the bridge network.

Once the objective function for the network-level analysis is defined, the user then defines the following constraints through the user form shown in Figure 4.11:

1. The minimum BCR for all bridges should be ≥ a user defined value (similar to that for the project level):

$$BCR \geq User\ Value \tag{4.9}$$

2. The minimum element condition rating (ECR) for all elements through the planning horizon for all bridges should be ≥ a user-defined value:

$$ECR \geq User\ Value \tag{4.10}$$

3. The repair cost at a specific year T for the network should be ≤ the allowed budget:

$$repair\ cost_T \leq allowed\ Budget_T \tag{4.11}$$

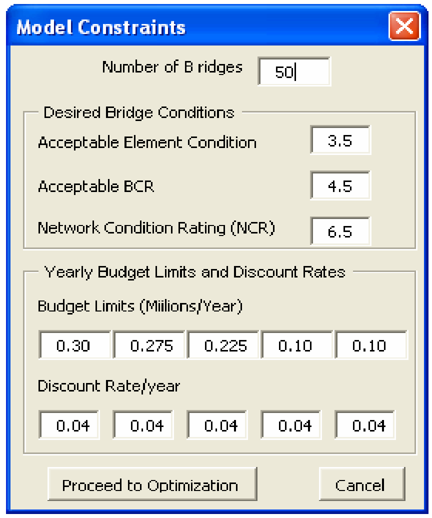


Figure 4.11: Network-Level Constraints

4.7.1 Network-level implementation

The developed network-level optimization was implemented on a commercial spreadsheet program (Microsoft Excel) in order to utilize its user friendly facilities. The network-level decision support system shares the same input as the project-level one (Figure 4.6). Sample output for a network of 50 bridges is shown in Figure 4.12. Part (a) of the figure shows the total life cycle cost ($971,344), which is very close to the allowed budget ($1,000,000). Part (b) shows the element repair decisions for the first year that resulted from the project-level decision support analysis, while part (c) shows the selection year for the bridges (network decision). It can be noted that bridge 3 is selected to be repaired in the first year of the analysis, and the element repair decisions resulted from the project level (the previous optimization on project level) are shown in part (b). Similarly, bridge 9 is selected to be repaired in the same year. The resultant bridge condition rating (BCR) because of repairing a bridge is shown in part (d). For example, the BCR for bridge 3 was 6.13 before repair and 6.73 after repair. The estimated cost of repairing the elements is shown in part (e). For example, it would require $17,088 to do the repairs of bridge 3 with the element repair decisions described in part (b). It should be noted from the sample of 50 bridges (Figure 4.12) that the optimization process resulted in a network condition rating (NCR) of 6.36, which is greater than the constraint value of 6.0 (Figure 4.11). Similarly, the optimization produced a minimum BCR through the planning horizon for the network of 5.23, which is greater than the constraint value of 4.5 (Figure 4.11), and the resulting minimum element condition rating for all the elements in the network was 3.5, which meets the constraint value defined in Figure 4.11.

As shown in Figure 4.12, for any changes required by the user, the ME-BMS is transparent and flexible. For example if the user would like to force a specific repair decision for the deck of bridge 7, the user can input the value of the required repair manually, and instantaneously the ME-BMS shows the impact of this repair decision on the budget, on the element condition rating, on the BCR, and on the NCR.

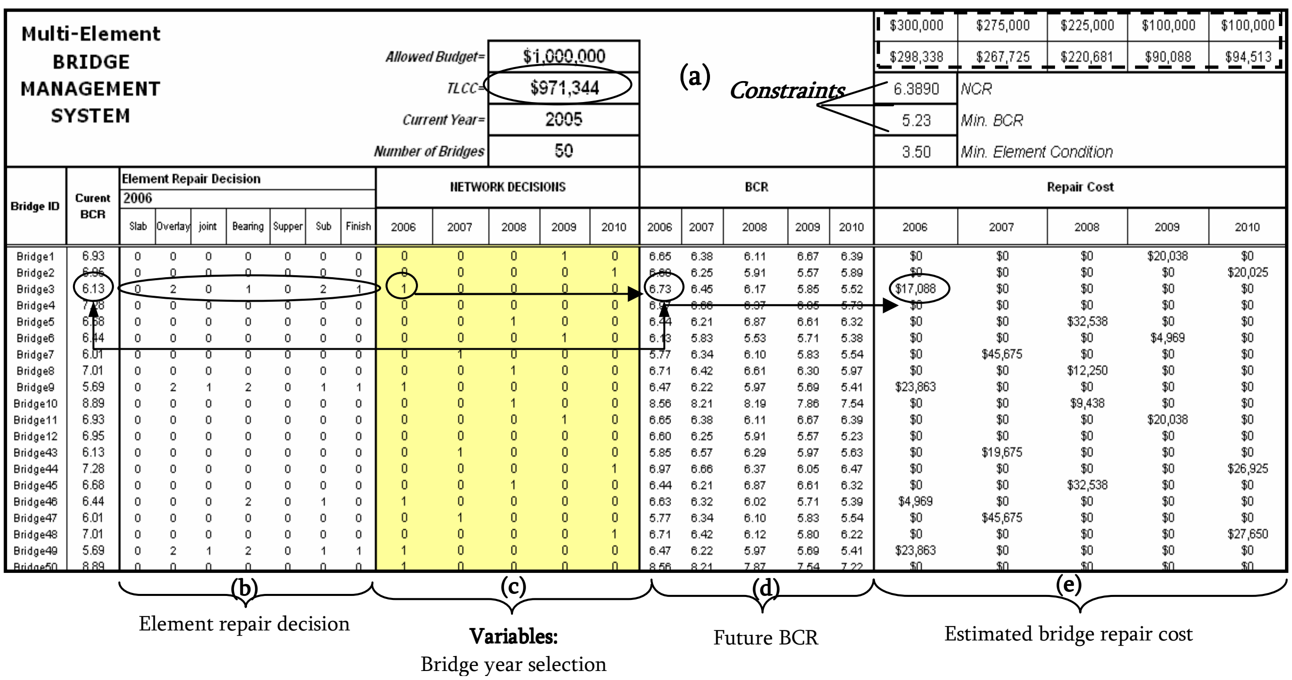


Figure 4.12: ME-BMS Output

4.7.2 Experimentation with Large Numbers of Bridges

A network of 10 bridges was constructed with an allowed budget of $200,000, an overall network condition rating of 5.93, a minimum bridge condition rating (BCR) of 4.37, and an element condition rating of 2.20. Larger networks (50, 100, 250, 500, 1000, and 2000) were constructed by repeating the 10-bridge network several times. Repeating the 10-bridge network provides a quantitative approach for measuring the performance of large-scale networks. Based on the experiments carried out in Chapter 3, in which it was concluded that the best objective function is to maximize the condition rating, the objective function was set to maximize the overall average network condition rating represented by OB1 in Equation 4.12. Another objective function was introduced that maximizes the benefits gained in the condition rating relative to the money spent to improve the condition. This function, also, is targeted at minimizing the difference between the repair cost and the allowed budget. The two proposed objective functions are:

$$OB1 = Max(NCR) \tag{4.12}$$

$$OB2 = Max\left(\frac{(NCR - NCR_c)}{Repair\ cost} + \frac{1}{Diff}\right) \tag{4.13}$$

where *NCR* = the network condition rating after repair, NCR_c = the network condition rating before repair (5.93), *Repair cost* = the total repair costs of implementing the repairs to the elements, and *Diff* = sum of difference between the budget limit and the repair costs. Ten trial runs were conducted for different numbers of bridges. The criteria used to compare the two objective functions is based on the average network condition rating within the 10 runs, the best (highest) network condition rating (NCR) reported through the 10 trial runs, the average repair cost, and the processing times.

Table 4.3 shows the results for the two objective functions (Equations 4.12 and 4.13), while Figure 4.13 shows a graphical representation of the best network condition (column (e) in Table 4.3) obtained in the 10 trial runs for both objective functions with respect to the different numbers of bridges. The two objective functions are similar in terms of their processing time. For small bridge networks (50, 100, and 250), the performance of the two objective functions was almost similar; however, with the increase in numbers of bridges, the degradation of OB1 (maximum NCR) was higher than that for OB2 (maximum benefit) (Figure 4.13). The NCR obtained from using OB2 is higher than that for OB1 for the case of 1000-, and 2000-bridge networks. In addition, a comparison of the total life cycle cost reveals that most of the TLCC resulting from OB2 is less than that from OB1, although most of the NCR for OB2 is higher than that for OB1.

Table 4.3: Results for Network Level Decisions

(a) No of Bridges	(b) Budget Limits	(c) Average TLCC	(d) Average NCR	(e) Best NCR	(f) Time
*OB1: **Max (NCR)***					
50	1,000,000	977,245	6.412	6.423	0:01:33
100	2,000,000	1,982,930	6.417	6.429	0:03:39
250	5,000,000	4,988,721	6.416	6.424	0:04:02
500	10,000,000	9,989,979	6.404	6.414	0:05:16
1000	20,000,000	19,985,121	6.387	6.396	0:19:53
2000	40,000,000	39,981,343	6.379	6.380	6:00:00
*OB2: **Max (Benefits/C)***					
50	1,000,000	974,701	6.418	6.424	0:01:42
100	2,000,000	1,981,053	6.422	6.431	0:02:15
250	5,000,000	4,965,564	6.418	6.424	0:04:07
500	10,000,000	9,974,836	6.404	6.408	0:05:02
1000	20,000,000	19,985,495	6.401	6.406	0:25:00
2000	40,000,000	39,980,308	6.401	6.402	6:55:11

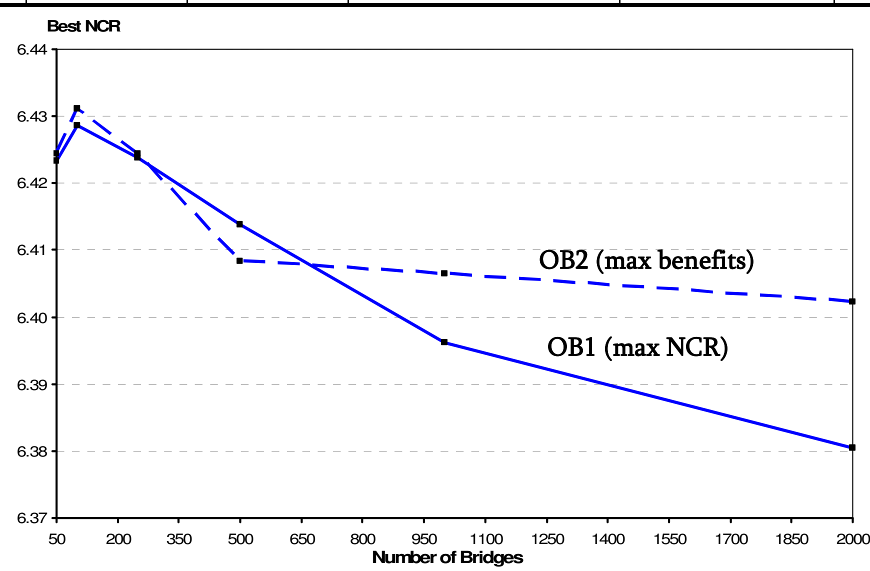


Figure 4.13: The Best NCR for OB1 and OB2

The results shown in Table 4.3 indicate that the network-level decisions of OB2 are better utilizing the money spent to improve the condition of the bridge network in the case of large networks.

4.8 Reporting Output Results

To add practicality to the ME-BMS, 10 automated reports that summarize the results obtained on both the project-level and network-level decisions were developed. These reports are presented in the form of pivot tables in Microsoft Excel. Figure 4.14 shows the ten reports that can be generated with different options. Report 1 shows the bridge condition rating (BCR) based on the year of repair (Figure 4.14), for example if the year of repair is selected to be 2006, then only the bridges repaired in this year will be shown, and the BCR for these bridges throughout the planning horizon is then illustrated. At the right hand side of the table, the average BCR for each bridge throughout the planning horizon is calculated, also, the average BCR for each year is shown at the bottom of the table. Figure 4.15 a, b, and c show reports 2, 3, and 10, respectively. Report 2 shows the repair costs required for each bridge according to the year of repair, also, Report 3 shows the bridges that are selected to be repaired in year 2006 and the benefits gained with respect to the user costs for each year through the planning horizon. Report 10 summarizes the results on the network level, where it shows the required repair costs, the benefits gained in the user costs and the network condition rating for the whole network throughout the five-year planning. These reports are proved to be useful in summarizing the output and in better sorting the results.

You can customize the report for any bridge by selecting one of the following options

View Report

At the Project Level

1 ☑ View all Bridges, Year of Repair and BCR through the planning horizon

2 ☐ View all Bridges, Year of Repair and Repair Cost through the planning horizon

3 ☐ View all Bridges, Year of Repair and Benefits in User Costs

4 ☐ View Element Repair Decisions

5 ☐ View Element Repair Costs

6 ☐ View Element Condition Ratings

At the Network Level

7 ☐ Network Condition Rating through the Planning Horizon

8 ☐ Network Benefits in User Costs

9 ☐ Network Repair Costs

10 ☐ Combined Report for Network Condition, Repair Costs, and User Costs

Year of Repair	2006						
Average of BCR	Year						
Bridge_ID	2005	2006	2007	2008	2009	2010	Grand Total
9	5.69	6.47	6.22	5.97	5.69	5.41	5.91
11	6.93	7.48	7.21	6.94	6.66	6.39	6.93
12	6.95	7.14	6.79	6.45	6.11	5.77	6.53
13	6.13	6.73	6.45	6.17	5.85	5.52	6.14
15	6.68	7.16	6.92	6.68	6.42	6.14	6.67
16	6.44	6.63	6.32	6.02	5.71	5.39	6.08
19	5.69	6.47	6.22	5.97	5.69	5.41	5.91
26	6.44	6.63	6.32	6.02	5.71	5.39	6.08
28	7.01	7.45	7.15	6.86	6.54	6.22	6.87
29	5.69	6.47	6.22	5.97	5.69	5.41	5.91
39	5.69	6.47	6.22	5.97	5.69	5.41	5.91
43	6.13	6.73	6.45	6.17	5.85	5.52	6.14
45	6.68	7.16	6.92	6.68	6.42	6.14	6.67
49	5.69	6.47	6.22	5.97	5.69	5.41	5.91
Grand Total	6.27	6.82	6.54	6.27	5.98	5.68	6.26

Figure 4.14: Report 1 – Bridge Condition Rating Throughout the Planning Horizon

Year of Repair	2006
Sum of repair cost	
Bridge_ID	Total
9	$23,862.5
11	$20,037.5
12	$15,712.5
13	$17,087.5
15	$31,662.5
16	$4,968.8
19	$23,862.5
26	$4,968.8
28	$27,650.0
29	$23,862.5
39	$23,862.5
43	$17,087.5
45	$31,662.5
49	$23,862.5
Grand Total	$290,150.0

a) Report 2: Repair Costs

Year of Repair	2006					
Sum of benefits in user cost	Year					
Bridge_ID	2006	2007	2008	2009	2010	Grand Total
9	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
11	$380,321.5	$387,927.9	$395,686.5	$403,600.2	$411,672.2	$1,979,208.2
12	$421,467.9	$491,311.2	$501,137.4	$511,160.1	$579,314.8	$2,504,391.5
13	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
15	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
16	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
19	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
26	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
28	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
29	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
39	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
43	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
45	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
49	$0.0	$0.0	$0.0	$0.0	$0.0	$0.0
Grand Total	$801,789.4	$879,239.1	$896,823.9	$914,760.3	$990,987.0	$4,483,599.7

b) Report 3: Benefits in User Costs

Bridge_ID	(All)					
	Year					
Data	2006	2007	2008	2009	2010	Grand Total
Sum of Repair cost	$290,150.0	$300,075.0	$243,887.5	$90,375.0	$42,393.8	$966,881.3
Sum of benefits in user cost	$801,789.4	$879,239.1	$2,980,707.1	$4,062,641.6	$4,375,620.3	$13,099,997.5
Average of BCR	6.74	6.58	6.48	6.24	5.97	6.40

c) Report 10: Summary of Network Results

Figure 4.15: Reports 2, 3, and 10

4.9 Summary and Conclusions

In this chapter an integrated model has been presented for a multi-element bridge management system (ME-BMS) that integrates both network-level and project-level decisions. Seven bridge elements are considered in the model: deck, overlay, joints, bearings, superstructure, substructure, and finishing. For each element, a separate deterioration model for different working environments is defined as well as separate repair options and their associated repair costs are presented.

A project-level decision model was introduced in order to maximize the benefit/cost ratio of repairing the elements of each bridge in a given year in the planning horizon. A network-level decision model was then developed in order to integrate the repair decisions chosen at the project-level and to optimize the selection of the bridges for each year. Experiments have been carried out for different numbers of bridges in order to examine the performance of the developed system. It was demonstrated that the model is simple, transparent, and easy to use. The ME-BMS proved to perform efficiently for optimizing large-scale bridge networks.

Chapter 5

Bridge User Cost and Work Zone Models

5.1 Introduction

Chapter 4 presented a multi-element bridge management system that incorporates both network-level and project-level decisions. However, when decisions are made with respect to repairing a network of bridges, consideration should be given to the impact of the repairs on the public. User costs are costs incurred by users of the bridge as a result of deteriorated conditions of the bridge which sometimes lead to detouring and/or accidents. Therefore, developing optimum cost-effective maintenance and repair programs that have greater benefits for the users is a complex task.

This chapter presents the development of two user cost models; the first one estimates the user cost for a network of bridges under service conditions, and the other estimates the user costs incurred when crossing work zones during repair activities. The latter model optimizes the work zone strategies in order to minimize the user costs. The two proposed models and their implementation are described in this chapter along with an example application that demonstrates the benefits of these models to departments of transportation. Figure 5.1 is a schematic diagram of the developed models that shows the components of each model.

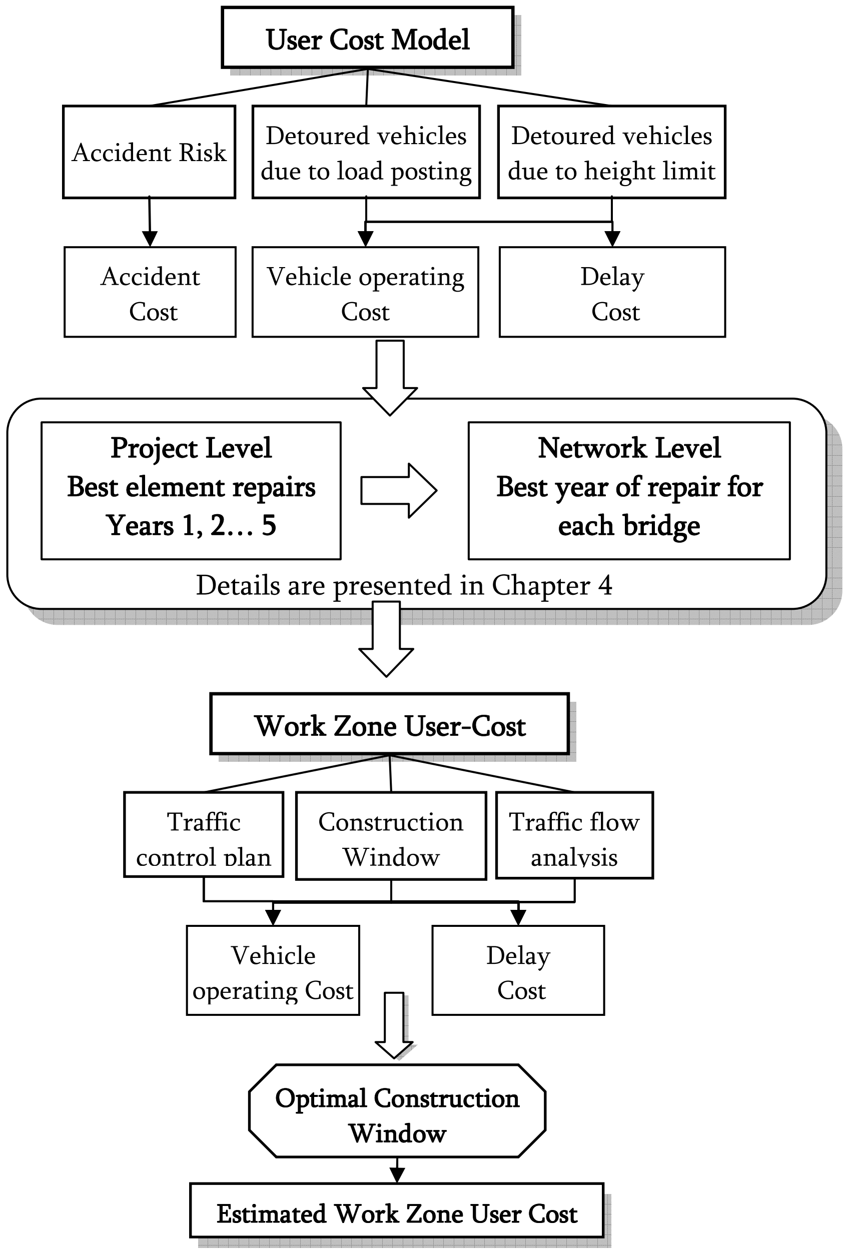


Figure 5.1: Schematic Diagram of the User Cost and Work Zone User Cost Models

5.2 User Costs – Background

User costs are costs incurred by the public because of deficiencies in bridges, such as a narrow width which causes accidents, low load capacity, or low vertical clearance. Bridges with such deficiencies cause some vehicles to detour thus leading to an increase in vehicle operating costs and an increase in the trip time which is translated into user delay costs.

User costs contribute significantly to the total life cycle cost and should be considered in the analysis of bridge networks. A study by the Florida Department of Transportation (Thompson et al., 1999) estimated that user costs may exceed the repair costs by a factor of 5 or more. This Section provides a detailed background of existing user cost models, and then Section 5.3 presents the developed user cost model for ME-BMS that includes consideration of the annual traffic growth, the accident rate, vehicle operating costs, and user delay costs. An example application for calculating the benefits gained in user costs is then presented. The incorporation of the user cost model into the ME-BMS and the modifications in both the project-level and network-level formulations are then discussed.

In the literature, several efforts have been directed at developing user cost models for bridge management systems. The user costs are incurred either because of the high risk of bridge accidents or because of traffic detour. The user cost model in Pontis (1992) estimates the user benefits of three types of functional improvements as follows:

- Widening the bridge approach roadway primarily reduces the risk of accidents on the bridge.
- Raising the height of the clearance affects the ability of tall trucks to pass under the bridge. The Pontis user model predicts the savings with respect to truck detours.
- Strengthening the bridge affects the ability of heavy trucks to cross the bridge. The model predicts the potential savings with respect to truck detour costs. The method of estimating the bridge load capacity is discussed in the following subsections.

Johnston et al. (1994) stated that user costs are incurred because of bridge deficiencies such as narrow width, low clearance, poor alignment, and low load capacity. The user costs in any year are given by Equation 5.1:

$$AURC_{(t)} = 365\ ADT_{(t)}\left[C_{WDA}U_{AC} + C_{ALA}U_{AC} + C_{CLA}U_{AC} + C_{CLD}U_{DC}DL + C_{CLD}U_{DC}DL\right] \quad (5.1)$$

where $AURC_{(t)}$ = the annual user cost of a bridge at year t ($), $ADT(t)$ = the average daily traffic using the bridge at year t, C_{WDA} = the coefficient for the proportion of vehicles incurring accidents due to a deficiency in the width, C_{ALA} = the coefficient for the proportion of vehicles incurring accidents due to poor alignment, C_{CLA} = the coefficient for the proportion of vehicles incurring accidents due a deficiency in vertical clearance, C_{CLD} = the coefficient for the proportion of vehicles that detoured due a deficiency in vertical clearance, C_{LCD} = the coefficient for the proportion of vehicles that detoured due to a deficiency in load capacity, U_{AC} = the unit cost of the vehicle accidents on the bridges, U_{DC} = the unit cost of the average vehicle detours due a deficiency in vertical clearance, U_{DL} = the unit cost of vehicle detours due to a deficiency in load capacity, and DL = the detour length in km. It should be noted that this model includes many terms that are rarely included in the bridge inventory and is difficult to be implemented in real life.

The key factors in any user cost model are risk of accidents, and the detouring vehicles due to restricted load capacity or vertical clearance. The following subsections present the efforts to quantify these two elements of user cost as given in the literature.

5.2.1 Bridge-Related Accident Rate

Although bridge-related accidents represent only about 1.7% of all traffic accidents, the degree of severity is estimated to be from 2 to 50 times the severity of general roadway traffic accidents (Abed-Al-Rahim and Johnston, 1993). In a study by the North Carolina Department of Transportation (NDOT), the average number of people killed in bridge related accidents was determined to be 0.019 persons/accident, while this number is reduced to 0.009 persons/accident in other traffic accidents (Abed-Al-Rahim and Johnston, 1991, 1993). This measure of accident severity implies that bridge-related accidents are twice as severe as other traffic accidents.

A model developed by Chen and Johnston (1987) to estimate the bridge-related accidents assuming that accidents are due primarily to deficiencies in deck width and the approach roadway alignment was based on the following equation:

$$ACCR = 6.28 \times 10^{7.5} \times CDW^{-6.5}\left[1 + 0.5\frac{(9 - ALI)}{7}\right] \tag{5.2}$$

where $ACCR$ = the accidents per million vehicles crossing the bridge, CDW = the clear deck width (feet), and ALI = the alignment appraisal condition. However, it is noted that this model is not sensitive to the traffic volume on the bridge or to the number of lanes. Aded-Al-Rahim and Johnston (1991, 1993) proposed another model for calculating the risk of accidents that considers the average daily traffic (ADT) and the bridge length, as follows:

$$NOACC = 0.783(ADT^{0.073})(LENGTH^{0.033}) \times (WDIFACC + 1)^{0.05} - 1.33 \tag{5.3}$$

where $NOACC$ = the number of accidents per year, $LENGTH$ = the bridge length in feet, and $WDIFACC$ = the difference in the width between the clear deck width goal for an acceptable level of service and the actual bridge width. However, this model does not consider the functional classification of the roadway and the condition of the deck.

The accident count used in Pontis was developed by Thompson et al. (2000), who investigated different variables that affect the accident rate, such as the narrowness, the approach alignment, the condition of the deck, the length of the bridge, the number of lanes, the direction of the traffic, whether the pedestrians are allowed, the traffic volume, the percentage of trucks, and the weather conditions. A regression model was then developed using these variables which resulted in the following equation for calculating the annual accident count:

$$AC = 0.001 \times (C1 + C2 \times lanes \times length + C3 \times Narrowness \times ADT) \tag{5.4}$$

where AC = the annual accident count; $C1$, $C2$, and $C3$ are dependent on the deck condition rating and highway type as given in Table 5.1; and Narrowness = the number of lanes divided by the width of the roadway. This user cost model has been adopted for use in the developed ME-BMS user cost model.

Associated with the accident rate is the average unit cost per accident. Since this unit cost is not yet known with great precision, there are a wide range of results, with values in the literature from \$10,000 to \$40,000 per accident. The Pontis default value is \$37,600 (Thompson et al., 1999b). However, Soares (1999) recommended modifying this value to be \$68,404.39 per accident based on data collected from traffic accidents in Florida, the latter value is used in the development of ME-BMS user cost model.

Table 5.1: Accident Count Model

Highway type/deck condition	Variable	Coefficient
Interstate	Constant	886.0098 (C1)
Other state	Constant	-377.3701 (C1)
All bridges	Lanes x length	0.7323 (C2)
Deck Condition > 6	Narrowness x ADT	0.3904 (C3)
Deck Condition < 6	Narrowness x ADT	0.7899 (C3)

5.2.2 Detours Because of Deficiencies in Bridge Load Capacity

Bridge load capacity may deteriorate due to section loss or material degradation. Causes include spalling, cracking, or corrosion of the steel reinforcement. Load capacity reduction is also influenced by environmental conditions. To determine the deterioration rate in the load capacity, a study conducted by the North Carolina Department of Transportation recommends posting bridges for load capacity based on the condition rating of the bridges (Johnston et al., 1994). Regression analysis of bridge rating versus age was conducted using inspection data from North Carolina bridges. The study showed that the lowest value for the substructure or superstructure condition rating is assumed to control the deterioration and that the condition of the deck rarely controls the load capacity. The relationship between the rate of deterioration in the load capacity and the substructure or superstructure condition rating is presented in Table 5.2.

The amount of traffic that must detour because of posted load capacity is predicted by Johnston et al. (1994) based on the functional classification of the roadway and the value of the bridge posting measured in tons as shown in Table 5.3. The values presented in Table 5.3 were used in the development of the present ME-BMS user cost model.

Table 5.2: Bridge Load Capacity Deterioration Rates (Johnston et al., 1994)

Lowest value for the condition rating of the superstructure and substructure	Deterioration Rate (tons/year)		
	Timber	Concrete	Steel
6-9	0.00	0.00	0.00
5	0.30	0.20	0.20
4	0.60	0.30	0.30
3 or less	1.00	0.50	0.50

Table 5.3: Percentage of ADT that Detoured Because of Bridge Load Posting (Johnston et al., 1994)

Bridge Load Posting (tons)	Interstate	Other State
3	16.90%	7.90%
4	16.32%	7.40%
5	15.75%	6.89%
6	15.18%	6.38%
7	14.60%	5.87%
8	14.03%	5.37%
9	13.76%	4.97%
10	13.28%	4.57%
.	.	.
.	.	.
36	0.00%	0.00%

Table 5.4 and Figure 5.2 show the detoured percentage of trucks that detoured, as calculated using Pontis. For example, for a bridge with an 18-ton weight limit, it is expected that 50.425% of the trucks crossing the bridge will have to detour (Thompson et al., 1999b). It should be noted that Pontis model for predicting detoured vehicles because of weight limit is not sensitive to the highway's functional classification. Therefore, the model presented by Johnston et al. (1994) is used in the development of ME-BMS user cost model (Tables 5.2 and 5.3).

Table 5.4: The Percentage of Trucks that Detoured Because of the Weight Limit (Thompson et al., 1999b)

Point	Weight limit (tons)	Percent Detoured
A	2.3	100.0 %
B	18.0	50.425%
C	41.0	0.0%

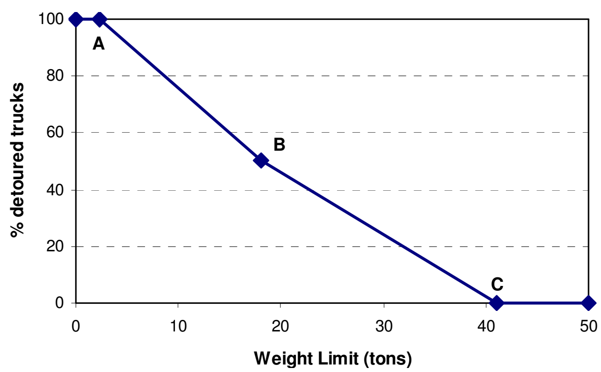


Figure 5.2: The Percentage of Trucks that Detoured because of Weight Limit According to Pontis (Thompson et al., 1999b)

Associated with the percentage of detoured traffic is the unit cost of operating vehicles. In the literature, truck operating costs range from 19 cents to 31 cents per kilometre. According to Johnston et al. (1994), the unit vehicle operating cost is \$0.28/km. Pontis uses a value of \$0.25/km (Thompson et al., 1999b). However, Soares (1999) recommended using \$0.313/km based on a study conducted at the Florida Department of Transportation (FDOT), this value is used later in the development of ME-BMS user cost model.

5.2.3 Detours Because of Deficiencies in Vertical Clearance

Trucks passing through or under a bridge must detour if they are higher than the allowed vertical clearance of the bridge. The proportion of detoured vehicles depends on the truck height distribution in the traffic stream, which depends on the roadway's functional classification. Table

5.5 shows the expected percentage of detoured vehicles compared to the bridge clearance posting level, and according to the functional classification of the roadway (Johnston et al., 1994). For example, if the height limit posted on a bridge is 10 feet, it is expected that 15.30% of the trucks in the traffic will detour if the bridge is on an interstate highway and that only 6.23% of the trucks will detour for any other highway.

Table 5.5: The Percentage of the ADT Detoured as a Result of Bridge's Vertical Clearance Posting Level (Johnston et al., 1994)

Vertical clearance (feet)	Interstate	Other State
8.0	16.90%	7.90%
8.5	16.50%	7.48%
9.0	16.10%	7.06%
9.5	15.70%	6.65%
10.0	15.30%	6.23%
10.5	13.12%	5.43%
11.0	10.94%	4.45%
11.5	8.77%	3.46%
12.0	6.59%	2.68%
12.5	4.41%	1.79%
13.0	2.23%	0.90%
13.5	0.06%	0.01%
14.0	0.01%	0.0%
14.5	0.01%	0.0%

Pontis calculates the percentage of trucks detoured by comparing the vertical clearance against a stepwise linear graph shown in Figure 5.3 and Table 5.6 (Thompson et al., 1999b). However, it is noted that the Pontis model does not consider the roadway classification. In addition, the discontinuity in the step function shown in Figure 5.3 between points B and C leads to inaccurate results. For example, if a bridge crosses the threshold from C to B, the user costs increase by a factor of 60.

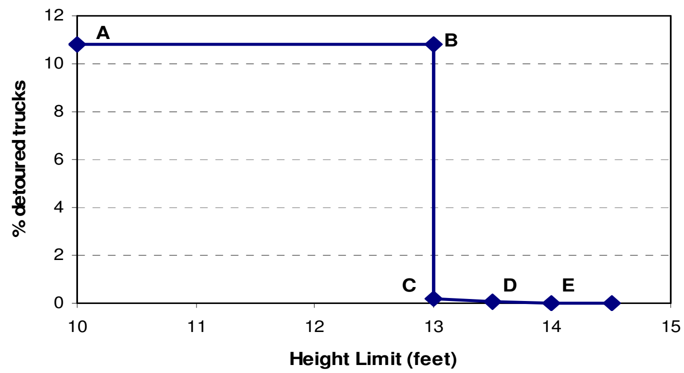


Figure 5.3: Pontis Percentage of Trucks Detoured due to the Vertical Clearance Posting (Thompson et al., 1999b)

Table 5.6: Pontis Percentage of Trucks Detoured due to the Vertical Clearance Posting (Thompson et al., 1999b)

Point	Height Limit (m)	Percent Detoured
A	≤ 0.00	0.00
B	≤ 3.96	10.810%
C	≤ 4.11	0.18%
D	≤ 4.27	0.05%
E	≤ 4.42	0.027%

Because of the problems associated with the Pontis vertical clearance detour model, the ME-BMS user cost model incorporates the work done by Johnston et al. (1994) (Table 5.3). The unit truck operating cost used in calculating the user costs due to vertical clearance restrictions is the same as that mentioned in subsection 5.2.2.

5.3 ME-BMS User Cost Model

The user cost model presented in this Chapter and integrated with the ME-BMS considers the annual traffic growth, the annual accident rates, the vehicle operating cost, and the user delay costs. The latter two components are considered when a bridge load capacity and/or a vertical clearance limit are posted. The general model for calculating the user costs for bridge i is as follows:

$$UC_i = AC_i \times Acost + VOC_i + UD_i \tag{5.5}$$

where AC_i = the accident count for bridge i, $Acost$ = the accident cost, VOC_i = the vehicle operating costs for bridge i, and UD_i = the user delay costs for bridge i. The following subsections discuss the proposed ME-BMS user cost model, and present an example application in order to demonstrate the model's capability.

5.3.1 Traffic Growth

Due to factors such as population growth and economic prosperity, the volume of traffic on roadways increases each year. Highways with different functional classifications have different traffic growth rates. Johnston et al. (1994) estimated that the traffic growth on interstate highways is 4.06% and on other highways is 1.94%. Calvano (2003) stated that in Canada the traffic growth between 2006 and 2011 is estimated to be 1.1%. Based on these values, the current ADT estimate in the present user cost model is given Equation 5.6.

$$ADT_t = ADT \times (1 + 1.1\%)^{Year_t - Year_M} \tag{5.6}$$

where ADT_t = the ADT to be used in the analysis at year t, ADT = the measured average daily traffic, $Year_t$ = the current year, and $Year_M$ = the last year in which the ADT is measured. Although the annual traffic growth is constant through the analysis; the user of the system has the flexibility to change this value.

5.3.2 Annual Accident Rate

The annual accident rate is predicted using the Pontis accident rate model developed by Thompson et al. (1999b) as given in Equation 5.4. Having calculated the accident rate, the user cost due to accident risk will be the accident rate multiplied by the cost per accident. The cost per accident was assumed to be $68,404.39 (Soares, 1999). The user has the flexibility to modify the value of the cost per accident any time through the analysis process.

5.3.3 Vehicle Operating Costs

The vehicle operating costs (VOC) are incurred because of detours. Vehicles might be required to detour if a load capacity is posted for a bridge and they weigh more than the posted limit: such as trucks and similar vehicles that weigh more than 3 tons (27 kN). Another reason for vehicles to be required to detour is that their vertical clearance is greater than the allowed height posted on the bridge. The VOC is dependent on the length of the detour and the percentage of traffic required to detour. According to the national bridge inventory (NBI) detour is the bypass detour distance that a vehicle must travel for a closed and detour–posted bridge (FHWA, 1995).

Based on the roadway's functional classification, the percentage of trucks that detour due to restricted load capacity is calculated from Table 5.3, and the percentage of trucks that detour because of a vertical clearance limitation is calculated from Table 5.5 (Johnston et al., 1994).

Given the percentage of detoured trucks, the vehicle operating cost (VOC) is then computed based on the average vehicle operating cost per detoured km. The unit vehicle operating cost per km used in the proposed model is $0.313/km (Soares, 1999). The user of the developed system, however, has the flexibility to change this value at any time throughout the analysis. The VOC for a bridge (i) is given by

$$VOC_i = ADT \times CV_c \times D_{ri} \times (P_W + P_C) \tag{5.7}$$

where ADT = current average daily traffic, CV_c = the operating cost per km of detour, D_{ri} = the difference between the length of detour and the length of the bridge in km, P_W = the percentage of trucks that must detour because of the weight limit (Table 5.3), and P_C = the percentage of trucks that must detour because of the restricted height clearance (Table 5.5).

5.3.4 User Delay Cost

The vehicles that must detour because of posted load or height limits are expected to require extra travel time because of the extra distance travelled. Therefore, the user delay cost (UD) is calculated based on the difference between the time taken to cross the bridge and the time taken to finish the detour which is a function of the bridge length, bridge speed, detour length, and detour speed. The UD for a bridge i is given by Equation 5.8.

$$UD_i = ADT \times CT_c \times \left(\frac{D_{ri}}{DS_{r_i}} - \frac{L_i}{DS} \right) \times (P_W + P_C) \tag{5.8}$$

where D_{ri} = the detour length, DS_{ri} = speed on the detour route, which is estimated to be 80 percent of the bridge speed; L_i = the length of bridge i; DS = the bridge speed, P_W = the percentage of trucks that must detour because of weight limit (Table 5.3); P_C = the percentage of trucks that must detour because of height clearance (Table 5.5); and CT_c = the travel time cost per hour of detour. The travel time cost per hour of detour is estimated in the literature as hourly truck travel time, which ranges from $17.34 to $34.79. The value used in the present model is $19.34 which is the Pontis default value. However, the user of the developed model can change this value any time during the analysis.

5.3.5 ME-BMS User Cost Model Implementation and Example Application

The developed user cost model for the ME-BMS was implemented on a commercial spreadsheet program (Microsoft Excel). The developed application includes different modules for calculating user costs before and after repair decisions. The data for a network of bridges are shown in Figure 5.4. For each bridge in the network, the input is the year built, the narrowness (number of lanes/roadway width), the highway type, the percentage of heavy trucks in the traffic (assumed to be 5% if not recorded in the bridge inventory), the last major repair year, the average daily traffic (ADT), the bridge length, the detour length, and the vertical clearance.

Once the bridge data are input, the user can experiment with the effect of the repair decisions at the project and network levels. Part (a) of Figure 5.5 shows the repair options decided on at the project level for a sample 10-bridge network, and part (b) shows the year of repair for the network level. For example, bridge 1 is selected to be repaired in year 1 of the planning horizon with a repair option of type 2 for the overlay and the bearing, a repair option of type 1 for the substructure and finishing, and the do-nothing option for the rest of the elements.

No.	BR. Name	year built	Narrowness	Highway Type	% heavy Veh.	Last Major Repair	Measured ADT	Length (km)	Detour length (km)	Clearance (feet)
1	Bridge1	1985	0.267	Otherstate	5%	1994	50,000	0.050	2.00	10.00
2	Bridge2	1998	0.133	Interstate	5%	0	20,000	0.080	2.50	14.00
3	Bridge3	1977	0.143	Otherstate	10%	0	5,000	0.040	1.40	13.00
4	Bridge4	1991	0.160	Interstate	12%	0	30,000	0.060	3.00	13.00
5	Bridge5	1980	0.111	Interstate	10%	0	6,000	0.060	1.20	14.00
6	Bridge6	1989	0.333	Otherstate	10%	0	30,000	0.040	2.00	13.50
7	Bridge7	1975	0.067	Interstate	2%	1985	5,000	0.060	1.25	10.00
8	Bridge8	1987	0.286	Interstate	5%	0	50,000	0.055	2.20	14.00
9	Bridge9	1980	0.091	Interstate	6%	1985	10,000	0.035	3.00	14.00
10	Bridge10	2001	0.400	Interstate	10%	0	90,000	0.065	4.00	14.00

Figure 5.4: Input Data for the User Cost Model

		Element Repair Decision 2006							NETWORK DECISIONS				
No.	BR. Name	Slab	Overlay	joint	Bearing	Supper	Sub	Finish	2006	2007	2008	2009	2010
1	Bridge1	0	2	0	2	0	1	1	1	0	0	0	0
2	Bridge2	0	0	0	0	0	0	0	0	1	0	0	0
3	Bridge3	0	0	0	0	0	0	0	0	0	1	0	0
4	Bridge4	0	0	0	0	0	0	0	0	0	0	1	0
5	Bridge5	0	0	0	0	0	0	0	0	1	0	0	0
6	Bridge6	0	0	0	0	0	0	0	0	0	1	0	0
7	Bridge7	0	0	0	0	0	0	0	0	0	0	1	0
8	Bridge8	0	0	0	0	0	0	0	0	1	0	0	0
9	Bridge9	0	0	0	0	0	0	0	0	0	1	0	0
10	Bridge10	0	0	0	0	0	0	0	0	0	0	0	1

(a) (b)

Figure 5.5: Network-Level and Project-Level Decisions

The user costs for the bridge network are first calculated without any repair decisions as shown in Figure 5.6. For example, for bridge 2, the user costs in year 1 are estimated to be $510,338, and the user costs continue to escalate to $668,295 by the end of the planning horizon. An example of the user cost calculation is shown for 2006. The shaded columns (a), (b), and (c) show the accident costs, vehicle operating costs, and delay costs, respectively using Equations 5.6, 5.7, and 5.8.

		2006		(a)					(b)	(c)		2007	2008	2009	2010
No.	BR. Name	ADT	Accident Rate	Accident Cost	Load posting (tons)	% detoured veh. (weight limit)	% detoured veh. (Height limit)	Detoured Veh.	VOC cost	Delay Cost	Total User Cost	Total User Cost	Total User Cost	Total User Cost	Total User Cost
1	Bridge1	66,000	6.64	$249,669	31.8	1.24%	6.23%	4,930	$877,267	$1,413,863	**$2,540,799**	$2,586,622	$2,633,361	$2,681,035	$2,729,662
2	Bridge2	23,200	2.33	$87,532	33.2	3.15%	0.01%	733	$161,891	$260,915	**$510,338**	$580,208	$590,062	$600,112	$668,295
3	Bridge3	6,600	0.43	$16,017	25.85	1.75%	0.90%	175	$21,705	$34,981	**$72,703**	$73,837	$74,993	$78,670	$79,923
4	Bridge4	39,000	3.50	$131,519	36	0.00%	2.23%	870	$233,319	$376,032	**$740,870**	$753,057	$765,488	$778,167	$791,100
5	Bridge5	7,320	1.62	$60,774	36	0.00%	0.01%	1	$76	$123	**$60,973**	$60,977	$60,981	$60,985	$60,990
6	Bridge6	40,200	5.03	$189,118	30.05	1.32%	0.01%	535	$95,624	$154,114	**$438,856**	$461,088	$466,528	$488,017	$493,995
7	Bridge7	5,600	1.12	$42,098	28.65	5.09%	15.30%	1,142	$123,990	$199,830	**$365,918**	$372,394	$379,000	$385,738	$392,611
8	Bridge8	69,000	8.90	$334,816	36	0.00%	0.01%	7	$1,351	$2,177	**$338,343**	$338,414	$338,486	$338,559	$338,634
9	Bridge9	13,200	1.89	$70,882	36	0.00%	0.01%	1	$357	$576	**$71,814**	$71,833	$71,852	$71,871	$71,891
10	Bridge10	99,000	16.73	$628,922	36	0.00%	0.01%	10	$3,555	$5,729	**$638,206**	$638,391	$638,581	$638,774	$638,971

Figure 5.6: User Cost Before-Repair Decisions

Based on the element repair decisions and the selected year of repair shown in Figure 5.5, the user costs are automatically calculated and presented, as shown in Figure 5.7. A comparison of Figure 5.6 and Figure 5.7 reveals a reduction in the user costs by $380,221 for bridge 1 in 2006 because of repair decisions that include repairing the substructure, thus raising the condition rating, which results in a reduction in the percentage of vehicles that must detour because of a load limit. Similarly, if bridge 2 is repaired in year 2 of the planning horizon, the benefits gained in user costs can be noted for year 2. Figure 5.8 shows, for each bridge, the benefits gained from implementing repair decisions in each year of the planning horizon. The total benefits gained with respect to user costs for the overall network are estimated to be $4,986,208 (Figure 5.8).

		2006										2007	2008	2009	2010
No.	BR. Name	ADT	Accident Rate	Accident Cost	Load posting (tons)	% detoured veh. (weight limit)	% detoured veh. (Height limit)	Detoured Veh.	VOC cost	Delay Cost	Total User Cost	Total User Cost	Total User Cost	Total User Cost	Total User Cost
1	Bridge1	66,000	6.64	$249,669	36	0.00%	6.23%	4,112	$731,643	$1,179,165	**$2,160,478**	$2,198,694	$2,237,674	$2,277,434	$2,317,990
2	Bridge2	23,200	2.33	$87,532	33.2	3.15%	0.01%	733	$161,891	$260,915	**$510,338**	$88,897	$88,924	$88,952	$88,980
3	Bridge3	6,600	0.43	$16,017	25.85	1.75%	0.90%	175	$21,705	$34,981	**$72,703**	$73,837	$74,993	$78,670	$79,923
4	Bridge4	39,000	3.50	$131,519	36	0.00%	2.23%	870	$233,319	$376,032	**$740,870**	$753,057	$765,488	$778,167	$791,100
5	Bridge5	7,320	1.62	$60,774	36	0.00%	0.01%	1	$76	$123	**$60,973**	$48,760	$48,764	$48,768	$48,772
6	Bridge6	40,200	5.03	$189,118	30.05	1.32%	0.01%	535	$95,624	$154,114	**$438,856**	$461,088	$191,072	$191,111	$191,151
7	Bridge7	5,600	1.12	$42,098	28.65	5.09%	15.30%	1,142	$123,990	$199,830	**$365,918**	$372,394	$379,000	$385,738	$392,611
8	Bridge8	69,000	8.90	$334,816	36	0.00%	0.01%	7	$1,351	$2,177	**$338,343**	$338,414	$338,486	$338,559	$338,634
9	Bridge9	13,200	1.89	$70,882	36	0.00%	0.01%	1	$357	$576	**$71,814**	$71,833	$71,852	$71,871	$71,891
10	Bridge10	99,000	16.73	$628,922	36	0.00%	0.01%	10	$3,555	$5,729	**$638,206**	$638,391	$638,581	$638,774	$638,971

Figure 5.7: User Costs after Repair Decisions

		Reduciton in User Cost = $4,986,208				
No.	BR. Name	2006	2007	2008	2009	2010
1	Bridge1	$380,321	$387,928	$395,686	$403,600	$411,672
2	Bridge2	$0	$491,311	$501,137	$511,160	$579,315
3	Bridge3	$0	$0	$0	$0	$0
4	Bridge4	$0	$0	$0	$0	$0
5	Bridge5	$0	$12,217	$12,217	$12,217	$12,217
6	Bridge6	$0	$0	$275,456	$296,906	$302,845
7	Bridge7	$0	$0	$0	$0	$0
8	Bridge8	$0	$0	$0	$0	$0
9	Bridge9	$0	$0	$0	$0	$0
10	Bridge10	$0	$0	$0	$0	$0

Figure 5.8: Reduction in User Costs due to Repair Decisions

5.4 Incorporating User Costs into the ME-BMS Formulation

The incorporation of user costs into the ME-BMS involves adjustments at the project-level and network-level formulations. The objective of the project-level decision support system in the ME-BMS, as presented in Chapter 4, is to maximize the ratio of the benefits gained in the bridge condition rating to the associated repair cost. Using this formulation -without considering user costs- consistently favours the exclusion of elements with relatively high repair costs, e.g. deck (i.e., B/C becomes low). This is despite the fact that the deck has a significant impact on reducing user costs particularly due to accidents. Therefore, modifications are needed to be introduced at the project-level formulation in order to include user costs in the optimization process. Similarly, the ME-BMS network-level formulation needs to be modified to include user costs, as discussed later.

5.4.1 User Costs in Project-Level Decisions

As shown in Equation 4.4, the formulation of the objective function in the project-level of the ME-BMS is modified to include another term for the ratio of the benefits gained in user costs to the bridge repair cost, as follows:

$$PL2 = Max\left(\frac{(BCR_{Ri} - BCR_{Ci})\times 10^5 + B_{UCi}}{C_i}\right) \tag{5.9}$$

where BCR_{Ri} = the bridge condition rating after repair; BCR_{Ci} = the current bridge condition rating; B_{UCi} = the benefits gained with respect to user costs, which is the difference between the before-repair and after-repair user costs; and C_i = the bridge repair cost. As an example, a 50-bridge network (from Chapter 4) was selected in order to compare project-level decisions using the objective function in Equation 4.4 (PL1) and that in Equation 5.9 (PL2). Table 5.7 presents a summary of the results obtained from applying PL1 and PL2 based on the benefits gained in the bridge condition rating (BCR), the benefits gained in user costs (B_{UC}), and their respective ratios to the repair cost. The results shown in the Table clearly demonstrate the significant enhancement in the benefits gained in user costs when PL2 is used. This effect is attributed to the inclusion of the user cost benefits in the formulation. Although the benefits gained in the condition rating for PL1 are higher than those in PL2, the ratio of total benefits gained to the repair costs is higher if PL2 is used.

Table 5.7: Comparison of the Project-Level Objective Function with User Costs

Project-level objective function	Benefits in BCR (B_{BCR})	Benefits in user cost (B_{UC})	Repair Costs (C)	B_{BCR}/C	B_{UC}/C	Total benefits/repair costs (B/C)
PL1 *(without user cost)*	9.42	$1,049,650	$835,550	1.13	1.26	2.39
PL2 *(with user cost)*	9.20	$2,725,058	$842,300	1.09	3.24	4.35

5.4.2 User Costs in Network-Level Decisions

The objective function used in the network-level optimization of the ME-BMS was to maximize the overall network condition. However, with the consideration of user costs, the network-level objective function is modified as follows:

$$NL2 = Max\left(NCR + B_{UC} \times 10^{-5}\right) \quad (5.10)$$

where NCR = the network condition rating, and B_{UC} = the benefits gained in the user costs for the bridge network.

The same example used for experimenting at the project level is implemented in order to compare the objective function that considers user costs (NL2) and the objective function that maximizes only the network condition (NL1). The criteria used in the comparison are the ratio of the benefits gained in both the network condition and the user costs to the total repair costs. Table 5.8 shows the summary of the results for NL1 and NL2 for the average values for 10 trial runs for each objective function.

Table 5.8: Comparison of the Network-Level Objective Function with User Cost

Network-level objective function	Average NCR	Benefits in NCR (B_{NCR})	Benefit in user costs (B_{UC})	Repair Costs (C_R)	B_{NCR}/C_R	B_{UC}/C_R	Total benefits/repair costs (B/C)
NL1 *(without user cost)*	6.3941	1598.51	$12,082,364	$977,438	11.955	12.359	24.314
NL2 *(with user cost)*	6.4048	1601.19	$18,161,827	$974,686	12.265	18.634	30.899

The results shown in Table 5.8 clearly demonstrate that the inclusion of user costs in the network-level objective function (NL2) enhances the user cost benefits. The benefits gained in user costs (B_{UC}) using NL2 are higher than those with NL1, and the benefits gained in the ratio of the user costs to the repair cost (B_{UC}/C_R) is greater for NL2 than for NL1. Similarly, in terms of the benefits gained in the network condition rating (B_{NCR}), the B_{NCR}/C_R is higher when NL2 is used than when NL1 is used. More experiments were carried out for a network of 100 bridges, and similar results were observed. Thus, the best objective function to implement at the network level is to maximize both the network-level condition rating (NCR) and the benefits gained in user costs (B_{UC}).

5.5 Work Zone User-Costs – Background

Although work zones provide the means of performing repair and rehabilitation projects without fully closing the bridge, they have a significant impact including higher user costs, increased accident rates, and user delays (Martinlli and Xu, 1996). The latter impact is considered the most significant problem associated with work zones. In some cases, bridge repair operations may fail due to complete congestion at the bridge location, particularly during peak periods.

The problem with work zones usually arises from the conflict of interest among highway agencies, roadway users, and contractors (Najafi and Soares, 2001). While the objective of the contractor and the agency is to minimize costs, the users objective is to minimize delays. Therefore, it is important to investigate the impact of different work zone strategies and to select the optimal one.

Several efforts have been directed at quantifying the impact of work zones on user costs. Most of these efforts were related directly to pavement maintenance operations; few were related to bridge maintenance/rehabilitation operations. Martinlli and Xu (1996) stated that the factors that most affect user costs at work zones are traffic delay and safety, project costs, constructability, and the environmental impact. The two sources of traffic delay at work zones are speed reduction (moving delay), and congestion delay (stopping delay). Speed-reduction delays result from vehicles moving more slowly than the normal freeway speed. The delays increase with the increase in ADT and percentage of trucks in the traffic. Martinlli and Xu (1996) presented different tables that show the average traffic speed due to work zones for a range of traffic volumes and percentages of trucks under different types of terrain. On average, the work zone speed is estimated at 50 km/hr compared to a free-flow speed of 80 km/hr (Chen and Schonfeld, 2003). Congestion occurs when the hourly traffic volume is greater than the capacity of a work zone for a significant period of time. When the demand exceeds the capacity in one time period, a queue forms, which if not dissipated is transferred to the next time period and eventually grows over time. The queue decreases only during time periods when the demand is less than the capacity. Najafi and Soares (2001) also stated that work zone user-costs are usually evaluated with respect to the travel time delay costs (TTDC), the additional vehicle operating costs (VOC) to cross the work zone, and the work zone related-accident-costs (WZAC). The following equation is used to determine work zone user costs (Najafi and Soares 2001):

$$Work\ \ zone\ user\ cos\,t = TTDC + VOC + WZAC \tag{5.11}$$

The travel time delay cost (TTDC) results from the increase in travel time through the work zone due to speed reductions, congestion delays, or increased distance as a result of a detour (USDOT/FHWA, 1989). The Federal Highway Administration (USDOT/FHWA, 1989) assumed that the value of one hour of travel time per vehicle is $8.00 regardless of vehicle type; however, He et al. (1997) recommended the use of $25/hr, and Chen and Schonfeld (2003) estimated that the value of user time is $12/veh.hr. Martinlli and Xu (1996) stated that for an average daily traffic (ADT) value of less than 10,000, the delay cost is not significant. However, when the ADT is greater than 40,000, the delay cost is very high. Al-Asssar et al. (2000) presented look-up tables for estimating user delay costs (UDC) per day for different highway configurations and different volumes of traffic. Values for a sample of 4-lane undivided highway are shown in Table 5.9.

Table 5.9: User Delay Costs for a 4-lane Undivided Highway (Al-Assar et al., 2000)

ADT	UDC ($/day)
6,000	135
7,000	158
8,000	182
9,0000	203
.	.
.	.
40,000	141,698

A number of computer programs have been developed for calculating user costs associated with work zones. Among these programs are USER; QUEWZ (queue and user cost evaluation at work zone), which estimates time and vehicle operation costs associated with lane closures (Krammes and Ullman, 1994), and MicroBENCOST (MTO, 1997). As well, HERS (highway economic requirements system) estimates the benefits resulting from improvements in terms of travel time, operating costs, and safety (USDOT/FHWA, 1996). The Ontario pavement analysis of costs (OPAC) OPAC-2000 has been developed for estimating work zone user-costs for flexible and rigid pavements (He et al., 1997). It should be noted that none of these software has been developed for bridge work zones, and is therefore difficult to use in a BMS system. In addition these programs are used only for evaluating work-zone configurations, and not for providing the optimum strategy to minimize user costs at work zones. The presented work zone user-cost model is integrated with the ME-BMS. The advantage of the presented model stems from its ability to optimize the work-zone strategies in order to minimize user costs.

5.6 ME-BMS Work Zone User-Cost Model

The work zone user-cost model developed in this chapter has been integrated with the multi-element bridge management system (ME-BMS) presented in Chapter 4. The user can activate the work zone model once the ME-BMS has arrived at optimal repair decisions for both the project and network levels. Calculating the user costs at a work zone requires the analysis of three main components: the traffic control plan, the work zone construction schedule (work zone window), and the traffic flow analysis (Elbehairy et al., 2006a). Details about calculating user costs at work zones are described in the following subsections.

5.6.1 Traffic Control Plan

The basic concept of a traffic control plan is to permit the contractor to work on a bridge while maintaining a safe and uniform flow of traffic. Various types of traffic control plans (TCPs) are available for highway maintenance and are chosen based on the number of highway lanes and the type of repair required. He et al. (1997) suggested the traffic control plans shown in Figure 5.9 for a variety of highway configurations. The task of adapting the traffic control plans in Figure 5.9 to a bridge environment is summarized in Table 5.10. The costs associated with these TCPs are discussed in Subsection 5.6.3. It should be noted that the TCP is not a variable in the present model; rather, each bridge has a suitable TCP, depending on its configuration as determined from Table 5.10.

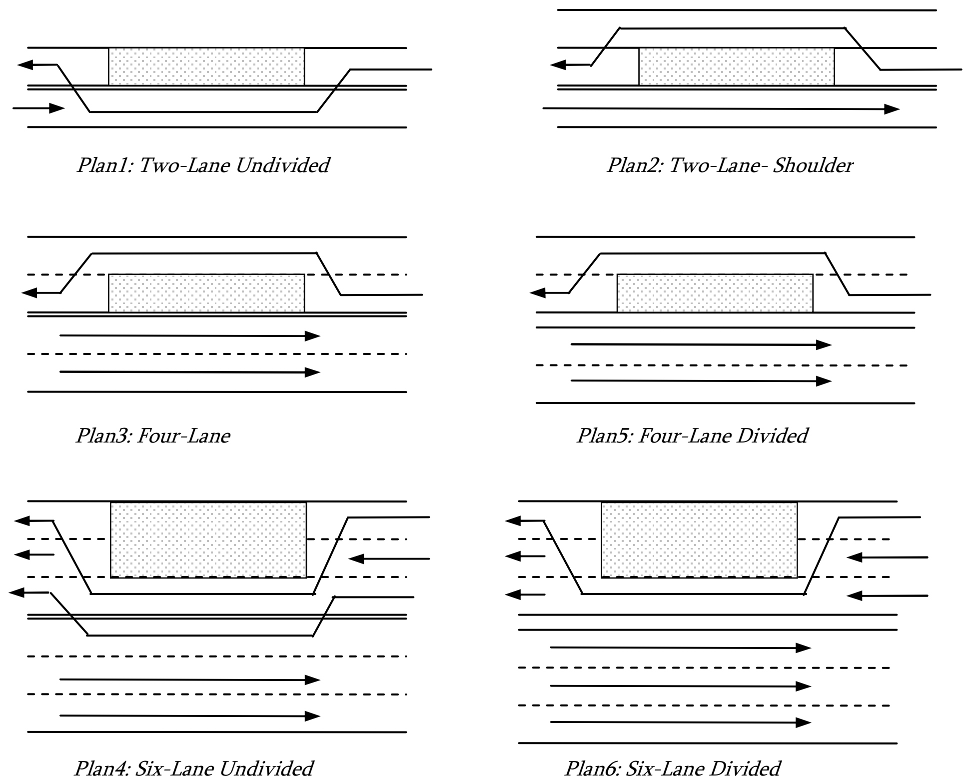


Figure 5.9: Traffic Control Plans for Different Highway Configurations (He et al., 1997)

Table 5.10: Suggested Traffic Control Plans for Bridge Configurations (Elbehairy et al., 2006a)

Bridge description	TCP	Notes
2-lane	Plan 1	Only one lane open for traffic in two directions
2-lane- wide shoulder	Plan 2	The shoulder used as a lane in the work zone area
4-lane-divided	Plan 3	One lane closed in one direction
4-lane-undivided	Plan 5	One lane closed in one direction
6-lane-divided	Plan 4	Two lanes closed in one direction
6-lane-undivided	Plan 6	Two lanes closed in one direction and one lane in the other direction
8-lane-divided	Plan 8	Two lanes closed in each direction
Deck full replacement	Plan 9	Full bridge closure and complete detour

5.6.2 Work Zone Construction Window

Highway repair and rehabilitation window (time of day to do the work) traditionally occur at nighttime because daytime closures cause unacceptable delays to weekday peak travel. However, the disadvantage of having nighttime closures is that they may lead to lower work quality. Nighttime closures may also result in longer closure time, higher construction and traffic control plan costs, and greater traffic delays for users (Lee and Ibbs, 2005). Other construction window strategies for accelerating the construction have been proposed by Lee and Ibbs (2005): continuous (round-the-clock) operations either during a 55-hour weekend closure or during a 72-hour weekday closures. Based on this information, four construction window strategies are proposed for the current work zone user-cost model: nighttime shifts, weekend closure, weekday closure, and full closure. Alternatively, combinations of the four construction windows are used as a variable for each bridge, with associated user costs as explained in the Subsection 5.6.3.

5.6.3 Traffic Flow Analysis and Cost Calculation

Given a TCP and a selected work zone window, a detailed analysis of the user costs is carried out through a traffic flow analysis. The developed work zone user-cost model considers the vehicle operating costs (VOC), and the user delay costs. These costs are discussed in the following steps of a detailed traffic flow analysis:

Step 1: Calculate hourly traffic volume

User costs are directly dependent on the volume and operating characteristics of the traffic on the bridge. The important characteristics of the traffic in a work zone are the average daily traffic (ADT) and the hourly flow distribution related to the daily ADT. Martinlli and Xu (1996) mentioned that an effective procedure for quantifying speed reduction delay and the congestion delay is to convert the ADT into an hourly volume, estimate the delay on an hourly basis, and cumulate the hourly delay into a daily delay. Data related to the ADT and the hourly traffic distribution are often available from the municipalities. As an illustration, Table 5.11 shows an example of hourly traffic distribution (USDOT/FHWA, 1998) and provides a distribution factor

(% ADT) for each hour of the day for different highway types. Based on this distribution factor, the hourly traffic can be calculated as:

$$Hourly\ Traffic = ADT \times Distribution\ Factor \tag{5.12}$$

In the work zone model, Equation 5.12 and the distribution factors shown in Table 5.11 are used to calculate the hourly traffic at different bridge locations as a function of the highway type linked to the bridge and the ADT associated with that bridge.

Table 5.11: Example of Hourly Traffic Distribution (USDOT/FHWA, 1998)

Hour		Distribution Factor (% ADT)		Hour		Distribution Factor (% ADT)	
From	*To*	*Interstate*	*Other*	*From*	*To*	*Interstate*	*Other*
0	1	1.7%	0.9%	12	13	5.7%	5.7%
1	2	1.4%	0.5%	13	14	5.9%	5.9%
2	3	1.3%	0.5%	14	15	6.3%	6.6%
3	4	1.3%	0.5%	15	16	6.9%	7.7%
4	5	1.4%	0.9%	16	17	7.2%	8.0%
5	6	2.1%	2.3%	17	18	6.6%	7.4%
6	7	3.7%	4.9%	18	19	5.3%	5.5%
7	8	4.9%	6.2%	19	20	4.4%	4.3%
8	9	4.9%	5.5%	20	21	3.8%	3.6%
9	10	5.2%	5.3%	21	22	3.4%	3.0%
10	11	5.5%	5.4%	22	23	2.9%	2.3%
11	12	5.8%	5.6%	23	24	2.4%	1.5%

Step 2: Calculate free flow and work zone capacity

Once the hourly traffic volume is calculated at the bridge location, the user delay at the bridge depends on the free-flow capacity of the highway upstream of the work zone as well as the capacity of the work zone to dissipate the traffic. The maximum free-flow capacity of a highway can be determined from the highway capacity manual (HCM, 1994), which states that for a two-lane highway, the free-flow capacity is estimated to be 2,200 passenger cars per hour per lane (pcphpl) and 2,300 pcphpl for three or more lanes. The dissipation rate of a work zone for a two-lane highway is estimated to be 1,818 pcphpl (USDOT/FHWA, 1998).

Step 3: Calculate user cost at work zone

Once the free-flow and work zone capacities have been determined, a detailed analysis on an hourly basis is conducted using an Excel spreadsheet. Figure 5.10 shows an example for a bridge with 4 lanes for which the TCP is to have only one lane opened for traffic, and the work zone strategy is nighttime shifts. The shaded areas in column (c) indicate the work zone construction window timing which starts at 7:00PM and lasts until 5:00AM the next morning. Column (d) shows the number of queued vehicles. The user costs at the work zone depend on whether the traffic experiences free flow (i.e., no full stopping at the work zone), or whether the traffic experiences forced flow. The user costs for each case are calculated separately, as below.

Traffic Control Plan = 5
Work Zone Window = NightTime Shift

a		b	c	d	e	f	g	h	i	j	k	l	m	n
Hour		Hourly Volume	Capacity	Queued Vehicles	Traverse WZ	Slow Down	Traverse queue	Stop	No. of Lanes	Q.Vehicle/ lane	Queue length (m)	Queue Speed	Queue delay Time	Idling
0	1	1,020	1,818	0	1,020	1,020	0	0	1	0	0	0	0:00:00	0.00
1	2	840	1,818	0	840	840	0	0	1	0	0	0	0:00:00	0.00
2	3	780	1,818	0	780	780	0	0	1	0	0	0	0:00:00	0.00
3	4	780	1,818	0	780	780	0	0	1	0	0	0	0:00:00	0.00
4	5	840	1,818	0	840	840	0	0	1	0	0	0	0:00:00	0.00
5	6	1,260	1,818	0	1,260	1,260	0	0	1	0	0	0	0:00:00	0.00
6	7	2,220	4,150	0	0	0	0	0	2	0	0	0	0:00:00	0.00
7	8	2,940	4,150	0	0	0	0	0	2	0	0	0	0:00:00	0.00
8	9	2,940	4,150	0	0	0	0	0	2	0	0	0	0:00:00	0.00
9	10	3,120	4,150	0	0	0	0	0	2	0	0	0	0:00:00	0.00
10	11	3,300	4,150	0	0	0	0	0	2	0	0	0	0:00:00	0.00
11	12	3,480	4,150	0	0	0	0	0	2	0	0	0	0:00:00	0.00
12	13	3,420	4,150	0	0	0	0	0	2	0	0	0	0:00:00	0.00
13	14	3,540	4,150	0	0	0	0	0	2	0	0	0	0:00:00	0.00
14	15	3,780	4,150	0	0	0	0	0	2	0	0	0	0:00:00	0.00
15	16	4,140	4,150	0	0	0	0	0	2	0	0	0	0:00:00	0.00
16	17	4,320	4,150	170	0	0	4,150	4,320	2	85	850	40	0:18:39	53.74
17	18	3,960	3,636	494	0	0	3,636	3,960	2	247	2,470	38	0:49:27	124.86
18	19	3,180	3,636	38	0	0	3,180	3,180	2	19	190	41	0:03:13	7.09
19	20	2,640	1,818	860	1,818	0	1,818	2,640	1	860	8,600	28	4:41:10	354.97
20	21	2,280	1,818	1,322	1,818	0	1,818	2,280	1	1,322	13,220	33	5:40:49	430.28
21	22	2,040	1,818	1,544	1,818	0	1,818	2,040	1	1,544	15,440	37	5:26:54	412.70
22	23	1,740	1,818	1,466	1,740	1,740	1,740	1,740	1	1,466	14,660	41	4:07:53	299.53
23	24	1,440	1,818	1,088	1,440	1,440	1,440	1,440	1	1,088	10,880	41	3:03:58	183.97

VOC slow down	$481	Free flow user cost
Delay Cost Slow down	$405	
Work zone reduced speed delay	$0	
Stopping VOC	$2,070	Forced flow user cost
Stopping delay Cost	$1,558	
Idling VOC	$1,310	
Queue reduced speed delay cost	$20,764	
TOTAL	**$26,589**	**Total user cost/day for nighttime shift**

Traffic control planes

(1 lane is opened)

Figure 5.10: Work Zone User Cost Calculation Sheet

In the case of free flow (i.e., cars do not stop at the work zone), three types of user costs are considered: the speed change delay, the speed change vehicle operating cost (VOC), and the reduced speed (Lindly and Clark, 2004). First, the speed change delay is calculated based on the additional time required for the users to decelerate from the upstream speed to the work zone speed. Second, the speed change VOC is the vehicle operating cost associated with decelerating from the upstream speed to the work zone speed and then accelerating back to the upstream speed. Third, the reduced speed delay is calculated based on the additional time required for the users to traverse the work zone at the reduced speed.

In the case of forced flow (i.e., the hourly traffic demand exceeds the work zone capacity), a queue is formed upstream of the work zone. The forced flow imposes four types of user costs: the stopping delay, the stopping VOC, the queue delay, and the idling VOC. First, the stopping delay is calculated based on the additional time required for the users to come to a complete stop from the upstream speed, and the additional time required for them to accelerate back to the downstream speed after leaving the work zone. Second, the stopping VOC is the vehicle operating cost associated with stopping from the upstream speed and accelerating back to the downstream speed after leaving the work zone. Third, the queue delay is calculated based on the time required for the users to pass through the queue. Fourth, the idling VOC is the vehicle operating cost associated with the stop-and-go driving through the queue. More details about calculating user costs can be found in Lindly and Clark (2004), and USDOT/FHWA (1998).

For the example of the nighttime construction window shown in Figure 5.10, the sum of the seven user costs is shown at the bottom of the Figure and indicates the impact of the TCP and the work zone strategy on the user costs. Given that a bridge can have a different work zone strategy for each day of the construction window, the total user costs for a bridge i is the sum of the user costs for each work zone strategy multiplied by the number of days of applying that strategy, as follows:

$$UserCostWZ_i = \sum_{j=1}^{4} (DailyUserCost_j \times Days_j) \tag{5.13}$$

where j = the work zone strategy (1= nighttime shifts; 2 = weekend shifts; 3 = weekday closure; and 4 = full closure), and $Days_j$ = the number of days for applying work zone strategy j. Thus, the total user costs at the work zone ($Total\_WZUC$) for a network of bridges is given Equation 5.14.

$$Total\_WZUC = \sum_{i=1}^{N} UserCostWZ_i \tag{5.14}$$

where N= the number of bridges in the network.

5.6.4 Work Zone Duration

The duration of the maintenance/rehabilitation activity is a major factor in determining the number of days a work zone is required. The work zone duration is defined as the length of time a work activity occupies a specific location. The manual of uniform traffic control devices (MUTCD) (USDOT/FHWA, 1998) divides work duration into the following five categories:

1. Long-term: a work zone that occupies a location for several days or more
2. Intermediate-term: a work zone that occupies a location from a minimum of one day up to several days
3. Short-term: a work zone that occupies a location for no more than 12 hours
4. Short-duration: a work zone that occupies a location for up to one hour
5. Mobile-work: a work zone that moves continuously

Lindly and Clark (2004) collected data for highway reconstruction and rehabilitation projects with respect to the duration of the project, the length of the work zone, and lane closure scenarios. Table 5.12 presents the estimated average work zone duration for different reconstruction activities. The durations presented in Table 5.12 were used in the current model in order to estimate the duration required for performing repairs at the element level.

5.6.5 ME-BMS Work Zone Implementation

The network-level and project-level decisions shown in Figure 5.5 are the main input for the work zone user costs. The user costs at work zones will be estimated based on the repair options for the deck, the overlay, and the joints (since repairing these elements interrupts traffic flow). The proposed user cost model uses a GA-based optimization technique to determine the optimal work zone strategy for each bridge under repair. More details about GA can be found in

Appendix A. Implementing the GA technique for the problem at hand involves setting the solution representation (chromosome), deciding on the evaluation criteria, generating an initial population of solutions, and applying crossover/mutation to generate offspring chromosomes. The chromosome structure is made of a string of four elements. Each chromosome element represents the number of days for a specific work zone strategy, as shown in Figure 5.11.

Table 5.12: Work Zone Duration

Activity	Working days
Asphalt resurfacing	12.08 days/lane-km
Concrete pavement rehabilitation	8.82 days/lane-km
Concrete pavement removal and replacement	29.2 days/lane-km
Full-depth concrete pavement repair	12.8 days/lane-km
Patching and sealing joints	4.128 days/lane-km

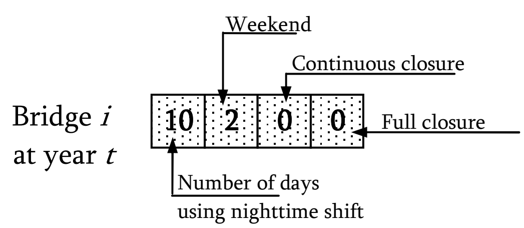


Figure 5.11: Work Zone Chromosome Structure

To evaluate a possible solution (chromosome), the objective function was constructed by summing the work zone user-costs for bridge i at year t as shown in Equation 5.15. The objective function, therefore, is to minimize the user costs for each bridge through the planning horizon.

$$Min\ (UserCostWZ_i) = \sum_{j=1}^{4} (DailyUserCost_j \times Days_j) \tag{5.15}$$

In addition to the objective function, the proposed user cost optimization model accounts for the following constraints:

- Total number of hours in the work zone ≥ the expected duration

- User predefined work zone strategy

The developed work zone user–cost model also considers practical logical relationships, such as if the repair strategy for the bridge is to go for extensive repair (repair options 4 or 5), then the recommended work zone construction window is to have full closure and a full traffic detour.

Once the objective function and constraints are defined, the GA procedure operates on a population of parent chromosomes. The population is generated randomly, through the assigning of random values for each gene from 0 to the required duration to finish the repair. Once the population is generated, the reproduction process takes place, either by crossover (marriage) or mutation (Goldberg, 1989). Many cycles (thousands) of offspring generations are conducted, and the population evolves with more-fit offspring chromosomes until an optimum solution is reached or the stopping criterion is met.

5.6.6 The Work Zone User-Cost Model Prototype and Example

The presented work zone user-cost optimization model and the GA procedure were implemented on a commercial spreadsheet program Microsoft Excel. Using the Macro Language of Microsoft Excel, the procedures were coded to form a complete work zone user cost optimization model. The data input for the work zone user-cost model are shown in Figure 5.12. Part (a) shows the input data for the fields representing the properties of the bridge network, and part (b) shows the network-level decision (selected year of repair) and project-level decision (element repair decisions for: the deck, overlay and joints in each bridge). It should be noted that although bridge 2 is selected to be repaired in 2007, the required duration for the repair is zero because the elements to be repaired at the project level do not include the deck, or overlay, or joints; therefore, there are no effects on traffic and do not require a work zone.

Once the bridge data are input, the user can start the optimization process. The evolutionary process continues until the desired number of offspring chromosomes is achieved. The work zone user cost model optimizes the work zone strategies for each bridge separately. The results of the current example are shown in Figure 5.13. Part (a) of Figure 5.13 shows the traffic control plan for each bridge and the selected work zone strategy. For example, traffic control plan number 5 is recommended for bridge 1 and requires 4 days of nighttime shifts in order to complete the repairs. Bridge 3 requires one weekend and uses TCP number 1. Part (b) in Figure 5.13 shows the associated work zone user costs according to the work zone strategy decided on in part (a). The total user costs estimated for the work zones for a network of bridges is the sum of the user costs for each bridge through the planning horizon, as given by Equation 5.14. For this example, the total work zone user costs are estimated to be $243,749.

No.	BR. Name	AADT	HighWay	Lanes	D/UD	%Trucks	Length (m)	Detour (Km)	WZ Length (m)	Speed (km/hr)	ADT - Year of Repair	Repair Year	Repair Decision			Required Duration (hr)
													Deck	Overlay	Joints	
1	Bridge1	50000	Otherstate	4	divided	0.05	0.05	2	0.1	80	66,000	2006	0	2	0	27.000
2	Bridge2	20000	Interstate	4	undivided	0.05	0.08	2.5	0.16	100	23,664	2007	0	0	0	0.000
3	Bridge3	5000	Otherstate	2	divided	0.1	0.04	1.4	0.08	80	6,867	2008	0	2	0	20.160
4	Bridge4	30000	Interstate	4	divided	0.12	0.06	3	0.12	100	41,387	2009	0	2	0	54.000
5	Bridge5	6000	Interstate	2	divided	0.1	0.06	1.2	0.12	100	7,466	2007	0	2	1	29.424
6	Bridge6	30000	Otherstate	6	divided	0.1	0.04	2	0.08	80	41,824	2008	0	0	0	0.000
7	Bridge7	5000	Interstate	2	undivided	0.02	0.06	1.25	0.12	100	5,943	2009	0	2	0	64.800
8	Bridge8	50000	Interstate	8	divided	0.05	0.055	2.2	0.11	100	70,380	2007	0	2	0	55.440
9	Bridge9	10000	Interstate	2	divided	0.06	0.035	3	0.07	100	13,733	2008	0	2	1	20.161
10	Bridge10	90000	Interstate	8	divided	0.1	0.065	4	0.13	100	107,161	2010	0	0	1	1.981

(a) (b)

Figure 5.12: Input Data for the Work Zone User-Cost Model

Total work zone user cost

		OPTIMIZATION					$243,749					
No.	BR. Name	Traffic Strategy	Construction Window				Total Cost ($)	Night Time Shifts	Week End Closure	Continuous closure (CC/SO)	Full closure (FC/CO)	Crash Cost
			Nighttime	Weekends	CC/SO	FC/CO						
1	Bridge1	5	4	0	0	0	$18,380	$2,287	$0	$0	$0	$13,030
2	Bridge2	3	0	0	0	0	$0	$0	$0	$0	$0	$0
3	Bridge3	1	0	1	0	0	$2,329	$0	$919	$0	$0	$1,022
4	Bridge4	5	0	0	0	0	$0	$0	$0	$0	$0	$0
5	Bridge5	1	0	1	0	0	$3,921	$0	$1,499	$0	$0	$1,769
6	Bridge6	6	4	0	0	0	$72,817	$52,708	$0	$0	$0	$7,973
7	Bridge7	1	0	1	0	0	$2,876	$0	$1,096	$0	$0	$1,301
8	Bridge8	8	0	0	0	0	$0	$0	$0	$0	$0	$0
9	Bridge9	1	0	1	0	0	$5,357	$0	$2,640	$0	$0	$1,824
10	Bridge10	8	1	0	0	0	$138,070	$81,861	$0	$0	$0	$33,197

(a) (b)

Figure 5.13: Work Zone User Cost Model Output

5.7 Summary and Conclusions

In this chapter, a procedural user cost model for a network of bridges was reviewed and a model for calculating user costs for bridges under service conditions was developed. The model considers:

- The effect on accident rate risk and costs due to a deteriorated bridge deck condition rating.
- The costs of vehicles being required to detour due to load capacity or vertical clearance postings.

The developed model assists decision makers in investigating the impact of repair actions on user costs. The user cost model was incorporated into the project-level and network-level formulations of the ME-BMS. A comparison was carried out to examine the added benefits of incorporating user costs into the optimization formulation. The results of the comparison clearly reveal that having the user costs in the objective functions enhances the decisions made at both the project and network levels. The user cost model was implemented on a spreadsheet program because of its familiar interface and ease of use, which provide the user with the flexibility to change the decision at network level or the project level and investigate the effect of these changes on the user costs.

A work zone user-cost model was developed and integrated with the ME-BMS. The purpose of the work zone model is to optimize work zone strategies in order to minimize the user costs incurred during repairs. The developed model considers different work zone strategies, such as the nighttime shifts, weekend closure, continuous closure, and full closure. The developed model incorporates genetic algorithms in order to arrive at the optimal work zone strategy. The developed model is flexible, and the user can change any work zone strategy in order to observe the impact of the change on user costs. An example application was carried out in order to demonstrate the capabilities of the model.

Chapter 6

Bridge Network Case Study

6.1 Introduction

This chapter covers the practical application of the developed multi-element bridge management system (ME-BMS) presented in Chapter 4, and modified in Chapter 5 to incorporate user costs in the decision making to a real-life case study involving a network of bridges in a transportation agency. The case study data are described, and the network-level and project-level decisions using the proposed ME-BMS are then presented. The decisions from the ME-BMS and those predicted to be made by the department of transportation (DOT) are compared with the benefits gained with respect to both the network condition rating and user costs, and the total repair costs. The application of the work zone model developed in Chapter 5 to the case study is presented. Finally, the feedback and the comments from the DOT engineers is summarized.

6.2 Case Study Description

The data for the case study selected for testing the proposed multi-element bridge management system (ME-BMS) were collected from the department of transportation abbreviated as (DOT). The DOT has adopted the Ontario Bridge Management System (OBMS); however, the OBMS is not fully utilized and is used only for data storage, for tracking of the performance of a bridge network, and for inspection reports. The DOT owns and operates 173 bridges; data for 47 bridges were provided by the DOT as a case study for the ME-BMS developed in this study. Some of the data were also collected through interviews with engineers from the DOT. The data included general information about the bridge network, such as the bridge ID, the road name, the bridge name, the annual average daily traffic (AADT), the percentage of trucks in the traffic, the bridge length (m), the bridge width (m), the last year of repair, and the last value of repair cost (Figure 6.1). In addition, the data included details about bridge element condition ratings, element weights, and repair costs. The raw data and their specific details are discussed in the following subsections.

Struct_ID	Bridge Name	Construction Year	AADT	% Heavy Veh.	ADT Year	Detour (Km)	Width (m)	Length (m)	Last Repairt	Value ($1000s)
0102	Hidden for Confidentiality	1960	5,111	10	2005	0.168	17.5	8.4	1980	265
0103		1998	2,095	3	2005	1.060	12.2	53.0	1998	1165
0104		1974	3,168	5	2005	0.104	28.5	5.2	1974	266
0401		1969	16,082	1	2005	0.292	20.1	14.6	1994	527
0402		1958	5,012	5	2005	0.196	12.6	9.8	1994	221
0404		1936	7,015	2	2005	0.850	11.4	42.5	2006	873
1603		1960	2,348	22	2005	0.136	12.3	6.8	1996	151
1702		1963	6,243	10	2005	2.470	11.5	123.5	2001	2556
1703		1967	2,265	8	2005	0.754	10.9	37.7	1994	740
1704		1967	2,265	8	2005	1.298	10.9	64.9	1994	1273
1705		1963	1,329	4	2005	0.414	11.6	20.7	1963	432
1706		1961	1,646	10	2005	0.190	11.7	9.5	1961	200
1902		1959	2,040	5	2005	0.180	12.5	9.0	2003	787
2101		1968	6,388	5	2005	0.414	13.1	20.7	2003	2260
2102		1973	3,060	5	2005	0.098	12.5	4.9	2003	122
2201		1960	9,231	5	2005	2.144	11.7	107.2	1959	203
2301		1992	4,286	5	2005	0.558	12.4	27.9	1997	488
2302		1974	3,596	8	2005	0.838	10.1	41.9	1973	110
7002		1959	3,826	6	2005	0.112	11.5	5.6	1982	2257

Figure 6.1: General Information for the Bridge Network Case Study

6.2.1 Condition Data

The condition assessment used by the DOT for bridge elements specifies the percentages of the elements that are in excellent (E), good (G), fair (F), or poor (P) condition states. Figure 6.2 shows a sample of the condition data for the elements. For example, for bridge 0504, 79% of the asphalt (surface) is in good condition, and 21% is in fair condition. Similarly, for the same bridge, 100% of both the deck and the joints are in good condition.

*

Bridge_ID	Joints	E	G	F	P	Seats	E	G	F	P	Surface	E	G	F	P	Deck		E	G	F	P
0102	---					---					Asphalt		100			Thick Slab	Cast-in-place concrete		99	1	
0103	Seals/Sealants		100			---					Asphalt		100			Thin Slab	Cast-in-place concrete		100		
0104	---					---					Asphalt		100			Thin Slab	Cast-in-place concrete		100		
0401	---					---					Asphalt		100			Thick Slab	Cast-in-place concrete		100		
0402	---					---					Asphalt		100			Thick Slab	Cast-in-place concrete		90	10	
0404	Seals/Sealants			100		not acc.					Asphalt			65	35	Thin Slab	Corrugated Steel			60	40
0501	Seals/Sealants		50	50		---					Asphalt		95		5	Thick Slab	Cast-in-place concrete		95	5	
0502	Seals/Sealants		100			---					Asphalt			95	5	Thick Slab	Cast-in-place concrete		100		
0504	Seals/Sealants		100			not acc.					Asphalt		79	21		Thin Slab	Cast-in-place concrete		100		
0505	---					---					Asphalt	100				Thick Slab	Cast-in-place concrete			100	
0506	---					---					Asphalt	100				Thick Slab	Cast-in-place concrete			100	
0507	---					---					Asphalt		100			Thick Slab	Precast concrete		100		
0702	Seals/Sealants		100			Bearings		100			Asphalt			50	50	Thin Slab	Cast-in-place concrete		100		
0802	---					---					Asphalt			85	15	Thick Slab	Cast-in-place concrete		75	25	
0803	Seals/Sealants		100			Bearings		100			Asphalt		100			Thin Slab	Cast-in-place concrete		100		
0804	Seals/Sealants		100			Bearings		100			Asphalt		100			Thin Slab	Cast-in-place concrete		100		
1706	---					---					Asphalt		96	4		Thick Slab	Cast-in-place concrete		100		

** E = Excellent; G = Good; F = Fair; P = Poor*

Figure 6.2: Condition Data for Sample Bridges

The condition percentages of the DOT bridges were converted to the federal highway administration (FHWA) condition rating scale (0-9). The conversion values shown in Table 6.1 were used to determine the sum of the percentages for the different conditions multiplied by the conversion values. For example, bridge 0504's asphalt, 79% of which is in good condition and 21% of which is in poor condition, has a condition rating of 5.58 (0.79 x 6 + 0.21 x 4).

Table 6.1: FHWA Condition Rating Conversion Table

Condition state	Condition Rating Range
Excellent	8
Good	6
Fair	4
Poor	1.5

6.2.2 Element Weights

Engineers from the DOT were interviewed in order to obtain values for the importance (1 – 10) of each bridge element in the overall bridge condition rating (BCR). Based on this information, the importance factors shown in Table 6.2 were determined and were used to calculate the contribution weight for each element.

Table 6.2: Element Weights

Element	Importance Factor	Weight
Deck	9	0.191
Overlay	6	0.128
Joints	4	0.085
Bearings	8	0.170
Superstructure	10	0.213
Substructure	8	0.170
Finishing (coating)	2	0.043
	$\sum = 47$	$\sum = 1.0$

The weights shown in Table 6.2 were employed in the ME-BMS to calculate the bridge condition rating (BCR) for each bridge. Figure 6.3 shows the BCR for each bridge and the overall network condition rating (NCR) for the bridge network was calculated to be 5.67.

	Current Condition Rating							5.67
Struct_ID	Deck	Overlay	Joints	Bearings	Supper Structure	Sub Structure	Finishing	BCR condition Rating
102	5.98	6.00			5.98	5.80	5.98	5.94
103	7.64	6.00	6.00		7.64	6.00	7.64	6.88
404	3.00	3.13	4.00		3.00	5.68	3.00	3.67
501	5.90	5.78	5.00		5.90	6.00	5.90	5.81
502	6.00	3.88	6.00		6.00	6.00	6.00	5.67
504	6.00	5.58	6.00		6.00	5.70	6.00	5.87
805	6.00	6.00			6.00	6.00	6.00	6.00
806	2.89	6.00	6.00		2.89	3.00	2.89	3.71
807	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
810	5.82	6.00			5.82	5.94	5.82	5.88
812	5.38	5.90	6.00	6.00	5.38	5.70	5.38	5.66
813	5.87	6.00			5.87	6.00	5.87	5.92
814	6.00	5.75	6.00	6.00	6.00	5.98	6.00	5.96
901	5.51	5.90	6.00		5.51	5.92	5.51	5.70
902	5.60	6.00			5.60	5.70	5.60	5.69
903	5.91	5.78	6.00		5.91	5.88	5.91	5.89

Network condition rating (NCR)

Figure 6.3: Condition Rating Calculation

6.2.3 Cost Data and Budget Limits

The cost data were collected through interviews with the DOT engineers, and from previous DOT contracts. Most of the contracts were for lump sums, and thus, no unit prices were available. However, with the use of CAD drawings and contract documents for sample bridges, it was possible to obtain unit prices for repair activities for different bridge elements. Table 6.3 shows a summary of the estimated repair/replacement costs.

With respect to budget limits, the DOT has a transportation capital plan (TCP) for major repairs and rehabilitation, with an approximate budget of $5,000,000/year for the whole network (173 bridges). This amount is in addition to a small budget of $150,000/year for regular maintenance and emergency situations.

Table 6.3: Cost Data for the Case Study

Element	Repair option	Unit	Unit price ($)
Deck	Concrete patches	m^3	4,530.00
	Concrete removal (partial depth)	m^3	1,667.00
	Concrete deck repairs	m^2	340.00
	Deck waterproofing	m^2	16.83.00
Overlay	Removal of asphalt pavement	m^2	8.00
	Concrete overlay and curing	m^2	88.50
	Concrete overlay	m^3	730.00
Joints	Hot rubberized asphalt joint	m	1,671.00
Bearings	Repair/replacement	each	600.00
Substructure	Excavation for structure footing	m^3	52.71
	Concrete in footings	m^3	430.00

6.2.4 Deterioration and Improvement Model

The DOT has no deterioration model for predicting future element conditions. The process of deciding whether the bridge requires a repair is based on a bi-annual inspection. There is also no improvement model for estimating the impact of a specific repair option on the element condition. Thus, the deterioration and improvement models used in the case study were adopted from Chapter 4.

6.3 Experimenting with the ME-BMS

While raw data was provided by the DOT for the bridges in the case study, no information was given about the coming five-year TCP that describes the repair strategy suggested for these bridges. The methodology used by the DOT to decide on repair decisions were assumed based on interviewing DOT engineers is as follows:

- At the project-level, to avoid the need to revisit the bridge in the near future, if the DOT decided to repair a bridge, then all the elements should be returned to a good condition rating based on engineering judgment and on the size and nature of repair. The level of improvement where the DOT will decide on returning all the elements is 7.5 (on scale 0 – 9) as discussed with the DOT engineers.
- At the network level, on a yearly basis, the DOT sorts the bridges according to their condition ratings, and the most deteriorated bridges are selected for repair until the budget is exhausted. That is, the bridges are sorted according to the bridge condition rating for selecting which one to be repaired.

Following these processes, it was possible to simulate the decisions made by the DOT and then compare them with the decisions from the ME-BMS. The criteria used in the comparison include:

- Project-level decisions: ratio of the benefits gained for both the BCR and the user costs to the repair cost.
- Network-level decisions: total repair budget cost, the overall network condition rating (NCR), and the benefits gained in user costs.

6.3.1 Comparison of Project-Level Decisions

As discussed in Chapters 4 and 5, the project-level decision support system in the ME-BMS aims to maximize the ratio of the benefits gained in both the bridge condition rating and the user costs to the repair costs, this ratio is used as the criterion to compare between the repair decisions made according the DOT strategy versus those obtained from the ME-BMS as indicated in Equation 6.1.

$$B_{PL} / C_R = \sum_{i=1}^{N} \frac{B_{BCR_i} \times 10^5 + B_{UC_i}}{C_{R_i}} \tag{6.1}$$

where B_{PL} / C_R = the ratio of the total project-level benefits to the repair cost for bridge *i*; B_{BCRi} = the benefit gained in the bridge condition rating for bridge *i*, which is equal to the difference between the after-repair and before-repair BCR; B_{UCi} = the benefits in user cost for bridge *i*, which is the difference between the after-repair and that before-repair user cost; and C_{Ri} = the total element repair cost for bridge *i*. (The reason of multiplying the benefits in BCR by 10^5 is because this is relatively small compared to the value of the benefits in the user costs which is expressed in millions) .

Project-level decisions by the DOT: Figure 6.4 shows the element repair decisions obtained using the DOT strategy. Parts (a) and (b) show the element repair decisions and the element repair costs, respectively. Part (c) shows the predicted after-repair element condition ratings; the calculated bridge condition rating is shown in column (d). The total element repair cost is shown in column (e), and the benefit gained in user costs from implementing the repairs is shown in column (f). For example, for bridge 504, the deck, joints, superstructure, and substructure require repair option 1, while the bearings and the finishing require repair option 2 with a total repair cost of $20,137 and an improvement in the BCR from 5.87 to 7.08. This result means that the benefit in the BCR for this particular bridge is 1.21 (7.08-5.87), and the benefit gained in user costs from implementing the repair options is equal to $15,570 (part f of Figure 6.4). The sum of the benefits gained in the bridge condition rating (B_{BCR}) for the network is 73.28 (340.46 - 267.18). The total repair cost for the whole network if it is decided to be repaired in year 1 is shown at the top of column (e) and is equal to $4,063,681. Thus, the ratio of the benefit gained in the network condition rating to the repair cost (B_{BCR}/C_R) is 1.80x10^{-5}. The sum of the benefits gained in the user costs after implementing the repair decisions is shown at the top of column (f) of Figure 6.4, and is equal to $2,684,494. Thus the ratio of the benefit with respect to user costs to the repair cost (B_{UC}/C_R) is equal to 0.66. Therefore, the ratio of the project-level benefit to the repair cost (B_{PL}/C_R) based on the DOT strategy is equal to 2.46 (1.80 + 0.66).

NCR Before Repair

NCR After Repair

User Cost Benefits

Bridge ID	5.67	B/C	Element Repair Decision							Element Repair Cost				ment Condition Ra			7.24	Repair Cost	User Cost Benefits
	BCR		2007							2007				2007			BCR	$4,063,681	$2,684,494
		2007	Slab	Overlay	joint	Bearing	Supper	Sub	Finish	Slab	Overlay	Sub	Finish	Slab	Sub	Finish	2007	2007	2007
102	5.94	34.52	1	2	0	0	1	1	2	$3,675	$1,029	$3,281	$5,145	6.98	6.80	7.98	7.17	$14,718	$26,169
103	6.88	7.76	0	2	1	0	0	1	0	$0	$4,526	$13,725	$0	7.42	7.00	7.14	7.37	$28,011	$6,013
104	5.96	21.04	1	2	0	0	1	1	2	$3,705	$1,037	$10,688	$5,187	7.00	6.84	8.00	7.19	$21,530	$15,335
401	5.87	92.45	1	2	0	0	1	1	2	$7,337	$2,054	$7,538	$10,271	6.90	6.68	7.90	7.09	$32,795	$88,706
402	5.88	36.03	1	2	0	0	1	1	2	$3,087	$864	$4,725	$4,322	6.80	6.98	7.80	7.10	$14,799	$27,725
404	3.67	53.11	4	5	3	0	4	1	5	$101,745	$15,504	$6,413	$38,760	7.00	6.68	8.00	7.16	$295,989	$51,930
501	5.81	38.81	1	2	2	0	1	1	2	$14,250	$3,990	$8,550	$19,950	6.90	7.00	7.90	7.12	$109,776	$37,621
502	5.67	23.61	1	4	1	0	1	1	2	$13,746	$11,547	$8,700	$19,244	7.00	7.00	8.00	7.19	$96,218	$22,033
504	5.87	21.55	1	2	1	0	1	1	2	$3,393	$950	$4,350	$4,750	7.00	6.70	8.00	7.08	$20,137	$15,570
505	5.14	15.36	3	0	0	0	3	1	4	$11,466	$0	$4,388	$8,026	7.00	7.00	8.00	7.11	$27,913	$8,309
506	5.14	14.51	3	0	0	0	3	1	4	$12,402	$0	$4,388	$8,681	7.00	7.00	8.00	7.11	$30,190	$7,995
507	5.98	25.16	1	2	0	0	1	1	2	$1,469	$411	$4,238	$2,057	7.00	6.90	8.00	7.21	$8,580	$10,838
702	5.59	26.63	1	5	1	2	1	1	2	$22,754	$29,125	$12,263	$31,855	7.00	7.00	8.00	7.31	$217,440	$25,833
802	5.08	133.32	2	4	0	0	2	0	2	$9,975	$2,993	$0	$4,988	7.50	9.00	7.50	7.53	$21,893	$122,158
803	6.09	259.28	1	2	1	2	1	1	0	$65,276	$18,277	$32,906	$0	7.00	7.00	7.50	7.32	$299,192	$258,872
804	6.00	231.95	1	2	1	2	1	1	2	$28,341	$7,935	$15,075	$39,677	7.00	7.00	8.00	7.34	$194,809	$231,266
805	6.00	135.56	1	2	0	0	1	1	2	$4,950	$1,386	$7,425	$6,930	7.00	7.00	8.00	7.23	$22,941	$130,207
806	3.71	206.09	4	2	1	0	4	4	5	$39,060	$1,302	$39,060	$14,880	6.89	7.00	7.89	7.14	$110,562	$202,981
807	6.00	242.44	1	2	1	2	1	1	2	$42,026	$11,767	$21,656	$58,837	7.00	7.00	8.00	7.34	$309,953	$242,003
810	5.88	141.92	1	2	0	0	1	1	2	$6,365	$1,782	$10,050	$8,911	6.82	6.94	7.82	7.11	$29,816	$137,801
812	5.66	126.32	2	2	1	2	2	1	2	$49,218	$4,922	$10,575	$24,609	7.38	6.70	7.38	7.40	$155,998	$125,198
813	5.92	51.68	1	2	0	0	1	1	2	$3,315	$928	$7,313	$4,641	6.87	7.00	7.87	7.15	$17,237	$44,552

$\sum = 267.18$ $\sum = 340.46$

(a) Repair Decisions (b) Repair cost (c) Condition Rating (d) (e) (f)

Figure 6.4: Project-Level Decisions for Year 1 of the Planning Horizon Using DOT Strategies

Project-level decisions from the ME-BMS: Using the ME-BMS, project-level optimization was carried out to maximize the ratio of both the condition benefit and the user cost benefit to the repair cost. The results of the optimization for year 1 are presented in Figure 6.5. Parts (a), (b), (c), (d), (e), and (f) are similar to those mentioned in Figure 6.4. The after-repair network condition rating is 7.26 with total repair costs of $3,057,849. The sum of the benefits in the bridge condition rating (B_{BCR}) is 73.99 (341.14 - 267.18). Therefore, the benefit in the bridge condition rating to the repair cost (B_{BCR}/C_R) is equal to 2.42x10^{-5}. The ratio of the benefit gained in the user cost (B_{UC}) as shown in Figure 6.5 is $2,629,464; therefore, the B_{UC}/C_R ratio is 0.86. Based on these values, the total project-level benefit to repair cost ratio (B_{PL}/C_R) is 3.28 (2.42 + 0.86).

NCR before repair | NCR after repair | Total repair cost

Bridge ID	5.67	Project-Level Decisions							Element repair Cost				Element Condition				BCR	Repair Cost	BUC
	BCR condition Rating	2007							2007				2007				7.26	$3,057,849	$2,629,464
		Slab	Overlay	joint	Bearing	Supper	Sub	Finish	Slab	Bearing	Supper	Finish	Slab	Supper	Sub	Finish	2007	2007	2007
102	5.94	1	3	0	0	3	1	0	$3,675	$0	$4,445	$0	6.98	8.98	6.80	5.48	7.77	$13,607	26,169
103	6.88	0	3	0	0	0	1	0	$0	$0	$0	$0	7.42	7.46	7.00	7.14	7.38	$23,424	6,013
104	5.96	1	2	0	0	3	0	0	$3,705	$0	$2,555	$0	7.00	9.00	5.76	5.50	7.37	$7,298	13,892
401	5.87	1	3	0	0	2	1	0	$7,337	$0	$9,400	$0	6.90	7.90	6.68	5.40	7.41	$28,676	88,706
402	5.88	1	3	0	0	2	0	0	$3,087	$0	$3,025	$0	6.80	7.80	5.81	5.30	7.15	$7,964	24,856
404	3.67	5	5	1	0	3	3	2	$116,280	$0	$75,863	$16,958	8.00	6.00	8.68	5.00	7.18	$257,094	51,930
501	5.81	1	3	1	0	1	2	0	$14,250	$0	$37,500	$0	6.90	6.90	8.00	5.40	7.24	$87,375	37,621
502	5.67	1	5	0	0	1	2	0	$13,746	$0	$33,701	$0	7.00	7.00	8.00	5.50	7.27	$83,312	22,033
504	5.87	1	3	0	0	2	0	0	$3,393	$0	$3,450	$0	7.00	8.00	5.53	5.50	6.98	$8,878	13,817
505	5.14	3	1	0	0	5	1	1	$11,466	$0	$6,454	$1,433	7.00	9.00	7.00	5.00	7.80	$24,314	11,377
506	5.14	3	1	0	0	5	1	1	$12,402	$0	$7,551	$1,550	7.00	9.00	7.00	5.00	7.80	$26,510	11,204
507	5.98	0	2	0	0	2	0	0	$0	$0	$681	$0	5.83	8.00	5.75	5.50	6.78	$1,093	0
702	5.59	1	5	0	3	1	2	0	$22,754	$5,400	$104,584	$0	7.00	7.00	8.00	5.50	7.42	$187,614	25,833
802	5.08	1	4	0	0	2	0	0	$3,563	$0	$3,938	$0	6.50	7.50	9.00	5.00	7.01	$10,493	122,158
803	6.09	1	3	0	3	1	1	0	$65,276	$10,800	$140,072	$0	7.00	7.00	7.00	7.50	7.50	$288,220	258,872
804	6.00	1	3	1	3	1	2	0	$28,341	$6,000	$83,500	$0	7.00	7.00	8.00	5.50	7.70	$182,583	231,266
805	6.00	1	2	0	0	3	0	0	$4,950	$0	$6,300	$0	7.00	9.00	6.00	5.50	7.43	$12,636	130,207
806	3.71	5	3	0	0	5	3	3	$44,640	$0	$10,080	$9,300	7.89	7.89	6.00	5.89	7.33	$94,710	202,981
807	6.00	1	3	0	3	1	2	0	$42,026	$9,900	$145,636	$0	7.00	7.00	8.00	5.50	7.58	$268,257	242,003
810	5.88	1	3	0	0	3	1	0	$6,365	$0	$7,581	$0	6.82	8.82	6.94	5.32	7.71	$27,815	137,801
812	5.66	1	3	0	3	1	1	1	$17,578	$3,600	$31,472	$8,789	6.38	6.38	6.70	6.38	7.13	$82,561	125,198
813	5.92	1	3	0	0	3	1	0	$3,315	$0	$2,913	$0	6.87	8.87	7.00	5.37	7.75	$15,530	44,552

$\sum = 267.18$ | $\sum = 341.14$

(a) Repair Decisions | (b) Repair cost | (c) Condition Rating | (d) | (e) | (f)

Figure 6.5: Project-Level Decisions for Year 1 of the Planning Horizon Using the ME-BMS

Table 6.4 presents a summary of results for year 1 in the planning horizon for the project-level decisions obtained using the DOT strategy and those obtained from the ME-BMS. The results clearly show that the ratio of the benefits gained for both the bridge ratio bridge condition rating and the user costs to the repair cost is higher using the ME-BMS than using the DOT. This comparison shows that the project-level repair decisions using the ME-BMS would result in more efficient spending with respect to the benefits gained. The DOT and Me-BMS network-level decisions using the project-level repair decisions are compared in the next section.

Table 6.4: Project-Level Comparison Results

Strategy	Total BCR		B_{BCR}	Repair Cost (C_R)	B_{BCR}/C_R ($\times10^{-5}$)	B_{UC}	B_{UC}/C_R	B_{PL}/C_R
	Before-repair	after-repair						
DOT	267.10	340.46	73.28	$4,063,681	1.80	$2,684,494	0.66	**2.46**
ME-BMS	267.10	341.09	73.99	$3,057,849	2.420	$2,629,464	0.86	**3.280**

6.3.2 Network-Level Decisions

The DOT annual budget for the bridge network is about $5,000,000. In this case study, the annual budget limit for the 47 bridges is assumed to be $700,000. Figure 6.6 shows the case study without any repair decisions; the network condition rating (NCR) is estimated to be 4.86, and the minimum bridge condition rating (BCR) is 2.34.

The constraints considered at the network level are to meet the budget limits while satisfying the predefined user values for the bridge condition rating (BCR) and the element condition rating (ECR) as follows:

$$Yearly\,Repair\ Cost_t \leq Allowed\ Budget_t \tag{6.2}$$

$$BCR \geq \quad 4.0 \tag{6.3}$$

$$ECR \geq \quad 3.0 \tag{6.4}$$

ME-BMS
Multi Element BRIDGE MANAGEMENT SYSTEM

Allowed Budget	$3,500,000	$700,000	$700,000	$700,000	$700,000	$700,000
Total Repair Cost	$0	$0	$0	$0	$0	$0

2006	*Current Year*
47	*Number of Bridges*
4.86	*Average Network Condition*
2.34	*Minimum BCR*
0.00	*Minimum Element Condition*

Bridge ID	5.67 Current BCR	Network-Level Decision					BCR					Repair Cost				
		2007	2008	2009	2010	2011	2007	2008	2009	2010	2011	2007	2008	2009	2010	2011
102	5.94	0	0	0	0	0	5.71	5.48	5.26	5.04	4.82	$0	$0	$0	$0	$0
103	6.88	0	0	0	0	0	6.56	6.25	5.93	5.63	5.33	$0	$0	$0	$0	$0
104	5.96	0	0	0	0	0	5.75	5.54	5.32	5.11	4.90	$0	$0	$0	$0	$0
401	5.87	0	0	0	0	0	5.58	5.29	5.01	4.74	4.47	$0	$0	$0	$0	$0
402	5.88	0	0	0	0	0	5.59	5.30	5.02	4.75	4.48	$0	$0	$0	$0	$0
404	3.67	0	0	0	0	0	3.43	3.17	2.88	2.57	2.34	$0	$0	$0	$0	$0
501	5.81	0	0	0	0	0	5.49	5.18	4.88	4.58	4.28	$0	$0	$0	$0	$0
502	5.67	0	0	0	0	0	5.39	5.11	4.84	4.57	4.30	$0	$0	$0	$0	$0
504	5.87	0	0	0	0	0	5.57	5.28	4.99	4.70	4.42	$0	$0	$0	$0	$0
505	5.14	0	0	0	0	0	4.85	4.57	4.29	4.02	3.75	$0	$0	$0	$0	$0
506	5.14	0	0	0	0	0	4.85	4.57	4.29	4.02	3.75	$0	$0	$0	$0	$0
507	5.98	0	0	0	0	0	5.70	5.40	5.08	4.76	4.44	$0	$0	$0	$0	$0
702	5.59	0	0	0	0	0	5.27	4.95	4.64	4.36	4.15	$0	$0	$0	$0	$0
802	5.08	0	0	0	0	0	4.82	4.54	4.22	3.89	3.56	$0	$0	$0	$0	$0

Figure 6.6: Bridge Network Case Study without Repair

As mentioned earlier, the methodology used by the DOT is based on sorting the bridges according to their condition rating and then, until the budget is exhausted, selecting for repair the bridges with the worst condition. On the other hand, the ME-BMS network-level optimization is based on maximizing the benefits gained with respect to both the NCR and the user costs. Four experiments were designed in order to examine the efficiency of the network-level repair decisions obtained from the ME-BMS as compared to those obtained from using the DOT strategy. The four experiments are described as follows:

1. Experiment 1: using the project-level decisions and DOT network-level strategy.
2. Experiment 2: using the DOT project-level decisions and then the ME-BMS network-level strategy.
3. Experiment 3: using the project-level decisions from the ME-BMS and then the DOT network-level strategy.
4. Experiment 4: using the project-level decisions and network-level strategy from ME-BMS.

Experiment 1: In this experiment the project-level decisions from the DOT strategy as shown in Figure 6.4 were considered in the network-level decision making. The results of the network-level decisions using the DOT strategy are shown in Figure 6.7. The after-repair NCR is 5.90, the BCR is 4.35, and the ECR is 0.67. The total repair cost is $3,481,400, and the benefit gained with respect to user costs after the repair decisions were implemented is $4,822,785. It should be noted that both the BCR and ECR are below the constraint values indicated in Equations 6.3 and 6.4. It should be noted that the ECR value is below the minimum safe condition rating, which means that some bridges with critical element conditions were not selected for repair.

Experiment 2: This experiment is based on the assumption that the DOT is satisfied with their project-level repair decisions; however, the question is whether the ME-BMS provides any added benefits at the network level as compared to the DOT's decision-making process. Therefore, the project-level decisions from the DOT shown in Figure 6.4 were considered as the project-level decisions for this experiment, and the network-level decisions were obtained from the ME-BMS. The results of the network-level decisions are shown in Figure 6.8. The NCR after-repair is 6.00, the BCR is 3.86, and the ECR is 2.34. The total repair cost is $3,468,0032, and the benefit gained with respect to user costs from implementing the repair decisions is $6,176,684. Although the

ECR value is below the constraint safe value, the ECR and NCR improved significantly compared to the results in experiment 1 with almost the same repair cost. There was also great enhancement in the benefits gained with respect to user costs.

ME-BMS

Multi-Element Bridge Management System

	Total					
Allowed Budget	$3,500,000	$700,000	$700,000	$700,000	$700,000	$700,000
Total Repair Cost	$3,481,400	$699,347	$698,478	$689,848	$696,070	$697,656

2006 Current Year

47

Optimization

5.90 Average Network Condition (NCR)

4.35 Minimum Bridge Condition (BCR)

0.67 Minimum Element Condition (ECR)

Project Level Decisions

☑ DOT Project level decisions

☐ ME-BMS Project level decisions

Network Level Decisions

☑ DOT Strategy

☐ ME-BMS Optimization

Benefits in user cost

Bridge ID	5.67	Network-Level Decision					BCR					Repair Cost					Project Level Decisions							User Cost	$4,822,785	
	BCR	2007	2008	2009	2010	2011	2007	2008	2009	2010	2011	2007	2008	2009	2010	2011	Slab	Overlay	joint	Bearing	Supper	Sub	Finish	2007	2010	2011
102	5.94	0	0	0	0	0	5.72	5.50	5.29	5.08	4.87	$0	$0	$0	$0	$0	0	0	0	0	0	0	0	0	0	0
103	6.88	0	0	0	0	0	6.57	6.26	5.96	5.66	5.37	$0	$0	$0	$0	$0	0	0	0	0	0	0	0	0	0	0
104	5.96	0	0	0	0	0	5.76	5.56	5.35	5.15	4.95	$0	$0	$0	$0	$0	0	0	0	0	0	0	0	0	0	0
401	5.87	0	0	0	0	0	5.59	5.31	5.04	4.78	4.52	$0	$0	$0	$0	$0	0	0	0	0	0	0	0	0	0	0
402	5.88	0	1	0	0	0	5.60	7.37	7.10	6.84	6.58	$0	$21,580	$0	$0	$0	2	2	0	0	2	1	2	0	27,900	27,961
404	3.67	1	0	0	0	0	7.16	6.90	6.63	6.32	6.00	$295,989	$0	$0	$0	$0	4	5	3	0	4	1	5	51,930	52,755	53,041
501	5.81	0	0	0	0	1	5.50	5.20	4.90	4.61	7.38	$0	$0	$0	$0	$230,067	2	5	4	0	2	2	4	0	0	38,646
502	5.67	0	0	0	0	1	5.40	5.13	4.87	4.60	7.27	$0	$0	$0	$0	$206,581	2	5	3	0	2	2	4	0	0	22,675
504	5.87	0	0	0	0	0	5.58	5.30	5.01	4.74	4.46	$0	$0	$0	$0	$0	0	0	0	0	0	0	0	0	0	0
505	5.14	1	0	0	0	0	7.11	6.84	6.57	6.30	6.05	$27,913	$0	$0	$0	$0	3	0	0	0	3	1	4	8,309	11,444	11,468
506	5.14	1	0	0	0	0	7.11	6.84	6.57	6.30	6.05	$30,190	$0	$0	$0	$0	3	0	0	0	3	1	4	7,995	11,276	11,300
507	5.98	1	0	0	0	0	7.21	6.91	6.60	6.29	5.99	$8,580	$0	$0	$0	$0	1	2	0	0	1	1	2	10,838	10,865	10,875
702	5.59	0	0	0	1	0	5.27	4.96	4.66	7.34	7.04	$0	$0	$0	$397,515	$0	2	5	3	3	2	2	3	0	26,585	26,845
802	5.08	1	0	0	0	0	7.53	7.25	6.95	6.63	6.28	$21,893	$0	$0	$0	$0	2	4	0	0	2	0	2	122,158	122,856	123,099
803	6.09	0	0	0	0	0	5.73	5.38	5.04	4.70	4.36	$0	$0	$0	$0	$0	0	0	0	0	0	0	0	0	0	0

Figure 6.7: Network-Level Decisions for Experiment 1

ME-BMS

Multi-Element Bridge Management System

	Total					
Allowed Budget	$3,500,000	$700,000	$700,000	$700,000	$700,000	$700,000
Total Repair Cost	$3,468,032	$693,322	$697,401	$699,678	$697,359	$680,272

2006 Current Year

47

Optimization

6.00 Average Network Condition (NCR)

3.86 Minimum Bridge Condition (BCR)

2.34 Minimum Element Condition (ECR)

Project Level Decisions

☑ DOT Project level decisions

☐ ME-BMS Project level decisions

Network Level Decisions

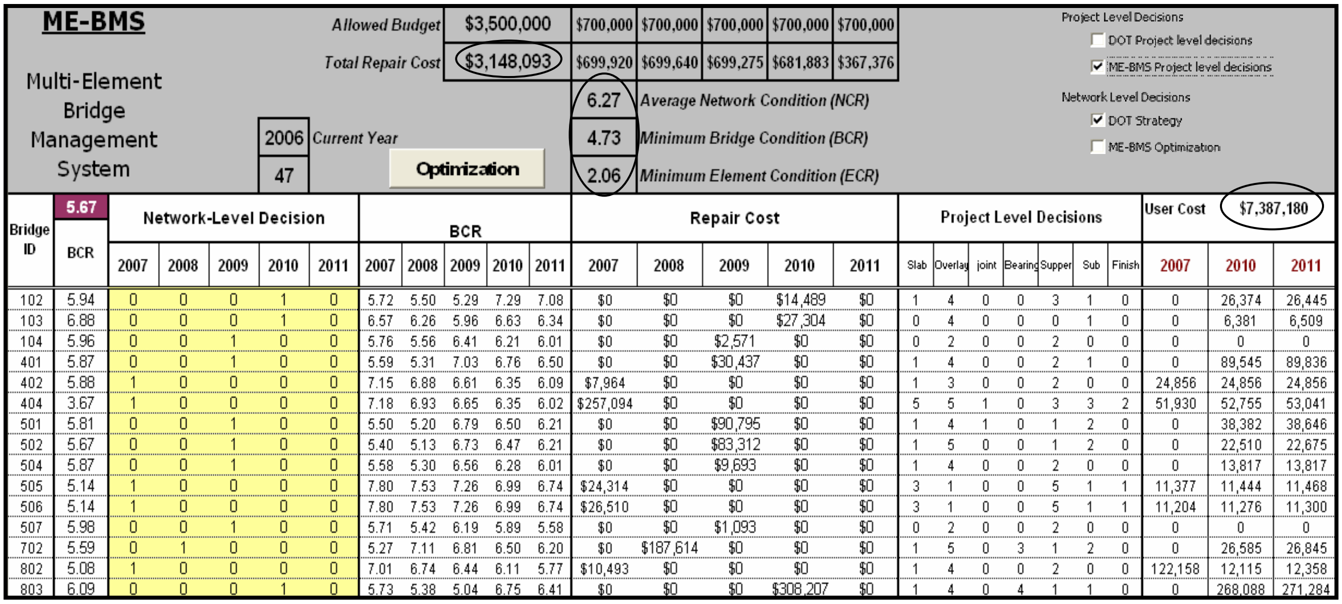
☐ DOT Strategy

☑ ME-BMS Optimization

Bridge ID	5.67	Network-Level Decision					BCR					Repair Cost					Project Level Decisions							User Cost	$6,176,684	
	BCR	2007	2008	2009	2010	2011	2007	2008	2009	2010	2011	2007	2008	2009	2010	2011	Slab	Overlay	joint	Bearing	Supper	Sub	Finish	2007	2010	2011
102	5.94	0	0	1	0	0	5.72	5.50	6.96	6.75	6.54	$0	$0	$18,099	$0	$0	1	3	0	0	1	1	3	0	26,374	26,445
103	6.88	0	0	1	0	0	6.57	6.26	7.30	7.00	6.71	$0	$0	$73,932	$0	$0	0	3	2	0	0	2	1	0	6,381	6,509
104	5.96	0	0	1	0	0	5.76	5.56	7.01	6.81	6.61	$0	$0	$24,938	$0	$0	1	3	0	0	1	1	3	0	15,423	15,454
401	5.87	0	0	0	1	0	5.59	5.31	5.04	7.44	7.19	$0	$0	$0	$66,607	$0	2	4	0	0	2	2	3	0	89,545	89,836
402	5.88	0	0	0	1	0	5.60	5.32	5.05	7.45	7.20	$0	$0	$0	$30,358	$0	2	4	0	0	2	2	3	0	27,900	27,961
404	3.67	1	0	0	0	0	7.16	6.90	6.63	6.32	6.00	$295,989	$0	$0	$0	$0	4	5	3	0	4	1	5	51,930	52,755	53,041
501	5.81	0	0	0	1	0	5.50	5.20	4.90	7.47	7.18	$0	$0	$0	$212,397	$0	2	4	4	0	2	2	3	0	38,382	38,646
502	5.67	0	1	0	0	0	5.40	7.17	6.90	6.64	6.38	$0	$118,971	$0	$0	$0	1	5	2	0	1	1	2	0	22,510	22,675
504	5.87	0	0	0	1	0	5.58	5.30	5.01	7.48	7.20	$0	$0	$0	$50,281	$0	2	4	3	0	2	2	3	0	15,677	15,714
505	5.14	0	1	0	0	0	4.86	6.83	6.56	6.30	6.04	$0	$27,913	$0	$0	$0	3	0	0	0	3	1	4	0	11,444	11,468
506	5.14	0	1	0	0	0	4.86	6.83	6.56	6.30	6.04	$0	$30,190	$0	$0	$0	3	0	0	0	3	1	4	0	11,276	11,300
507	5.98	0	1	0	0	0	5.71	6.94	6.62	6.31	6.01	$0	$8,580	$0	$0	$0	1	2	0	0	1	1	2	0	10,865	10,875
702	5.59	1	0	0	0	0	7.31	7.00	6.69	6.39	6.09	$217,440	$0	$0	$0	$0	1	5	1	2	1	1	2	25,833	26,585	26,845
802	5.08	0	1	0	0	0	4.84	7.58	7.28	6.95	6.61	$0	$25,598	$0	$0	$0	2	5	0	0	2	0	3	0	122,856	123,099
803	6.09	0	0	0	0	0	5.73	5.38	5.04	4.70	4.36	$0	$0	$0	$0	$0	0	0	0	0	0	0	0	0	0	0

Figure 6.8: Network-Level Decisions for Experiment 2

Experiment 3: This experiment was designed based on the assumption that the DOT is satisfied with their network-level strategy; however, the question is whether any added benefits result from the use of the project-level decisions obtained by the ME-BMS. Therefore, the project-level decisions obtained from the ME-BMS shown in Figure 6.5 were used. The results of the network-level decisions following the DOT strategy are shown in Figure 6.9.

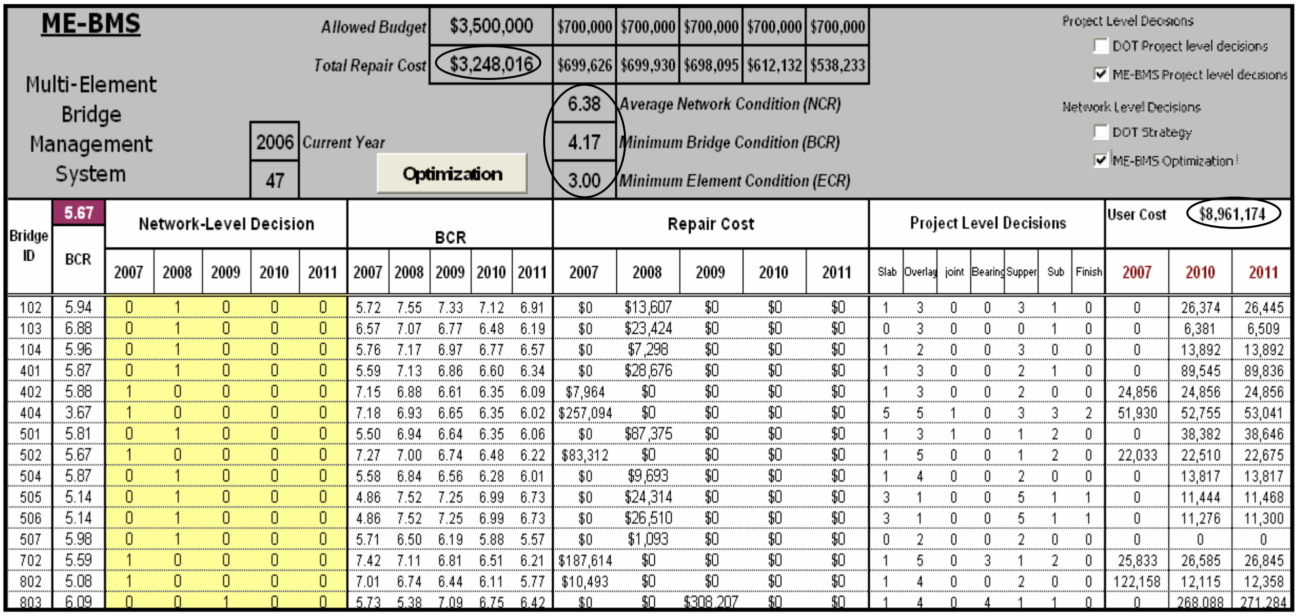


Bridge ID	BCR	Network-Level Decision					BCR					Repair Cost					Project Level Decisions							User Cost		
	5.67	2007	2008	2009	2010	2011	2007	2008	2009	2010	2011	2007	2008	2009	2010	2011	Slab	Overlay	joint	Bearing	Supper	Sub	Finish	2007	2010	2011
102	5.94	0	0	0	1	0	5.72	5.50	5.29	7.29	7.08	$0	$0	$0	$14,489	$0	1	4	0	0	3	1	0	0	26,374	26,445
103	6.88	0	0	0	1	0	6.57	6.26	5.96	6.63	6.34	$0	$0	$0	$27,304	$0	0	4	0	0	0	1	0	0	6,381	6,509
104	5.96	0	0	1	0	0	5.76	5.56	6.41	6.21	6.01	$0	$0	$2,571	$0	$0	0	2	0	0	2	0	0	0	0	0
401	5.87	0	0	1	0	0	5.59	5.31	7.03	6.76	6.50	$0	$0	$30,437	$0	$0	1	4	0	0	2	1	0	0	89,545	89,836
402	5.88	1	0	0	0	0	7.15	6.88	6.61	6.35	6.09	$7,964	$0	$0	$0	$0	1	3	0	0	2	0	0	24,856	24,856	24,856
404	3.67	1	0	0	0	0	7.18	6.93	6.65	6.35	6.02	$257,094	$0	$0	$0	$0	5	5	1	0	3	3	2	51,930	52,755	53,041
501	5.81	0	0	1	0	0	5.50	5.20	6.79	6.50	6.21	$0	$0	$90,795	$0	$0	1	4	1	0	1	2	0	0	38,382	38,646
502	5.67	0	0	1	0	0	5.40	5.13	6.73	6.47	6.21	$0	$0	$83,312	$0	$0	1	5	0	0	1	2	0	0	22,510	22,675
504	5.87	0	0	1	0	0	5.58	5.30	6.56	6.28	6.01	$0	$0	$9,693	$0	$0	1	4	0	0	2	0	0	0	13,817	13,817
505	5.14	1	0	0	0	0	7.80	7.53	7.26	6.99	6.74	$24,314	$0	$0	$0	$0	3	1	0	0	5	1	1	11,377	11,444	11,468
506	5.14	1	0	0	0	0	7.80	7.53	7.26	6.99	6.74	$26,510	$0	$0	$0	$0	3	1	0	0	5	1	1	11,204	11,276	11,300
507	5.98	0	0	1	0	0	5.71	5.42	6.19	5.89	5.58	$0	$0	$1,093	$0	$0	0	2	0	0	2	0	0	0	0	0
702	5.59	0	1	0	0	0	5.27	7.11	6.81	6.50	6.20	$0	$187,614	$0	$0	$0	1	5	0	3	1	2	0	0	26,585	26,845
802	5.08	1	0	0	0	0	7.01	6.74	6.44	6.11	5.77	$10,493	$0	$0	$0	$0	1	4	0	0	2	0	0	122,158	12,115	12,358
803	6.09	0	0	0	1	0	5.73	5.38	5.04	6.75	6.41	$0	$0	$0	$308,207	$0	1	4	0	4	1	1	0	0	268,088	271,284

Figure 6.9: Network-Level Decisions for Experiment 3

The after-repair NCR is 6.27, the BCR is 4.73, and the ECR is 2.06. The total repair cost is \$3,148,093, and the benefit gained with respect to user costs is \$7,387,180. It should be noted that the value of the BCR is meeting the constraint value indicated in Equation 6.4**Error! Reference source not found.**; however, the value of the ECR still does not meet the constraint value in Equation **Error! Reference source not found.**. The value of the NCR is significantly higher than that obtained in experiment 2 with less repair costs. In addition, the benefit gained with respect to user costs (B_{UC}), was higher than the values obtained in experiments 1 and 2.

Experiment 4: In this experiment, both the project-level decisions and the network-level decisions were those obtained from the ME-BMS. The results of the network-level decisions are shown in Figure 6.10. The after-repair NCR is 6.38, the BCR is 4.17, and the ECR is 3.00. It should be noted that both the values for the BCR and ECR meet the constraint values. The total repair cost is \$3,248,016. Although the NCR achieved in this experiment is higher than that from experiment 3, the total repair cost is less. The benefit gained in the user cost from implementing the repairs is $8,961,174, which is higher than the user cost benefits obtained in any other experiment.



ME-BMS

Multi-Element Bridge Management System

Allowed Budget	$3,500,000	$700,000	$700,000	$700,000	$700,000	$700,000	
Total Repair Cost	$3,248,016	$699,626	$699,930	$698,095	$612,132	$538,233	
2006	Current Year	6.38	Average Network Condition (NCR)				
47	Optimization	4.17	Minimum Bridge Condition (BCR)				
		3.00	Minimum Element Condition (ECR)				

Project Level Decisions
DOT Project level decisions
ME-BMS Project level decisions
Network Level Decisions
DOT Strategy
ME-BMS Optimization

Bridge ID	5.67 BCR	Network-Level Decision 2007	2008	2009	2010	2011	BCR 2007	2008	2009	2010	2011
102	5.94	0	1	0	0	0	5.72	7.55	7.33	7.12	6.91
103	6.88	0	1	0	0	0	6.57	7.07	6.77	6.48	6.19
104	5.96	0	1	0	0	0	5.76	7.17	6.97	6.77	6.57
401	5.87	0	1	0	0	0	5.59	7.13	6.86	6.60	6.34
402	5.88	1	0	0	0	0	7.15	6.88	6.61	6.35	6.09
404	3.67	1	0	0	0	0	7.18	6.93	6.65	6.35	6.02
501	5.81	0	1	0	0	0	5.50	6.94	6.64	6.35	6.06
502	5.67	1	0	0	0	0	7.27	7.00	6.74	6.48	6.22
504	5.87	0	1	0	0	0	5.58	6.84	6.56	6.28	6.01
505	5.14	0	1	0	0	0	4.86	7.52	7.25	6.99	6.73
506	5.14	0	1	0	0	0	4.86	7.52	7.25	6.99	6.73
507	5.98	0	1	0	0	0	5.71	6.50	6.19	5.88	5.57
702	5.59	1	0	0	0	0	7.42	7.11	6.81	6.51	6.21
802	5.08	1	0	0	0	0	7.01	6.74	6.44	6.11	5.77
803	6.09	0	0	1	0	0	5.73	5.38	7.09	6.75	6.42

Bridge ID	Repair Cost 2007	2008	2009	2010	2011	Project Level Decisions Slab	Overlay	joint	Bearing	Supper	Sub	Finish	User Cost $8,961,174 2007	2010	2011
102	$0	$13,607	$0	$0	$0	1	3	0	0	3	1	0	0	26,374	26,445
103	$0	$23,424	$0	$0	$0	0	3	0	0	0	1	0	0	6,381	6,509
104	$0	$7,298	$0	$0	$0	1	2	0	0	3	0	0	0	13,892	13,892
401	$0	$28,676	$0	$0	$0	1	3	0	0	2	1	0	0	89,545	89,836
402	$7,964	$0	$0	$0	$0	1	3	0	0	2	0	0	24,856	24,856	24,856
404	$257,094	$0	$0	$0	$0	5	5	1	0	3	3	2	51,930	52,755	53,041
501	$0	$87,375	$0	$0	$0	1	3	1	0	1	2	0	0	38,382	38,646
502	$83,312	$0	$0	$0	$0	1	5	0	0	1	2	0	22,033	22,510	22,675
504	$0	$9,693	$0	$0	$0	1	4	0	0	2	0	0	0	13,817	13,817
505	$0	$24,314	$0	$0	$0	3	1	0	0	5	1	1	0	11,444	11,468
506	$0	$26,510	$0	$0	$0	3	1	0	0	5	1	1	0	11,276	11,300
507	$0	$1,093	$0	$0	$0	0	2	0	0	2	0	0	0	0	0
702	$187,614	$0	$0	$0	$0	1	5	0	3	1	2	0	25,833	26,585	26,845
802	$10,493	$0	$0	$0	$0	1	4	0	0	2	0	0	122,158	12,115	12,358
803	$0	$0	$308,207	$0	$0	1	4	0	4	1	1	0	0	268,088	271,284

Figure 6.10: Network-Level Decisions for Experiment 4

6.3.3 Network-Level Discussions and Results

The criteria used to evaluate the results of the experiments are based on the benefits gained in both the network condition rating (B_{NCR}) and the user cost (B_{UC}) to the total network repair cost (C_{TR}). A network-level benefits/cost ratio (B_{NL}/C_{TR}) is used to represent the quality of the results. The B_{NL}/C_{TR} ratio is the sum of the benefits gained relative to the total repair cost, as follows:

$$B_{NL} / C_{TR} = \frac{B_{NCR} \times 10^6 + B_{UC}}{C_{TR}} \tag{6.5}$$

where B_{NL} = the benefits gained at the network level, B_{NCR} = the benefits gained in the network condition rating, B_{UC} = the total benefits gained in user costs, and C_{TR} = the total network repair cost.

Table 6.5 summarises the results of the four experiments carried at the network level in order to examine the efficiency of the decisions made using the DOT strategy versus those obtained from the ME-BMS decision-support system. When DOT project-level decisions were used in experiments 1 and 2, it was noted that the value of the ECR is always below the constraint value, 3.00, Equation 6.4. The DOT project-level repair decisions are considered relatively high since the DOT strategy aims to bring all the elements to a certain condition level; therefore, it costs more to repair a single bridge, and consequently, some bridges are not selected for repair because the budget has been exhausted before all the deficient bridges are repaired. Only experiment 4 met the constraint value of the ECR, because of the use of ME-BMS strategy that considers the minimum value of ECR as a constraint in the project-level and network-level optimization process. The value of the BCR in experiments 1, 3 and 4 meets the constraint value, with the highest value recorded in experiment 3, this is attributed to the use of the project-level decision of ME-BMS which allows to include more bridges in the prioritization.

Table 6.5: Results for Network-Level Experiments

Experiment No.	Experiment 1	Experiment 2	Experiment 3	Experiment 4
Project-level strategy	DOT	DOT	ME-BMS	ME-BMS
Network-level strategy	DOT	ME-BMS	DOT	ME-BMS
Element condition rating (ECR)	0.67	2.34	2.06	3.00
Bridge condition rating (BCR)	4.35	3.86	4.73	4.17
Network condition rating (NCR)	5.90	6.00	6.27	6.38
Benefits in network condition (B_{NCR})	1.04	1.14	1.41	1.52
Total network repair cost (C_{TR})	$3,481,400	$3,468,032	$3,148,093	$3,248,016
Benefits in user cost (B_{UC})	$4,822,785	$6,176,684	$7,387,180	$8,961,174
Condition benefits to cost **B_{NCR}/C_{TR}**	**0.298**	**0.329**	**0.448**	**0.467**
User cost benefits to cost **B_{UC}/C_{TR}**	**0.139**	**0.178**	**0.235**	**0.276**
Total benefits to repair cost **B_{NL}/C_{TR}**	**0.437**	**0.507**	**0.683**	**0.744**

A comparison of experiments 1 and 2 with respect to the ratio of the benefits gained in the network condition rating to the repair cost (BNCR/CTR) shows a significant improvement in the benefits gained, since the value of the NCR is higher for experiment 2. This result indicates that the use of the ME-BMS with the project-level decisions from the DOT leads to better results than using both the project-level and network-level decisions using the DOT strategy. Similarly, the ratio of the benefit gained with respect to the user costs to the repair cost (BUC/CTR) in experiment 2 is higher than that in experiment 1, since ME-BMS aims at maximizing both the network condition and the benefits gained in user costs. Experiment 3, which considers the ME-BMS project-level decisions and follows the DOT strategy at the network level, produced better results in terms of the NCR and the benefits in user cost as compared to experiment 2. The highest BNCR/CTR and BUC/CTR values were obtained in experiment 4 which incorporates both the project-level and network-level decisions from the ME-BMS. These results show the efficiency of implementing the ME-BMS for the case study as compared to using decisions made according to the DOT strategies.

6.4 Feedback from the Department of Transportation

In an effort to validate the system's practicality and performance, a meeting was held with bridge management professionals from the DOT who provided the case study data. Prior to the meeting, detailed information was given to them regarding the case study and the results produced. In the meeting, the system details were explained along with how their data were analyzed. The results shown in Table 6.5 comparing the DOT assumed decision results and those of the ME-BMS were discussed in great detail.

The DOT professionals showed interest in implementing the ME-BMS into practice. The feedback they provided about the features and strength of the system can be summarized as follows:

- The model is relatively simple yet effective in prioritizing bridges.
- The transparency of the ME-BMS model in terms of its flexibility for customizing various parameters, e.g., customizing the element weights and the unit costs, was considered advantageous.

- The flexibility of the model in changing repair decisions at either the network level or the project level and automatically viewing the consequences of such changes with respect to the condition ratings, repair costs, and benefits in user costs was an efficient feature in the opinion of the DOT professionals, as the engineers often like to investigate "what-if" scenarios.

- The ability to take into account different deterioration models for each element type is considered a significant contribution of the ME-BMS in predicting the future condition of the elements. Moreover, the feature of customizing the transition probability matrix based on inspected data was considered to be very practical and improve the use of the bi-annual inspection data.

- The ability of the ME-BMS to perform more than one cycle for a five-year analysis is useful for both short-term and long-term planning. The system can optimize more cycles by running the first five-year optimization, then taking the last year's condition ratings as the input for the next five-year planning horizon.

It should be noted that the analysis of the DOT data included in this chapter focused on simulating their decision process and comparing its predicted results with those of the ME-BMS. Since the ME-BMS provided interesting and practical decisions, the DOT engineers expressed interest in using the ME-BMS on upcoming maintenance plans for which DOT decisions have been already made. This would serve as realistic testing of the ME-BMS.

The DOT representatives recommended modifications to the ME-BMS to suit their system. These modifications can be summarized as follows:

1. Improve the ability of the ME-BMS to feed directly from the inspection program currently used by the DOT, and improve the ability of the ME-BMS to link to the existing database.

2. Increase the ability to track and save more "what-if" scenarios.

3. Forecast beyond five-years in one cycle rather than repeating the process through several cycles.

4. Develop importance factor for each bridge. Although this aspect is reflected in the benefits gained in user costs, more development and testing are needed.

6.5 Application of the ME-BMS Work Zone Model

The ME-BMS work zone user-cost model developed in Chapter 5 was applied to the case study in order to show the applicability of the work zone model to be implemented in real life. Since, there were no work zone strategies provided by the DOT, the network-level and project-level decisions for experiment 4 were then used. Figure 6.11 shows the optimized work zone strategies for the case study and the associated user costs estimated for the work zone for each bridge.

	OPTIMIZATION					$425,377						
No.	Traffic Strategy	Construction Window				Total Cost ($)	Total Time (hr)	Night Time Shifts	Week End Closure	Continuous closure (CC/SO)	Full closure (FC/CO)	Crash Cost
		Nighttime	Weekends	CC/SO	FC/CO							
404	5	2	5	3	0	$8,663	348.6	$418	$4,342	$2,459	$0	$0
501	5	6	1	0	0	$3,762	103	$1,854	$1,281	$0	$0	$0
502	5	6	1	0	0	$3,809	103	$1,878	$1,296	$0	$0	$0
702	5	7	1	3	0	$4,180	168.6	$1,068	$632	$1,784	$0	$0
802	5	0	0	0	0	$0	0	$0	$0	$0	$0	$0
803	6	11	6	0	0	$117,871	418	$8,853	$89,373	$0	$0	$0
804	6	23	0	0	0	$59,529	184	$49,608	$0	$0	$0	$0
805	6	4	0	0	0	$9,868	32	$8,223	$0	$0	$0	$0
806	6	2	2	0	0	$124,323	126	$2,431	$101,171	$0	$0	$0
807	1	27	1	0	0	$41,645	271	$30,076	$4,628	$0	$0	$0
810	8	0	0	0	0	$0	0	$0	$0	$0	$0	$0
812	6	3	2	0	0	$8,594	134	$1,730	$5,431	$0	$0	$0
813	6	0	0	0	0	$0	0	$0	$0	$0	$0	$0
814	6	9	1	1	0	$14,823	146.2	$6,514	$3,004	$2,834	$0	$0
903	1	5	1	0	0	$4,180	95	$1,905	$1,579	$0	$0	$0
1003	1	3	3	0	0	$8,276	189	$1,342	$5,555	$0	$0	$0
1701	5	2	0	2	0	$6,334	54.4	$1,073	$0	$4,205	$0	$0
2201	5	1	3	0	0	$9,520	173	$589	$7,344	$0	$0	$0
2301	5	0	0	0	0	$0	0	$0	$0	$0	$0	$0
2302	1	0	0	0	0	$0	0	$0	$0	$0	$0	$0

Figure 6.11: ME-BMS Work Zone User Cost for the Case Study

For example, for bridge 803, the best strategy for performing the repairs on the bridge is to have 11 days of nighttime shifts and 6 weekends; the estimated user cost that will be incurred on this bridge during the repair period is estimated to be $117,871. The estimated total user costs to be incurred at work zone based on the strategies shown in Figure 6.11 are $425,377.

6.6 Summary and Conclusions

In this chapter, data for a real case study for a network of bridges were collected from the DOT; 47 bridges were tested using the proposed multi-element bridge management system (ME-BMS) and the DOT's strategies for making decisions at the project and network levels. The comparison shows that ME-BMS produces optimal element repair decisions that maximize the benefits gained with respect to the ratio of benefits gained in both the bridge condition rating and user costs to the repair cost. Similarly, in a number of experiments, the results obtained from the ME-BMS proved to be very efficient at the network level in terms of maximizing the network condition rating as well as the benefits gained with respect to user costs. An optimized work zone strategy that minimizes user costs incurred during the repair periods has also been implemented for the case study.

Chapter 7

Conclusions and Future Research

7.1 Summary and Conclusions

Bridges are important components of the transportation infrastructure. As bridges age, departments of transportation are faced with increasing pressure to keep their bridge networks healthy and operational with limited repair funds. The main objective of this research, therefore, is to develop a practical and efficient framework for managing large bridge networks. The proposed framework is innovative in its ability to optimize decisions at the network level (which bridge should be repaired and when) as well as at the project level (best type of repair for bridge elements).

An initial effort developed a new framework for bridge management that focuses only on bridge decks. The framework successfully integrates both project-level and network-level decisions. The developed framework incorporates a Markov chain deterioration model, an improvement model, and a repair-cost model. The initial framework served as a test bed for modeling the life cycle cost analysis at both the project and network levels.

Since mathematical optimization proved unsuitable for this problem, the life cycle optimization of the initial bridge deck management system (BDMS) utilized non-traditional optimization techniques based on evolutionary algorithms. Four state-of-the-art evolutionary algorithms were experimented with: genetic algorithms (GA), shuffled frog leaping (SFL), ant colony optimization (ACO), and particle swarm optimization (PSO). To compare the performance of these algorithms, several experiments were carried out with different numbers of bridges. Both GA and SFL were found to outperform the other evolutionary techniques, and their performance was comparable; therefore, they were used in further development.

Life cycle optimizing proved to be a complex task, particularly in the case of a large network of bridges. Because of the random nature of evolutionary algorithms, arriving at a feasible solution takes a great deal of time. In addition, some of the minimum condition constraints are very difficult to meet. Accordingly, to overcome these difficulties, extensive experimentation was carried out in order to determine the best methodology for modelling the life cycle cost optimization. A pre-processing function was developed for both the GA and SFL in order to prevent any bridge deck ultimately receiving a condition rating lower than the minimum acceptable. This process ensures that the funds are first allocated to the must-repair bridges.

To speed the optimization process for both the GA and SFL, an automated function was introduced to force some of the decisions in the initial population to be zeros. This process proved efficient and logical since many of the bridges are not expected to be included in the repair plan due to budget constraints. This function determines the suitable percentage of non-zeros in the initial population used in both the GA and SFL.

To obtain close to optimal life cycle costs and, accordingly, the best decisions, several objective functions were experimented with: using the minimum total life cycle cost (typically used), minimizing the difference between the actual repair cost and the available budget, and maximizing the network condition rating. These objective functions were applied to the case of a five-year analysis and the case of a five-step year-by-year analysis (both methods optimize the decisions for a five-year planning horizon). The results of these experiments revealed that the use of the year-by-year formulation with the objective function of maximizing the network condition is the best strategy in terms of producing the highest overall network condition while meeting all constraints, including the budget limit.

Based on this initial framework, a bridge deck management system prototype (BDMS) was developed and proved to be flexible, easy-to-use and capable of performing "what-if" analysis.

Based on the experiments carried out on the BDMS, the model was expanded and generalized to include other bridge elements. Based on the literature and interviews with bridge experts, seven bridge elements were considered in the development of the multi-element bridge management system (ME-BMS): the deck, overlay, joints, bearings, superstructure, substructure, and finishing. The interviews were also beneficial in soliciting the practical strategies that have been considered by professionals in making repair decisions. One of the important findings is that it is preferable to repair all the elements of a bridge once through the planning horizon in order to reduce the number of interruptions in traffic flow (single visit). These interviews also provided valuable input for the designing and structuring of the ME-BMS, and for defining some of the constraints involved in the optimization, such as budget limit.

As does the BDMS, the ME-BMS integrates project-level and network-level decisions. However, because the size of the optimization problem is exponentially large (seven elements as opposed to only the deck), the ME-BMS applies a different strategy for integrating project-level and network-level decisions. Rather than formulating the problem as one combined optimization, the ME-BMS incorporates two sequential optimizations: project-level optimization, in which the best repair decision for each element throughout the planning horizon is determined, and then network-level optimization which uses the results from the project-level optimization as input. The project-level optimization maximizes the ratio of the benefits gained in bridge condition to the repair cost (B/C). On the other hand, the network-level optimization maximizes the overall network condition in a five-step year-by-year life cycle analysis (Section 4.7). The ME-BMS proved efficient with large networks of bridges and satisfies the constraints of the project-level and network-level combined.

To add practicality to the generalized ME-BMS model, a user cost model was developed for calculating user costs before and after repairs. The ME-BMS user cost model considers the risk of accidents and the number of vehicles that are required to detour because of load and height postings. The user cost model is very flexible and transparent in that the user of the model can change the repair decision for any bridge element or change the year a bridge is to be repaired and examine the effect of this change on the benefits gained with respect to user costs.

To include the impact of user costs in the repair decisions, experiments were carried out for both the project-level and network-level formulations. The project-level optimization was then modified to include the user costs in the formulation. The project-level objective function was to maximize the ratio of the benefits gained in both the bridge condition rating and the user costs to the repair costs (Equation 5.9). Similarly, for the network level, the objective function was modified to maximize both the network condition rating and the benefits gained with respect to user costs (Equation 5.10). The modifications for the project-level and network-level objective functions resulted in better element repair decisions and better bridge prioritization.

To facilitate the practical use of the decisions produced by the ME-BMS, a model was developed for optimizing work-zone strategy during bridge maintenance. The model considers four construction windows: nighttime shifts, weekend shifts, continuous closure, and full closure. It is capable of calculating the expected user costs and delays due to the speed reductions or full stops associated with any strategy. The work zone model is integrated directly with the ME-BMS and selects the best work-zone strategy that minimizes the user costs incurred during the work zone periods.

The developed ME-BMS was validated through tests using data from a real-life network of bridges collected from a department of transportation (DOT). Several interviews were held with representatives from the DOT in order to solicit the decision strategy currently followed by the engineers in making repair decisions. A computerized model was then developed to simulate the DOT's strategies for both the project-level and network-level decisions. The resulting decisions based on the simulated DOT strategy were then compared to the decisions resulting from the implementation of the ME-BMS for the same case study. The comparison revealed the efficiency of the project-level and network-level decisions obtained by the ME-BMS: in all the experiments, the network condition rating was higher when the ME-BMS was used. A meeting was then held with the DOT's bridge management engineers to discuss the results, and the simplicity, practicality, and efficiency of the ME-BMS were confirmed. The DOT's engineers were interested in further testing and expansion of the ME-BMS to suit their needs.

Based on the current developments, this research makes a number of contributions:

- **Better understanding of bridge management needs:** This study has reviewed the research and practice regarding the identification of the components of a bridge management system. This knowledge was obtained from previous research and interviews with transportation agencies.

- **Customization of the Markov chain deterioration model:** This research resulted in the development of a practical, easy-to-use Markov chain deterioration model. The developed deterioration model builds on inspection data collected by municipalities. The developed Markov chain model customizes the deterioration matrices to produce new ones that realistically describe the deterioration of different bridge elements in different environments.

- **Integration of project-level and network-level decisions:** The main advantage of this research is the integration of the project-level and network-level decisions. This integration was simple in the case of only one component, for which both types of decisions are made at the same time in a single optimization process that considers all constraints on both levels. On the other hand, in the case of multiple bridge elements, the integration of the project-level and network-level decisions was made in two sequential optimization cycles. This methodology has been proven to arrive at good decisions on both the network and project levels.

- **Efficient handling of large-scale problems:** This research has investigated different techniques and methodologies for handling large-scale bridge networks, a typical infrastructure-asset-management problem. The performance of the optimization and the quality of the decisions are dependent to a great extent on the objective function, the problem size, and the formulation. The best strategy for optimizing the infrastructure problem is to prioritize the assets on a yearly basis while attempting to gain the maximum benefits from the repair.

- **Fine tuning of evolutionary algorithms:** Several methods enhance the performance of evolutionary algorithms. This research proposes to create an initial population that is random but close to the expected near-optimal solution. For large-scale problems in which one of the constraints might be hard to meet, it is also preferable to pre-process the population and the offspring to meet this constraint.

- **Consideration of experts' needs**: This research has led to a better understanding of the needs of the professionals in the field of bridge management, which can be summarized as follows:

  - A flexible system that is interactive and easy to use
  - A system that considers "what-if" scenarios in a simple, automated, and efficient way
  - A system that can forecast beyond five-year planning horizon
  - A system that accounts for the importance of a bridge to the network.

7.2 Future Research

Despite the capabilities and benefits of the developed ME-BMS, it has limitations that could be improved through further research:

1. Currently, the element weights considered in the system are fixed for all the bridges. While this assumption might be reasonable, from a practical point, each bridge in the network can have different element weights based on the expert opinion, age, and on the function of the element. For example, a deck in a slab-type bridge is expected to have more weight than a deck in a girder-type bridge.
2. Because the decisions provided by the ME-BMS are based on the initial condition of the elements, it is crucial to develop a clear and well-defined condition assessment model to help inspectors easily assess the condition of the element using recent visualization technologies.

3. The ME-BMS in its current format considers five repair options with their associated unit rates. A more precise repair cost model for each bridge element can be developed through surveys of consulting offices and transportation agencies involved in bridge repairs.

4. The improvement model considered in the developed ME-BMS is based on the assumption that the element condition rating will improve according to the repair option. More research is needed in order to determine better estimate of the improvement in the condition rating because of a specific repair. In the developed model, the values for the expected improvement in all the elements is fixed; for example, it is estimated that the deck condition is increased by 1 if the repair option is 1. Similarly, in the case of the joints. However, it is preferable to have an improvement model for each element separately based on a user definition.

5. Currently, the after-repair deterioration is assumed to be similar to the before-repair deterioration. However, in practice, the after-repair rate of deterioration is faster than that assumed. Therefore, more research is needed in order to estimate the after-repair behaviour for each bridge element.

6. The deterioration model considered in the development of the ME-BMS is based on a study that was presented in the literature and that has environmental conditions that differ from location to another. Therefore, it is recommended that accurate deterioration models for each bridge element be developed based on the regular inspection reports collected by DOTs. Such deterioration models can be developed using the methodology described in Chapter 3.

7. The user-cost model in the ME-BMS is based only on the condition rating for the deck, superstructure, and substructure; however, users are significantly affected by the condition of the rest of the bridge elements, such as the overlay and joints. Therefore, developing user-cost models for predicting the impact of the condition ratings of the different elements on the user costs is needed.

8. In the developed work zone user-cost model, the time needed for the work zone is based on rough estimates and it is assumed that all the bridge activities proceed in series; however, in reality, some activities run in parallel. Therefore, it is important to arrive at a better estimate of the time needed for each bridge repair activity and the relationships among them, and to link them to scheduling software.

9. The repair decisions and the work zone in the ME-BMS are based only on bridge networks and ignore the roadways connected to the network, so it would be beneficial to link the ME-BMS repair decisions to the roadway repair decisions and arrive at optimal traffic routing that minimizes interruptions for the highway as a whole.

10. The project-level and network-level decisions obtained from the ME-BMS were compared to the repair decisions that might be obtained by a department of transportation (DOT). However, to successfully test the model's repair decisions, it is important to examine them against a network of bridges for which a repair plan has already been determined. The author is currently implementing this step with engineers from the DOT.

11. The developed ME-BMS assumes that the repair cost, deterioration, and improvement are deterministic; however, it is important to incorporate uncertainty and probabilistic approach in the development of BMS components.

Appendix A
Evolutionary Algorithms

Evolutionary Algorithms (EAs) are stochastic search methods that mimic the metaphor of natural biological evolution and/or the social behaviour of species. The behaviour of such species is guided by learning, adaptation, and evolution (Lovbjerg, 2002). To mimic the efficient behaviour of these species, various researchers have developed computational systems that seek faster and more robust solutions to solve complex optimization problems. The first evolutionary-based technique introduced in the literature, was the genetic algorithms, (Holland, 1975; Goldberg, 1989). In an attempt to reduce processing time and improve the quality of solutions, particularly to avoid local optima, other EAs have been introduced during the past 10 years, including various GA improvements and recently developed techniques: shuffled frog leaping (SFL), particle swarm optimization (PSO), and ant colony optimization (ACO).

In general, EAs share a common approach for their application to a given problem. The problem usually requires some representation to suit each method, then, the evolutionary search algorithm is applied iteratively to arrive at optimum or near-optimum solution. Elbeltagi et al. (2005) compared the performance of five evolutionary algorithms for solving general optimization problems and reported the powerful performance of Genetic Algorithms and the Shuffled Frog Leaping (SFL) techniques. A brief description of these two algorithms is presented in the following subsections.

A.1 Genetic Algorithm (GA)

Genetic Algorithms were developed to mimic some of the processes observed in natural evolution; they employ a random yet directed search for locating optimal solution. John Holland (1975), from the University of Michigan began his work on genetic algorithms at the beginning of the 60s; the first publication of his work was on 1975. The basic techniques of the GA follow the principles first laid down by Charles Darwin of "survival of the fittest", since in natural competition among individuals for resources results in the fittest individuals dominating over the weaker ones (Forrest 1993). GA is a stochastic random optimization method for solving large scale problems. GA differs from normal optimization techniques in several ways. First, the algorithm works for a population of strings, searching many peaks in parallel. By employing genetic operators, it exchanges information between the peaks, thus lessening the possibility of ending at a local minimum and missing the global minimum. Second, the algorithm needs to evaluate only the fitness function to guide its search and not the derivatives or other auxiliary knowledge.

To start solving any problem, a coding scheme is formulated to encode the problem parameters. Usually this is done in the form of a string called chromosome (or gene) as presented in Figure A.7.1. This coding representation is dependent on the problem and not unique. The genes are generated in a random fashion, i.e. the values of the parameters that are coded in the genes are random values and each gene represents one solution that is better or worse for the problem. The construction of a GA for any problem is classified into the determination of chromosome representation, the determination of fitness function, the determination of population size and number of generations, and the determination of genetic operators (Chan and Tansri, 1994). Figure A.2 shows the basic steps of performing GA algorithms (Lin and Lee, 1996).

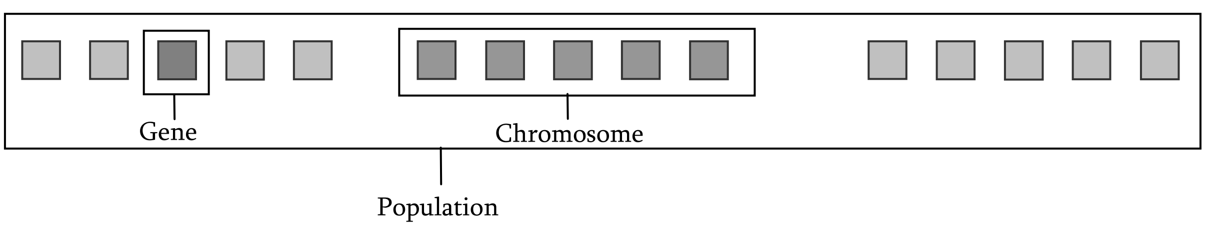


Figure A.7.1: Population, Gene and Chromosome Representation in GA

After defining the population, an objective function (fitness function) should be well defined for the problem. The fitness value of each string is computed from the fitness function. A good string is the one that scores a high fitness value. The size of the population is problem dependent and needs to be determined experimentally. Population size affects the quality of the end solution, as well as, the processing time it consumes. On the basis of the quality of a gene, the gene is assigned a fitness value. The solution will converge to near optimal solution after a certain number of generations (Chan and Tansri, 1994). The process continues for a large number of generations. Among all the possible solutions, the good solutions are selected, while the others are eliminated to simulate the process of "Survival of the fittest". The selected solutions undergo the processes of reproduction, crossover, and mutation to create new generations of possible solutions. The new set of generations are expected to perform better than the previous ones, they will be evaluated and assigned a new fitness value. The process continues until convergence is achieved within the population (Ross, 1995).

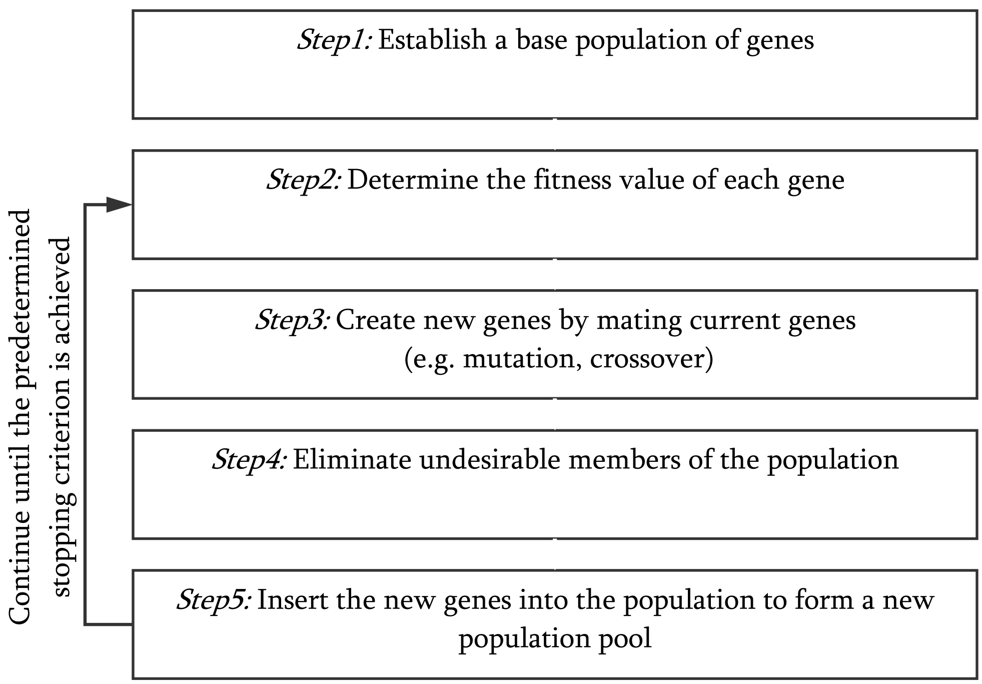


Figure A.2: Genetic Algorithm Process (Lin and Lee, 1996)

Fitness Normalization

Fitness normalization is the process of converting row fitness value to one that behaves better. It gives high probabilities for selecting good solutions in new generation, while maintaining some chances of survival to poor solutions (Boesel et al., 1999). Fitness normalization can be carried out in three forms: (1) inversion normalization, (2) linear ranking, and (3) non-linear ranking. The inversion normalization is considered the popular method in normalizing the fitness; it is calculated as follows:

$$F = \sum_{i=1}^{n} fitness\,(\,g_i\,) \tag{A.1}$$

$$F_i = \frac{fitness\,(\,g_i\,)}{F} \tag{A.2}$$

Selection

The selection process is conducted by one of the following techniques: roulette-wheel parent technique or tournament selection. The roulette-wheel technique starts with generating a random number (*m*) between 0 and the total fitness (*F*). Then return the first population whose fitness, added to the fitness of the preceding population members (running total) is greater than or equal to *m* (Lin and Lee, 1996). The wider span (best fit) for a chromosome, the higher the chance it will be selected. Figure A.3 shows a weighted roulette wheel for a population of 6 chromosomes. From Figure A.3, it can be noticed that chromosomes 2 and 5 are the fittest chromosomes and have higher probability over the rest of the population to be selected for further reproduction.

In the tournament selection, a number of chromosomes are chosen randomly from the population; the best fit chromosome is then selected and passed to the new generation (Goldberg and Deb, 1991). Tournaments are performed for a tournament of size "*S*" which represents the number of competing chromosomes in the tournament. Usually, tournaments consist of two chromosomes (*S=2*). The selection of the superior chromosome within a tournament is performed based on actual fitness values.

Crossover:

Crossover is the process by which the chromosomes are able to mix and exchange their desirable qualities in a random fashion; it is considered the most important operator in the genetic algorithm (Lane, 1993). Crossover (marriage) is conducted by selecting two parent chromosomes, exchanging their information, and producing an offspring. The two parent genes are selected randomly in a manner such that the probability of being selected is proportional to its relative fitness. This ensures that better chromosomes being selected in the process without violating the randomness. A random number is generated and compared to user-specified threshold value for crossover (P_c). The higher the crossover, the more quickly new structures are introduced to the population. The crossover proceeds in a simple way, for each couple of strings two random numbers are selected between 1 and m-1, where m is the chromosome length. The information between the two selected chromosomes is exchanged as shown in Figure A.4.This method is called "discrete crossover". Another method is called "arithmetic crossover", where an interpolation of genes values is performed in order to ensure that genes contents receive new values in the new generations (Kim and Adeli, 2001).

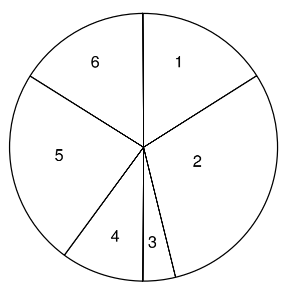


Figure A.3: Weighted Roulette Wheel (Lin and Lee, 1996)

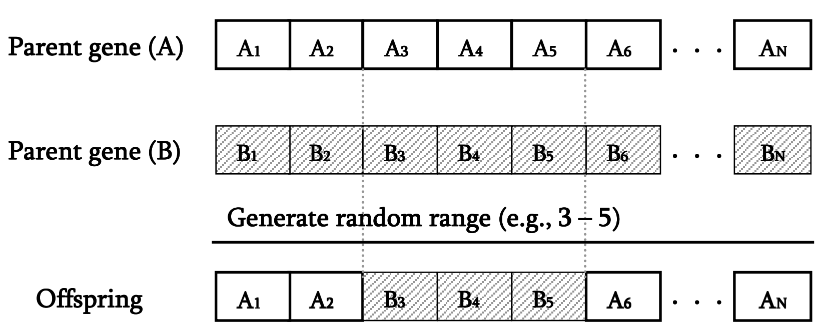


Figure A.4: Crossover Operator to Generate Offspring Genes (Elbeltagi and Hegazy, 2001)

Mutation

Mutation is a rare process that resembles the process of a sudden generation of an offspring that burns to be a genius (Goldberg, 1989). During the creation of a generation, it is possible that the entire population of strings is missing vital information that is important for determining the correct or the optimal solution. Future generations and crossover might not be able to arrive at this missing gene, sometimes the population is stagnated. The mutation process is capable to changing the properties of the gene, thus insures the introducing of the missing information. For each gene, a random number is generated and compared against the user-specified threshold value for mutation (P_m). Usually mutation is rare in nature, which is an order of once in one hundreds.

Elitism

Elitism is the process to overcome the problem of losing the best chromosome in each population due to the random nature employed in selection and the effect of crossover and mutation. In elitism, the chromosome with the best fitness in each population is retrieved and used to replace the least fit chromosome in new generation.

Many efforts had been carried out in the development and application of Genetic Algorithm (GA) in civil engineering. GA shows to be efficient in solving many optimization problems in Civil engineering, such as the site-layout optimization of facilities (Elbeltagi and Hegazy, 2001; Cheung et al., 2002; Li and Love, 2000, and Osama et al., 2003), cost optimization and cost trade off problems (Hegazy 1999b), and in resource levelling in construction (Leu et al., 2000; Hegazy, 1999a). The common conclusion among all the previous researches was the efficiency of implementing GA in solving complex problems and arriving at a near optimal solution in small time.

A.2 Shuffled Frog Leaping (SFL)

The SFL is another heuristic search algorithm. It attempts to balance between a wide scan of a large solution space and also a deep search of promising locations for a global optimum. The population in SFL consists of a set of frogs (solutions) each having the same solution structure as in the GA technique. The whole population of frogs is then partitioned into subsets referred to as memeplexes. The different memeplexes are considered as different cultures of frogs that are located at different places in the solution space (i.e. global search). Each culture of frogs performs a deep local search. Within each memeplex, the individual frogs hold information, that can be influenced by the information of their frogs within their memeplex, and evolve through a process of change of information among frogs from different memeplexes. After a defined number of evolution steps, information is passed among memeplexes in a shuffling process (Eusuff and Lansey, 2003). The local search and the shuffling processes (global relocation) continue until a defined convergence criterion is satisfied (Eusuff and Lansey, 2003).

As explained, the SFL formulation places emphasis on both global and local search strategies, which is one of its major advantages. As shown in Figure A.5a, the SFL algorithm starts with an initial population of "P" frogs created randomly. Frog i is represented as $X_i = (x_{i1}, x_{i2}, ..., x_{iS})$; where S represents the number of variables. Afterwards, the frogs are sorted in a descending order according to their fitness. Then, the entire population is divided into m memeplexes, each containing n frogs (i.e., $P = m \times n$). In this process, the first frog goes to the first memeplex, the second frog goes to the second memeplex, frog m goes to the m memeplex, and frog $m+1$ goes to the first memeplex, etc.

Within each local memeplex (Figure A.5b), the frogs with the best and the worst fitness are identified as X_b and X_w, respectively. Also, the frog with the global best fitness (the overall best frog) is identified as X_g. Then, an evolutionary process is applied to improve only the frog with the worst fitness (not all frogs) in each cycle.

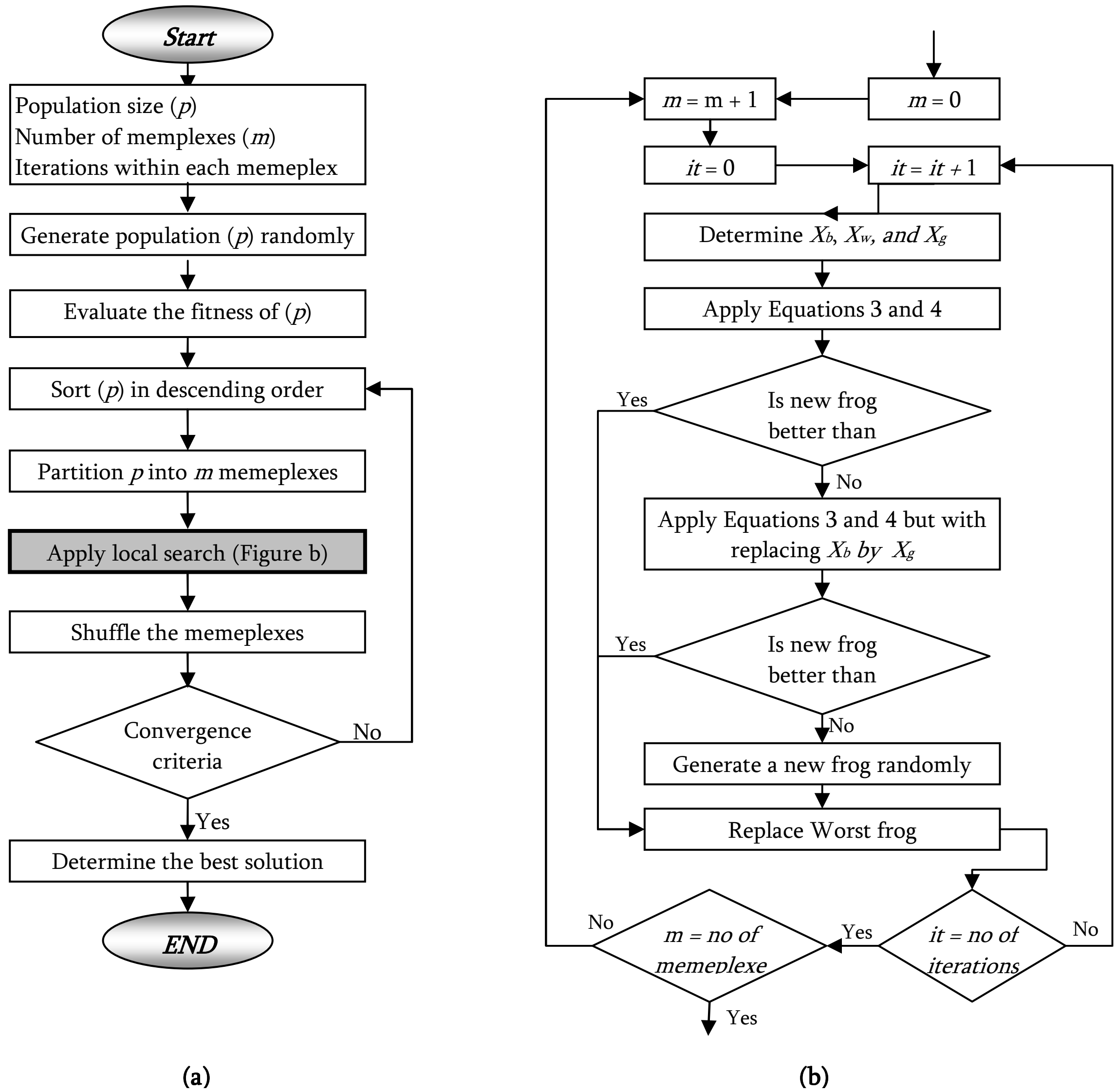


Figure A.5: Flowchart for SFL Algorithm (Elbehairy et al., 2006)

Accordingly, each frog updates its position to catch up with the best frog as follows:

$$\textit{Change in frog position } (D_i) = rand() \, . \, (X_b - X_w) \tag{A.3}$$

$$\textit{New position } X_w = \textit{current position } X_w + D_i;\ D_{max} \geq D_i \geq -D_{max} \tag{A.4}$$

where *rand()* is a random number between 0 and 1; and D_{max} is the maximum allowed change in frog's position. If this process produces a better solution, it replaces the worst frog. Otherwise, the calculations in Equations A.3 and A.4 are repeated with respect to the global best frog (i.e., X_g

replaces X_b). If no improvement becomes possible in this case, then a new solution is randomly generated to replace the worst frog. The calculations then continue for a specific number of iterations (Eusuff and Lansey, 2003). Accordingly, the main parameters of the SFL are the population size P, number of memeplexes, number of generations for each memeplex before shuffling, number of shuffling iterations, and maximum step size. More discussions about the SFL and its variations can be found in Elbeltagi et al. (2005).

A.3 Particle Swarm Optimization

Particle swarm optimization (PSO) is inspired by the social behaviour of a flock of migrating birds trying to reach a destination. In PSO, each solution is a "bird" in the flock and is referred to as a "particle". A particle is analogous to a chromosome (population member) in GAs. As opposed to GAs, the evolutionary process in the PSO doesn't create new birds from parent ones. Rather, the birds in the population only evolve their social behavior and accordingly their movement towards a destination (Kennedy and Eberhart, 1995).

The process is initialized with a group of random particles (solutions), N. The i^{th} particle is represented by its position as a point in an S-dimensional space, where S is the number of variables. Throughout the process, each particle i monitors three values: its current position ($X_i = x_{i1}, x_{i2}, \ldots\ldots, x_{iS}$); the best position it reached in previous cycles ($P_i = p_{i1}, p_{i2}, \ldots\ldots, p_{iS}$); and its flying velocity ($V_i = v_{i1}, v_{i2}, \ldots\ldots, v_{iS}$). In each time interval, the position (P_g) of the best particle (g) is calculated as the best fitness of all particles. Accordingly, each particle updates its velocity V_i as follows (Kennedy and Eberhart, 1995):

$$New\ V_i = \omega\ .\ current\ V_i + c_1\ .\ rand() \times (P_i - X_i) + c_2\ .\ Rand() \times (P_g - X_i) \qquad (A.5)$$

Using the new velocity V_i, the particle's updated position becomes:

$$New\ position\ X_i = current\ position\ X_i + New\ V_i\ ;\ V_{max} \geq V_i \geq -\ V_{max} \qquad (A.6)$$

where c_1 and c_2 are two positive constants named learning factors (usually $c_1 = c_2 = 2$); $rand()$ and $Rand()$ are two random functions in the range from 0 to 1, V_{max} is an upper limit on the maximum change of particle velocity, and ω is an inertia weight employed as an improvement proposed by

Shi and Eberhart (1998) to control the impact of the previous history of velocities on the current velocity. The operator ω plays the role of balancing the global search and the local search, and was proposed to decrease linearly with time from a value of 1.4 to 0.5 (Shi and Eberhart, 1998).

A.4 Ant Colony Optimization

Ant colony optimization (ACO) was developed by Dorigo et al. (1996) based on the fact that ants are able to find the shortest route between their nest and a source of food. This is done using pheromone trails, which ants deposit whenever they travel, as a form of indirect communication. Implementing the ACO for a certain problem requires a representation of S variables for each ant, with each variable i has a set of n_i options with their values l_{ij}, and their associated pheromone concentrations $\{\tau_{ij}\}$; where $i = 1, 2, \ldots. S$, and $j = 1, 2, \ldots n$. As such, an ant consists of S values that describe the path chosen by the ant as shown in Figure A.6.

In the ACO, The process starts by generating m random ants (solutions). An ant k ($k = 1, 2, \ldots.,$ m) represents a solution string, with a selected value for each variable. Each ant is then evaluated according to an objective function. Accordingly, pheromone concentration associated with each possible variable value is changed in a way to reinforce good solutions, as follows (Dorigo et al., 1996):

$$\tau_{ij}(t) = \rho\tau_{ij}(t-1) + \Delta\tau_{ij}; t = 1, 2, \ldots.., T \qquad \text{(A.7)}$$

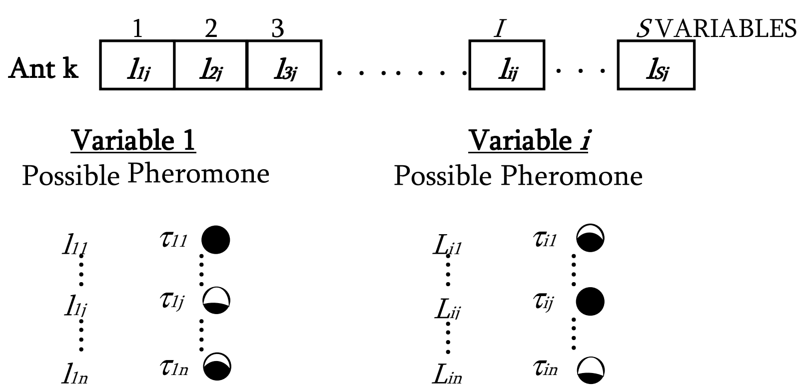


Figure A.6: Ant Representation (Elbeltagi et al., 2005)

where T is the number of iterations (generation cycles); $\tau_{ij}(t)$ is the revised concentration of pheromone associated with option l_{ij} at iteration t; $\Delta\tau_{ij}(t\text{-}1)$ is the concentration of pheromone at the previous iteration (t-1); $\Delta\tau_{ij}$ = change in pheromone concentration; and ρ = pheromone evaporation rate that ranges from 0 to 1 (0.4). The change in pheromone concentration $\Delta\tau_{ij}$ is calculated as (Dorigo et al. 1996):

$$\Delta\tau_{ij} = \sum_{k=1}^{m} \begin{cases} R / fitness_k \ (\text{if option } lij \text{ is chosen by ant } k) \\ 0 \qquad\qquad (\text{otherwise}) \end{cases} \tag{A.8}$$

where R is a constant called the pheromone reward factor, and $fitness_k$ is the value of the objective function (solution performance) calculated for ant k.

Once the pheromone is updated, the next iteration starts by changing the ants' paths (i.e., associated variable values) in a manner that respects pheromone concentration and also some heuristic preference. As such, an ant k at iteration t will change the value for each variable according to the following probability (Dorigo et al., 1996):

$$P_{ij}(k,t) = \frac{[\tau_{ij}(t)]^{\alpha} \times [\eta_{ij}]^{\beta}}{\sum_{l_{ij}} [\tau_{ij}(t)]^{\alpha} \times [\eta_{ij}]^{\beta}} \tag{A.9}$$

where $P_{ij}(k,t)$ = probability that option l_{ij} is chosen by ant k for variable i at iteration t; $\tau_{ij}(t)$ = pheromone concentration associated with option l_{ij} at iteration t; η_{ij} = heuristic factor for preferring among available options and is an indicator of how good it is for ant k to select option l_{ij} (η_{ij} is fixed for each option l_{ij}); and α and β are parameters that control the relative importance of pheromone concentration versus the heuristic factor. Both α and β can take values greater than zero.

Appendix B
Markov Chains

The following is a brief discussion on the definition of stochastic and Markov chains processes. Let X_t be the state of any system at time t, in most cases the value of X_t will not be known with certainty until the time arrives, so it may be viewed as random variable. In general, X_t depends on all previous states $X_0, X_1 \ldots X_{t-1}$. Discrete time stochastic process is a description of the relationship between these random variables $X_0, X_1 \ldots X_t$. A stochastic process is defined as the description of the change of states in a system in some probabilistic fashion at random interval of time; it is the process in which the past behaviour influences the future ones. The behaviour of a system is completely described by its defined states. Suppose $X_{(t)}$ describes the state of the system that has n values (matrix n x 1). That is, at any given time, $X_{1(t)}, X_{2(t)} \ldots\ldots\ldots\ldots X_{n(t)}$ are the possible states of the system. The system will move from one state to another in a random manner, where there is a probability attached to it called transition probability $p_{(t)}$, i.e. $p_{1(t)}$ is the probability of finding the system in state $X_{1(t)}$. In general, the predictive distribution for $X_{(t)}$ being a function of all previous state variables $X_{(t-1)}, X_{(t-2)}$ is quiet complicated. However, if $p_{(t)}$ depends only on the preceding state then the process is called "Markov Process". A Markov Process is a stochastic process which has transition probability from a given state $X_{(t)}$ to a future state $X_{(t+1)}$ is dependent only on the present state and not on the manner in which the current state was reached. The Markov Process should meet the following conditions (Collines, 1972):

- The system is defined by a set of finite states and that the system can be in one and only one state at a given time.
- The initial state of the system and the probability distribution of the initial state are known.
- The transition probabilities are assumed to be stationary over time and independent of how state i was reached.

The probability of transitioning from one condition state to another is represented in a matrix (n x n) that is called transition probability matrix P where n is the number of condition states. Each element in this matrix P_{ij} represents the probability that the system component will make a transition from state "i" to state "j" during a given period of time. If the present or the initial condition state is known, i.e., P_0, then the future condition can be predicted at any time T. The future state vector P_T can be obtained by multiplying the initial state vector P_0 by the transition probability matrix P raised to the power T (number of years) as follows (collins1972):

$$\text{The initial state of a system is given by}: p(0) = [p1, p2 \ldots\ldots\ldots pn] \quad \text{(B.1)}$$

$$P_T = P_0 \times P^T \quad \text{(B.2)}$$

where,

$$P = \begin{bmatrix} P_{11} & P_{12} & \ldots.. & P_{1n} \\ P_{21} & P_{22} & \ldots.. & P_{2n} \\ . & . & \ldots.. & . \\ . & . & \ldots.. & . \\ P_{n1} & . & \ldots.. & P_{nn} \end{bmatrix} \quad \text{(B.3)}$$

$p_{(1)} = p_{(0)} \times P$

$p_{(2)} = p_{(1)} \times P = p_{(0)} \times P \times P = p_{(0)} \times P^2$

Thus, for any k value:

$p_{(k-1)} = p_{(0)} \times P^{k-1}$

$p_{(k)} = p_{(0)} \times P^k$

The elements of P should meet the followings

$$\sum_{j=1}^{j=n} P_{ij} = 1 \quad \text{for all i (row sum)} \quad \text{(B.4)}$$

$$P_{ij} >= 0 \text{ for all } i \text{ and } j \quad \text{(B.5)}$$

$$R = \begin{pmatrix} 1 \\ 2 \\ . \\ . \\ n \end{pmatrix}$$

where R = the matrix of predefined condition states (n x 1)

$$\textit{The final condition}[1x1] = p_{(0)}[1xn] \quad x \quad PT[nxn] \quad x \quad R[nx1] \tag{B.6}$$

Jiang (1990) and Jiang et al. (1988) developed performance prediction model using the Markov chain for condition deterioration for the Indian Department of Highways (IDOH). One of the assumptions in this model was that the condition rating will not drop by more than one state in a single year. Thus the condition would either remain in its current state or make the transition to the next lower state in 1 year. In this model, the transition probability matrix was developed for three bridge elements: deck, superstructure, and substructure. The transition matrix is formulated as follows:

$$P = \begin{bmatrix} p_{(1)} & q_{(1)} & 0 & 0 & 0 & 0 & 0 \\ 0 & p_{(2)} & q_{(2)} & 0 & 0 & 0 & 0 \\ 0 & 0 & p_{(3)} & q_{(3)} & 0 & 0 & 0 \\ 0 & 0 & 0 & P_{(4)} & q_{(4)} & 0 & 0 \\ 0 & 0 & 0 & 0 & P_{(5)} & q_{(5)} & 0 \\ 0 & 0 & 0 & 0 & 0 & p_{(6)} & q_{(6)} \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{B.7}$$

where $p_{(1)}$ = the transition probability to remain in the same state, and $q_{(1)} = 1-p_{(1)}$ corresponds to $p_{i,j+1}$ (the probability of transferring to the lower level).

Example: The following is an example of implementing Markov Chains in predicting the future condition od a bridge. The deterioration transition matrix was build based on the FHWA condition rating with range from 0 to 9 with 9 being the maximum rating or near-perfect. Ten bridge condition rating are defined as ten states, with each condition rating corresponds to one of the states. According to the FHWA (1995) the lowest allowed condition rating number is 3, resulting in 7 condition states defined in a matrix R = [9,8,7,6,5,4,3]. Assume a bridge with steel deck in interstate highway has the following deterioration matrix and it is required to determine the condition rating after 6 years. The initial condition state, where the bridge is at condition 9, is given by:

$$\begin{array}{l} \\ p(0) = \end{array} \begin{array}{c} \begin{array}{ccccccc} 9 & 8 & 7 & 6 & 5 & 4 & 3 \end{array} \\ [\begin{array}{ccccccc} 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{array}] \end{array}$$

$$
P = \begin{array}{c c} & \text{Condition state:} \\ & \begin{array}{ccccccc} 9 & 8 & 7 & 6 & 5 & 4 & 3 \end{array} \\ \text{Condition state} \begin{array}{c} 9 \\ 8 \\ 7 \\ 6 \\ 5 \\ 4 \\ 3 \end{array} & \begin{bmatrix} 0.633 & 0.367 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.746 & 0.254 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.701 & 0.299 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.45 & 0.55 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.407 & 0.593 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.301 & 0.699 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \end{array}
$$

$$
\text{R = defined condition states} = \begin{pmatrix} 9 \\ 8 \\ 7 \\ 6 \\ 5 \\ 4 \end{pmatrix}
$$

The final condition then is equal to =

$$
= \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \times \begin{pmatrix} 0.633 & 0.367 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.746 & 0.254 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.701 & 0.299 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0.45 & 0.55 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.407 & 0.593 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.301 & 0.699 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1.00 \end{pmatrix}^{6} \times \begin{bmatrix} 9 \\ 8 \\ 7 \\ 6 \\ 5 \\ 4 \\ 3 \end{bmatrix} = 7.159
$$

Then the condition for steel deck bridge after 6 years will drop from 9.0 to 7.159.

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